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In-duct air cleaning devices: Ozone emission rates and test methodology

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Abstract

The ozone emission rate and the increase in indoor ozone concentrations from the use of electrically connected in-duct air cleaners were studied in this research. Electrically connected in-duct air cleaners (eight models) were tested on a laboratory test apparatus using a Standard Test Method that was developed for this project. Emission rates ranged from less than the method quantification limit of 2.3 mg h^{-1} to greater than 350 mg h^{-1}. With some exceptions, emission rates were generally not sensitive to flowrate or temperature. Field tests of electrically connected devices were completed in 7 residential buildings (1 in Tulsa, OK, 6 in the Davis/Sacramento area of California) and one classroom. The incremental increase in the ozone concentration due to the operation of these devices ranged from undetectable, to greater than 150 ppb, with devices operating normally. Estimated emission rates in field buildings ranged from undetectable to greater than 400 mg h^{-1}. For a typical California house, model analysis predicts that an emission rate of approximately 150 mg h^{-1} would raise the indoor concentration by about 50 ppb. Some in-duct air cleaners can raise indoor ozone concentrations above the current California limit set for other ozone generating devices.

Executive Summary

Introduction

Some commercially available devices that claim to remove contaminants from indoor air use electrostatic fields, ultraviolet light and photocatalysts. As such, these air-cleaning devices can intentionally or unintentionally generate ozone. Ozone is a Clean Air Act criteria pollutant (NAAQS) and its adverse health effects are well established (EPA, 1996). In indoor environments, ozone generating air cleaners can reduce air quality and can increase indoor ozone concentrations above ambient levels even in smog-prone areas. The State of California bans stand-alone air cleaners that can increase ozone concentrations to 50 ppb or more when tested with a standardized method (UL 867). In-duct devices are not yet regulated because the existing test method cannot adequately account for the conditions that exist in high-flow duct environments and no equivalent test for such devices has been developed. Thus, there is a need to develop such a method and to evaluate in-duct air cleaners for their potential to generate and increase indoor air concentrations of ozone.

Through laboratory and field measurements, the research reported here provides a test method and necessary data to support inclusion of in-duct air cleaners into the California Air Resources Board air cleaner regulation, if warranted. The two central objectives of the proposed research were to: **1**) develop and test a method of measuring the ozone emission of in-duct electrically-connected air cleaners ("device") and **2**) obtain real-world data on ozone concentration increases due to use of these devices in field sites. Two secondary objectives were to **3**) apply the method to a number of commercially available units in the lab to measure emission rates, and **4**) model the impact of in-duct air cleaners in California buildings.

Methods

This research included laboratory development of a test method and demonstration test apparatus, laboratory testing of in-duct air cleaners, field tests of devices in homes and one commercial site, and model simulations of indoor ozone concentrations for California residences.

The test method and test apparatus were based on the mass-balance principle that the ozone emission rate is the air flowrate multiplied by the increase in the ozone concentration across an in-duct air cleaner, accounting for any reactive losses of ozone to the surfaces of the apparatus. The method and apparatus were designed to accommodate a wide variety of devices, and to test devices under a variety of flow, temperature and humidity conditions that are consistent with conditions in typical ducted heating, ventilation and air conditioning systems (HVAC). Twelve devices (8 models) were tested in the laboratory apparatus using the standard method. The devices tested were chosen based a survey of manufacturers, installers,

stakeholders, availability and feedback from Air Resources Board and the project advisory committee.

In-duct air cleaners were tested in field locations in the Davis/Sacramento region of California and in Tulsa, OK. Field research in Tulsa developed test methods and tested several devices installed in an HVAC system of a house typical of small California residences. In California six air cleaners were tested in six houses; in some houses, more than one model of device was tested. One commercial air cleaner was tested in a California elementary school. Measurements included indoor and outdoor ozone concentrations, the incremental increase in the indoor ozone concentration due to device operation, the air exchange rate and the ozone decay rate. The device emission rate was also estimated based on other measurements.

The impact of ozone emitting devices on the indoor concentration of ozone in California homes was estimated using standard single and multi-zone mass balance models. Parameters for inclusion in those models were determined based on California residential building stock (volume, surface area, air exchange rates, etc.) and prior research regarding ozone removal rates in buildings. The results from model analysis included 1) steady state ozone concentrations as a function of building volume, reactivity, air exchange rates and other parameters, 2) dynamic ozone concentrations resulting from HVAC cycling and outdoor ozone infiltration and 3) room-to-room differences in the ozone concentration.

Results and Discussion

The following summarizes the results of this research.

Objective 1. *Develop and test a method of measuring the ozone emission rates for in-duct electrically-connected air cleaners*

The standard test method (STM) developed in this research includes specifications for apparatus sizing and configuration, air flow rates and measurement requirements for ozone, temperature, humidity, electrical power and flow rates. The fundamental basis for the test method is that the ozone mass emission rate is the product of the average ozone mass concentration rise across the air cleaner and the volumetric flow rate. The apparatus consists of four major sections/functions: the test section where the air cleaner is located and where ozone is measured; the treatment section where incoming or recirculated air is cleaned of ozone and particles before entering the apparatus, the flow generation section where airflow is generated (usually with variable speed fans), and an additional section, the contaminant and environmental variation section, can be considered optional, where ozone, dust, moisture, and conditioning are generated for specific optional tests. Detailed reporting and calculation procedures are included in the test method. The standard describes an example apparatus that conforms to the requirements of

the STM. This standard apparatus was tested extensively. This apparatus was determined to have a method quantification limit (MQL) of 2.3 mg of ozone per hour.

Objective 2. *Measure the incremental increase in the indoor ozone concentration due to the use of in-duct electrically connected air cleaners in field homes*.

Field tests of electrically connected devices were completed in seven residential buildings (one in Tulsa, OK, six in the Davis/Sacramento area of California). One commercial unit was tested in a classroom. The incremental increase in the ozone concentration due to the operation of these devices ranged from undetectable to as high as 130 ppb, when devices operated normally. Two electrostatic precipitator devices raised the indoor air concentration by between 5 and 22 ppb. All other devices used an ultraviolet light (germicidal/photocatalytic/ozone or oxidant generation). Two models increased the ozone concentration in field residences by greater than 50 ppb. Both devices are intentional ozone generators based on product literature. Combining the incremental increase in ozone with ozone decay rates in homes, it was possible to estimate the ozone emission rates in-situ. These emission rates ranged from undetectable to greater than 400 mg h^{-1}. Emission rates from several devices appeared to diminish over time, suggesting that "break-in" occurs early on. Two devices also exhibited erratic emission rates (sometimes not working at all) suggesting poor manufacturing quality.

Objective 3. *Apply the test method, developed to meet objective 1, to determine the ozone emission rate from commercially available in-duct air cleaners.*

A list of devices and device types to test was developed primarily through contact with California installers, discussions with federal and state agencies, internet searches for devices and contact with manufacturers. The project team contacted 72 installers in Bakersfield, Fresno, Los Angeles, Riverside, Sacramento, San Diego, San Jose and Stockton (34 responses), 13 manufacturers (3 responded) and four agencies. Six classes of devices that could potentially generate ozone were identified: electrostatic precipitators, electronically enhanced filters, ultraviolet light bulbs, photocatalytic oxidation systems, dedicated oxidant generators (ozone, hydroxyl radical, hydroperoxide radical), and hybrid systems. The majority of devices installed were of the electrostatic precipitator type with ultraviolet lights second. A list of seven device types and possible manufacturers was developed for testing. Devices included electrostatic precipitators, ozone and other oxidant generators, germicidal ultraviolet light and a photocatalytic oxidation system.

Some devices had emission rates at or below the MQL. The device with the highest emission rate, approximately 350 mg h^{-1}, was an intentional ozone generator that used an ultraviolet light bulb for "air cleaning". Three photocatalytic devices of the same model exhibited relatively low, and consistent, ozone emission rates. Most devices were insensitive to flow. One device exhibited an increasing ozone emission rate as the air flow rate increased. However, a second device of the same model was

not as sensitive to flow. An electrostatic precipitator exhibited higher emission rates at lower temperatures.

Objective 4. *Estimate, through building air quality simulation models, the indoor air concentration that could result from use of in-duct air cleaners.*

In steady-state indoor ozone concentration simulations, two "model" homes were included. The Standard Home was based on California (and National where necessary) average values of building volumes, areas, air exchange rates, ozone penetration, and ozone decay rates. The At-risk Home was based on a reasonable choice of parameters (such as small volume and low ozone reactivity) that, when combined, maximized the resulting indoor air concentration. Indoor ozone concentrations increase along with emission rates, but decline with increasing air exchange rates (in the absence of ambient ozone) and ozone decay rates. For the Standard Home, the incremental increase in indoor ozone concentration reaches 50 ppb when the emission rate is about 150 mg h^{-1}. The same concentration is reached in the At-risk House for an emission rate of only about 27 mg h^{-1}. The ozone concentration is more sensitive to air exchange rate in smaller buildings. Infiltration of ambient ozone contributes somewhat to indoor concentrations, depending on the magnitude of air exchange rates, outdoor concentrations and the device emission rates. A dynamic (time-dependent) multi-zone model found that separate rooms can have very different, and elevated, indoor air concentrations even when the air handler is off, but the device is operating. For 100 mg h^{-1} devices tied to the operation of the air handling system, the model predicts average indoor concentrations ranging from 15-20 ppb when the HVAC system is on 20% of the time and 35-50 ppb for HVAC that is on 50% of the time.

Discussion and conclusions

Some in-duct air cleaners generate ozone at rates that can increase indoor concentrations above accepted maximum levels. Model analysis suggests that in-duct devices with emission rates greater than about 30 mg h^{-1} can increase indoor ozone concentrations by 50 ppb or more in at least some California homes. Four devices were observed to emit ozone at or above this emission rate in laboratory and field tests. Two devices labeled as "ozone generators" were observed to increase indoor concentrations by greater than 50 ppb in field tests.

Simulated and measured indoor ozone concentrations were in reasonable agreement for devices tested in both laboratory and field settings. By combining laboratory tested emission rates and measured building parameters at field sites, indoor ozone concentration could be simulated using the steady-state indoor ozone concentration model. Measured and estimated ozone concentrations were within a factor of 2 for most devices. For the model that exhibited the most erratic emission rates, the simulated concentration was within a factor of ~3.

Overall, this research tells a consistent story: devices that emit ozone in buildings have the potential to raise indoor ozone concentrations beyond current California limits. A laboratory test method generates ozone emission rates that can, reasonably, be incorporated into mass balance models to predict the potential increase in indoor ozone concentrations. Therefore it is possible to establish a limit on the emission rate of in-duct air cleaners if the State of California sets a concentration limit and establishes what type of building they believe would provide an emission rate that is sufficiently protective of Californians.

While it is possible to set a standard, it is still unclear just how many highly emitting devices are installed or are available on the market place. An effort was made to determine which devices were popular among installers. However, this research did not generate a comprehensive list of devices that are, or have the potential to be, installed in California homes. Representatives from most HVAC companies (sales, installation, service) indicated that they would not install devices that purport to generate ozone or radicals. In this research, the ozone generators were the highest emitters. Further, some companies will not sell their devices in California, even though there is no current regulation covering in-duct air cleaners. These facts, however, do not necessarily mean that Californians are not exposed to excessive ozone concentrations from high ozone emitting in-duct air cleaners. Some devices can be ordered directly from manufacturers and installed by homeowners. From our testing, we observed erratic behavior of some devices, resulting a very wide range of ozone emission rates. Even devices not claiming to emit ozone could, unintentionally emit too much. Finally, this research did not comprehensively test all possible in-duct devices, and new devices have and will come on the market.

We do not recommend that further research take place on the impact of the devices on California homes. We believe it is clearly established that increasing ozone emissions increases ozone concentrations and that the resulting range of indoor concentrations can be predicted, within reason, for California building types. However, we do recommend that the State of California make an effort to better understand the market of these devices and determine the potential for their installation, especially in smaller homes that have low air exchange rates. This will be key to establishing risk to California residents. We further recommend that more testing be performed on multiple devices of the same model (consistency in manufacture), they be tested under adverse conditions (e.g. very high temperatures in attic spaces), they be tested for erratic behavior and establish how this impacts the Standard Test Method, and that they be tested over long periods in field sites to establish how age, temperature, humidity and real-world soiling affects performance.

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1 Introduction

In 2007, the ARB adopted a regulation that limits ozone emissions from indoor air cleaning devices. Air cleaners physically integrated within a central ventilation system, called "in-duct" air cleaners, were exempted from the requirements of ARB's regulation because no suitable test method was available for measuring ozone emissions from such devices, and few data were available on their ozone emissions to support regulation. However, there are a number of in-duct intentional ozone generators as well as in-duct electrostatic, ionizer, electrically-enhanced media (actively connected to AC/DC source), and ultraviolet air cleaners known to emit ozone that are marketed in California. There is reason to believe that some of these may generate significant amounts of ozone and/or ozone reaction byproducts such as formaldehyde.

The current California regulation relies on the test method described in Section 40 of Underwriters Laboratory Standard 867 (UL 867) to certify compliance of portable indoor air cleaning devices with the 0.050 ppm emission concentration limit. However, UL 867 does not include a suitable test method for measuring ozone emissions from in-duct devices.

1.1 Health Effects

The presence of ozone in the indoor environment has serious health consequences in addition to detrimental effects on building and household materials. Human exposure to ozone, even at relatively low levels, has been found to cause a variety of adverse health effects including decreases in pulmonary function and increases in reported symptoms such as headache, eye irritation, and cough (US EPA, 1996). Ozone concentrations below the National Ambient Air Quality Standard (NAAQS) have been associated with wheezing and difficulty breathing among infants, particularly those whose mothers have physician-diagnosed asthma (Trische et al. 2006). Both short-term (Bell et al., 2006) and long-term (Jerrett et al., 2009) exposure to increased ozone concentrations has also been linked to premature mortality.

Studies (Levy et al. 2005; Bell et al. 2005; Ito et al. 2005) have noted that the response function was higher in summer, when ozone levels are generally higher, than in winter. Levy (Levy et al. 2005) found that total mortality increased by 0.86% per 10 ppb in summer. Bell (Bell et al. 2005) found an increase of 0.83% per 10 ppb in total mortality overall, and concurred that U.S. and non-U.S. data were similar. Ito (Ito et al. 2005) provided a detailed seasonal breakdown of ozone and effects and demonstrated that the main effect of ozone on the population occurred in the warm season. A recent report of European data summarized data from 23 regions with mortality data over a 3-year period. The authors reported no association between ozone and mortality during the winter months but an association in summer, with a

mean increase of 0.33% in total mortality, 0.45% in cardiovascular deaths, and 1.13% in respiratory deaths per 10 μg m^{-3} ozone. The percentage increases should all be doubled for a 10-ppb (20μg m^{-3}) change as reported in the Bell and Levy studies.

1.2 Indoor ozone concentrations and sources

Concentrations of ozone in the indoor environment vary as a function of outdoor contributions and indoor sources. Indoor/outdoor ratios that result from outdoor ozone contributions alone range from 0.05 in tightly sealed buildings (or those utilizing charcoal filters), to 0.85 in buildings with very high air exchange rates. Excluding extremes, the I/O ratio is more often in the range of 0.2-0.7 (Weschler, 2000). Copiers, laser printers, electronic air cleaners and ozone generators can act as a source of indoor ozone with emission rates ranging from 0.1 to 220 mg h^{-1} (Brittigan et al., 2006; Mullen et al., 2005). This range is comparable to outdoor air as a source of ozone which can rise to ~100 mg h^{-1} for a typical residence on a highly polluted day.

Indoor sources of ozone have become a concern for the indirect effects of ozone chemistry as well as the direct effect of exposing occupants to more ozone. Ozone reactions with terpenoids released by cleaners (Nazaroff and Weschler, 2004), air fresheners and personal care products (Corsi et al., 2007) generate respiratory irritants (Anderson et al., 2007) and low-volatility species that condense to substantially increase sub-micron sized aerosol mass concentrations (Hubbard et al., 2005; Waring et al., 2008; Weschler and Shields, 1999). Ozone reactions with indoor surfaces such as carpet (Morrison and Nazaroff, 2002), ducts (Morrison et al., 1998), painted walls (Reiss et al., 1995) and soiled surfaces (Wang and Morrison, 2006) generate volatile aldehydes, carboxylic acids and ketones. In certain settings, much of the indoor ozone conversion rates are due to reactions with skin oils that coat humans, their clothing and other surfaces (Coleman et al., 2008; Weschler et al., 2007). Reactions taking place on (Pandrangi and Morrison, 2008) or near the body (Corsi et al., 2007) increase product and aerosol concentrations in the breathing zone (Rim et al., 2009), relative to the rest of the building space.

Use of ozone emitting appliances increase the indoor concentrations of all of these reaction products. Portable ion generators, which operate on the same principle as in-duct electrostatic precipitators and generate ozone as a byproduct, have been shown to increase aerosol concentrations when used in the presence of terpenes (Waring et al., 2008; Waring and Siegel, 2011) from consumer products such as air fresheners.

In-duct electronic air cleaners can generate ozone, but only a handful of experimental observations exist. Bowser (1999) studied 15 homes with in-duct "electronic air cleaners" (type not specified, but probably plate-and-wire electrostatic precipitators) and observed ozone emission rates ranging from 13 to 62 mg h^{-1}. They observed indoor concentrations of ozone, but were not able to

ascribe what fractional increase was due to device emissions. Hanley et al. (1995) measured an emission rate at 10 mg h^{-1} for a single electrostatic precipitator. Viner et al. (1992) studied three commercial in-duct electrostatic precipitators and observed ozone emission rates ranging from 20-30 mg h^{-1}. A 25 mg h^{-1} emission rate is equivalent to infiltration of outdoor ozone at the federal regulatory limit (75 ppb) in a typical house (300 m^3) with a typical air exchange rate (0.56). Therefore, an in-duct air cleaner can contribute substantially to the indoor ozone concentration of a typical home. Emmerich and Nabinger et al. (2000) used two in-duct air cleaners (electrostatic precipitators) in a full scale "test house". The resulting indoor concentration from use of one device as recommended rose as high as 200 ppb at an air exchange rate of 0.2 h^{-1} with an outdoor concentration equal to 22 ppb. A second device tested did not generate measurable emissions of ozone but also exhibited very low particle filtration efficiency. In a single home, use of an electronic air cleaner (plate and wire electrostatic precipitator) increased indoor concentrations of ozone by approximately 10 ppb over normal background levels (CMHC, 2003). They did not report an emission rate.

Some data exists for the impact of operating conditions on ozone emission rates. Mason et al. (2000) observed that ozone emission rates from electrostatic air cleaners decreased by about 30% as RH increased from 30 % to 70 %. Viner et al. (1992) did not observe a strong effect of humidity on the ozone output of three electrostatic precipitators, but they ascribed this to the limited set of data.

A much stronger effect on ozone production was due to accumulation of dust on the electrode observed by Dorsey and Davidson (1994). Using the air cleaner to filter Arizona road dust, they observed a 4.6 fold increase in ozone emission rates as electrodes became soiled over a 1 week period. They verified that accumulation of a dielectric material (dust) to the corona discharge wire increases the corona current. In laboratory testing of a plate and wire electrostatic precipitator, Huang and Chen (2001) found that soiling led to decreased ozone emissions because of decreased corona current. Bowser (1999) found no consistent trend in ozone emission rates and the extent of soiling on 15 electrostatic precipitators in homes. Rapid degradation of filtration efficiency was observed in several homes due to in-use soiling (CHMC, 2007) but ozone was not measured in this study. Phillips et al. (1999) observed a temporary increase in ozone emission rate from a personal air purifier (negative ion generator) when dust was intentionally applied to electrodes. In a study of corona changes under realistic conditions, Hanley et al. (2002) found that corona enhanced silicon dioxide vapor deposition, not particle soiling, caused corona intensity (and filtration efficiency) to decrease. Corona current is linearly proportional to ozone production rates (Viner et al., 1992). Interestingly, the manufacturers of the high-emitting device tested by Emmerich and Nabinger (2000) claimed that ozone emission rates would actually *diminish* with time/operation. The impact of soiling on ozone generation is a function of amount and composition of soiling particles, as well as how corona voltage is regulated (Huang and Chen, 2001). UL standard 867 includes an appliance run-in (break in period) to remove residual oil from manufacturing. Given that soiling and deposits can influence ozone

generation rates, the length of the run-in period could impact test results where devices are coated with differing types and amounts of machine oils. Therefore, residual oils, soiling or chemical vapor deposition in commercial or home devices could affect ozone generation rates, and possibly ozone-dust chemistry, and merits more study.

Other factors that may increase ozone emission include corona voltage and temperature. Liu et al. (2000) found that a 50% increase in voltage caused an eight-fold increase in ozone emission rate in a prototype in-duct electrostatic precipitator. Voltage variations with devices can be caused by manufacturing defects or by extensive soiling. Ozone emissions also increased with increased temperature, although a much smaller effect was reported and the temperatures range considered included much larger than typical indoor temperatures. Improper installation can impact removal efficiency and may influence ozone emission rates. A "swimming pool odor" was detected, and ascribed to high ozone emissions, from a device that may have had faulty electrical connections after cleaning and reseating (CMHC, 2007). Air velocity is generally observed to have little effect on emission rates because corona current is largely unaffected (Viner et al.,1992; Bowser, 1999).

The current California regulation relies on the test method described in Section 40 of Underwriters Laboratory Standard 867 (UL 867) to certify compliance of portable indoor air cleaning devices with the 0.050 ppm emission concentration limit. The revised U.L. Standard 867 states that a portable air cleaning device must not produce an ozone concentration exceeding 50 ppb by volume when tested as described in Section 40. The final intent of the Standard is to limit situations in homes where the sole use of an air cleaning device resulted in concentrations > 50 ppb, ignoring other influences. While the existing UL 867 standard is based on the 50 ppb concentration limit, the test protocols are designed so that 50 ppb corresponds to an explicit source emission rate equal to 3.6 to 4.1 mg h^{-1} (depending on chamber volume) The resulting concentration in the test is therefore proportional to the emission rate. As written, UL 867 applies only to portable indoor air cleaning devices and does not include a suitable test method for measuring ozone emissions from in-duct devices.

Given the paucity of data on the operation of in-duct electronic air cleaners, measurement of emission rates in modern devices is needed. Further, if a maximum ozone emission rate standard is promulgated, an accurate, readily transferrable test method for emission rates is also needed. Finally, the impact of their operation on the resulting ozone concentration in California homes will help ARB determine if and at what level an emission rate standard is necessary. To better understand the impact of these devices in California, this project completed the following tasks: developed a list of devices to test, developed a laboratory test method and tested devices using that method, measured the increase in indoor ozone due to use of these devices in at field sites and estimated the impact of these devices on small California homes using mass balance models.

1.3 Development of list of devices to test

In this task, the principal investigators (PIs) identified a list of in-duct electronic air cleaners and their potential use in California. The analysis was performed through direct contact (phone and email) with manufacturers, distributors and installers, as well as other means where possible (internet searches). The central goal of this analysis was to rapidly assess important technologies used for in-duct air cleaning that emit ozone. There are several known classes of existing technologies that emit ozone including: electrostatic precipitators (Viner et al., 1992), ultraviolet lights that emit at or below 254 nm, dedicated ozone generators, and electrically-enhanced filtration media (Agranovski et al., 2006). These technologies, as well as other potential ozone-emitting technologies were identified.

1.4 Laboratory test method development and device testing

The central goal was to develop a robust laboratory test method to measure the ozone emission rate (dimensions of mass/time, e.g., mg/h) of in-duct air cleaners. The emission rate is a characteristic of the air cleaner and emissions rate data that when combined with field data collected in Tasks 3 and Task 4 should allow for an assessment of the impact of an in-duct ozone-emitting air cleaner in a typical California home.

In developing this test method, we recognized several methodological issues with assessing the ozone emission rate, including:

- Even at relatively high emission rates, ozone concentrations can be diluted below the sensitivity of most ozone analyzers at typical HVAC air flow rates.
- Ozone emission may not be uniform across the device cross-section.
- Ozone emission may be a function of environmental parameters (temperature, relative humidity, air velocity) and cleanliness of the ozone generating part of the device (i.e., corona, pin ionizers, UV bulb).
- Emitted ozone may be consumed by reactions with deposited material or with other parts of the air cleaning device or HVAC system. These reactions are undesirable because of the potential for production of byproducts. If such reactions take place between the device and a downstream ozone measurement point, than they will cause the ozone emission rate to be underestimated.

The proposed laboratory technique explored these issues and resulted in a standard test method for ascertaining ozone emission rate.

1.5 Field testing

The objective of initial field research in Tulsa was to develop protocols and identify relevant parameters to guide the field studies of California homes. In addition, these field experiments allowed us to compare the performance of several units in the field that had already been tested in the lab. The primary objective of the California field tests was to measure the increase in ozone concentration that results from the

operation of in-duct ozone-emitting devices in California buildings. Estimates of the device emission rates were also obtained. In some cases, the influence of environmental conditions on concentration and emission rates was identified.

1.6 Building simulations

The objective of this task was to perform a range of building simulations to predict the indoor ozone concentration that results from operating in-duct air cleaners. Emissions from ozone-emitting in-duct devices are diluted by air exchange and attenuated by reactions with gases (e.g. NO and terpenes), ductwork and other indoor surfaces. Therefore, the resulting concentration at a supply vent or in the occupied space varies by building and temporally changing conditions. Using simple but realistic models, the ozone concentrations that result from use of these devices can be estimated relative to specific building configurations and conditions.

2 Materials and methods

2.1 Candidate device survey

Task 1 of *In-duct air cleaning devices: Ozone emission rates and test methodology* required the development of a list of in-duct electronic air cleaners that may emit ozone and are likely (or potentially) installed in California buildings. The analysis was performed through direct contact (phone and email) with manufacturers, distributors and installers, as well as other means where possible (internet searches).

2.1.1 Candidate device survey in California residences

To generate a reasonable estimate of candidate devices that may be installed in California homes, we contacted 72 HVAC installers in Bakersfield, Fresno, Los Angeles, Riverside, Sacramento, San Diego, San Jose and Stockton. Of the 72, we were able to get a manager or installer to answer some of our questions regarding the types of devices installed.

- We identified ourselves and requested that they share the following information with us:
    - Verify that they do residential installation of air cleaning equipment
        - If only commercial continue with survey
    - Do they install electronic in-duct air cleaners
    - What brands do they sell
    - Which model/brands are most popular or that are most likely to install based on their experience.
    - Which distributors they work with

2.1.2 Contact with agencies

We contacted agencies and organizations that we felt would have already spent some time considering in-duct devices and would have already developed opinions on what kinds of devices they would like tested. Agencies and organizations contacted were Underwriters Laboratory, the Consumer Product Safety Commission, the Environmental Protection Agency, Health Canada and the National Research Council of Canada.

2.1.3 Recommendations for device testing

In Task 2, a minimum of seven devices were to be tested. Based on the market survey results and feedback from agencies, organizations, the project advisory group and staff of the Air Resources Board, we developed a list of possible devices to

acquire and test. It is not possible to test all technologies and styles within a specific technology and this may include tests of different devices of same model. Given that the project relies heavily on donated devices, we designated preferred styles and manufacturers rather than specific models.

2.2 Laboratory test method development and device testing

In Task 2 of *In-duct air cleaning devices: Ozone emission rates and test methodology* the goal was to develop a standard for the laboratory measurement of ozone emission rates from electrically-connected in-duct air cleaners and to test air cleaners using the developed standard.

2.2.1 Standard Test Method development

This section is organized into a description of the motivation, methodology, and thought process that was used for designing the final version of the Standard Test Method, the apparatus that was developed for the standard testing.

The motivation for the standard arises from the fact that most standards for ozone emission from air cleaners are intended for portable air cleaners that operate in a low flow condition. These standards also explicitly exclude in-duct devices (i.e., UL 867). In contrast, in-duct air cleaners are usually designed to cycle on with the operation of the HVAC system and thus can have very high flow through them. These high flows cause a dilution in the ozone concentration. Figure 2.1 shows the theoretical concentration rise across an ozone emitting device as a function of flow for five emission rates for ozone. At typical residential flows of 1,600-3,200 m^3h^{-1}, ozone concentration rises are too small to measure accurately for a 5 mg h^{-1} ozone generator (note that such a device would exceed the allowable effective emission rate of 3.9 mg h^{-1} for a portable air cleaner in ARB 2007) and considerably less than 10 ppb for an air cleaner with a 25 mg h^{-1} emission rate (an air cleaner that emits more than six times the allowable limit in ARB 2007). One solution is to test in-duct devices in a static chamber test according to UL 867 or similar. Although conceptually simple, this has several drawbacks, including:

- Some air cleaners may emit different amounts of ozone when they are operating at low flow then at high flow. A static test may overestimate or underestimate the ozone emission rate when operating in a duct as intended.
- Some in-duct air cleaners have a flow switch and can only emit ozone when they have flow over them. It is unclear whether bypassing these devices would also alter the operation of the device.
- Some in-duct air cleaners have an ozone control device (i.e., activated carbon or a catalyst). These devices are best tested at realistic flow rates as they might consume more or less ozone at different flow rates.

In general, it is appropriate to test devices at as realistic and repeatable conditions as possible and thus the need for a robust in-duct test method.

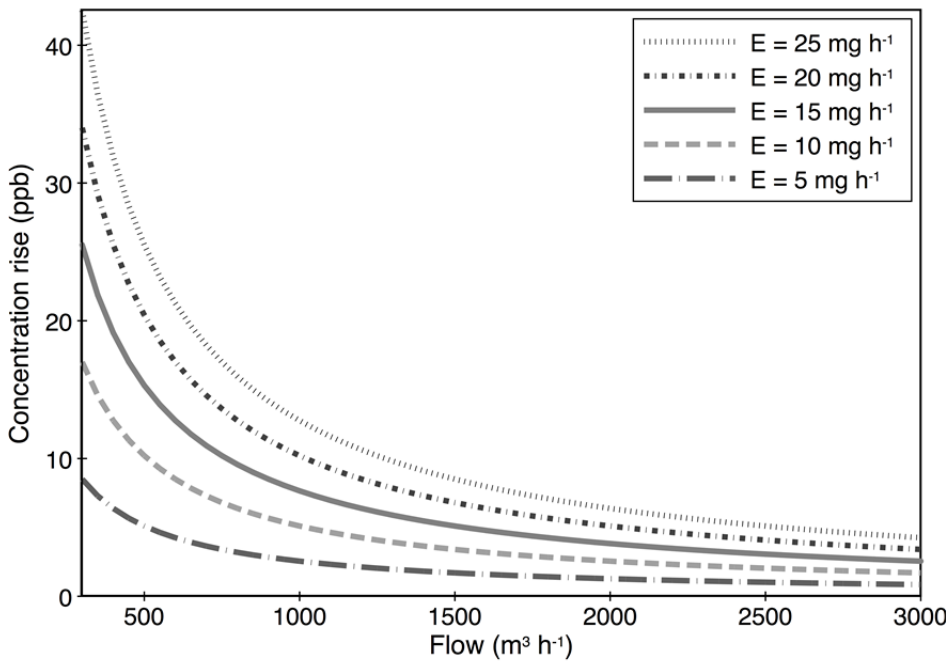


Figure 2.1. Concentration rise as a function of flow for in-duct air cleaners with different emission rates.

2.2.1.1 Basis of standard and apparatus

The ozone emission rate of a device is a product of the ozone concentration rise across the device and the flow going through the device. Any standard will have to have high-quality measurements of both of these quantities. A guiding principle for the apparatus and test method was that the standard should strike a balance between technical accuracy and being easy to follow and apply. This balance is necessary to achieve eventual adoption of any standard. The following section describes the key decisions that were made in designing the apparatus and test-method.

Test duct material: Ozone is chemically reactive and a test-duct that consumes ozone could affect the measured ozone rise across an air cleaner. Stainless steel was selected as the material for the apparatus. Because of the size of the test duct (described in more detail below), using all stainless steel would be prohibitive from a budgetary standpoint and thus just the section of the duct containing the air cleaner and ozone measurement apparatus was made of stainless steel and the rest of the duct was made with less expensive galvanized steel.

Test duct configuration: Generally test ducts are either open-loop (single pass) or closed-loop (multiple pass). Open loop systems are generally simpler but also can require a considerable energy expenditure to maintain environmental conditions in the duct air. The standard allows either configuration, but for the purposes of standard development a closed loop system was selected so that the air conditions could be changed if needed. A second configuration decision is the physical shape of

the duct. Open-loop systems can be straight ducts, but this requires a large amount of floor space. A floor-space efficient configuration is U-shaped (open-loop) or oval (closed-loop) and the latter was selected for the test apparatus.

Test duct size: A duct cross-section of 60 cm × 60 cm was selected to accommodate all sizes of air cleaners. This is consistent with many filter-testing apparatuses (e.g., ASHRAE Standard 52.2). The duct length was driven by the need to have adequate mixing between ozone emission and measurement and uniform flow in the test section. A general rule of thumb is that 5-7 duct diameters (3-4 m given the cross section above) are needed after every change in the duct (i.e., a bend, an emission source, etc.) and that gradual changes (such as a wide-radius curve) are preferable to abrupt changes. For this reason, as well as the physical space limitations in the laboratory, the duct was specified to be 9 m long. This allowed for adequate space after the major bends in the oval, a 2 m long test section, and space for mixing after the air cleaner.

Flow generation: Residential systems encounter a wide range of air flow rates. The rule of thumb in the air conditioning industry is that 400 CFM (680 m^3h^{-1}) of flow are needed for every ton of air conditioning. Typical residential air conditioning systems range from 1-5 tons. Newer homes may also have an outdoor intake for ventilation air and when the air conditioner or furnace is not needed, a much smaller flow (as small as 85 m^3h^{-1}) may be used. Thus the ideal apparatus could accommodate a wide range of flow rates. Intertwined with the issue of flow range is accurate measurement of the flow rate and this issue is discussed below.

For the test apparatus, two standard 5-ton residential indoor air handler units were selected. Both units are rated to be able to achieve 3400 m^3h^{-1} in a typical residential system, although it was anticipated the resulting flow rate would be lower due to the large pressure drop of the test apparatus components. Each unit was connected to a variable frequency drive (VFD) that allowed continuous adjustment from 0% to full power. Two fans were selected as this generally improves airflow uniformity. Honeycomb flow straighteners were used in three locations in the duct to further improve uniformity. Ultimately the fans working together at full power produced approximately 2500 m^3h^{-1} (with some variation based on the age of the HEPA filter and the particular air cleaner being tested). We considered going to a higher flow rate fan, but several issues led us away from this decision including

- Noise considerations: very powerful fans are very loud and the safety of personal in the laboratory (including those working on other projects) would have been impacted
- Heat generation: Larger fans consume more electricity and generate more heat. We were concerned about heat generation in the duct affecting ozone emission results.

- Apparatus air leakage: a larger fan (especially one with the motor external to the duct) would have led to much higher air leakage from the system which may have affected the results as well as emitted ozone into the lab
- Budgetary limitations: a new fan would have required additional electrical work that would have exceeded the budget for the apparatus
- Control: Finding a VFD that would control a large fan over the entire range would have compounded the budgetary issues (and may not have been available).

Air Cleaning: Both open-loop and closed-loop systems require ozone treatment because of release into the lab or contamination of emission results. Activated carbon was selected for this purpose because of its demonstrated track record and the large numbers of filters available on the marketplace. The test standard allows any ozone removal device that meets the criterion in the standard. A HEPA filter was selected to avoid contamination of the air cleaners. The HEPA filter was the largest pressure drop in the system and thus was the largest limitation on overall flow.

Ozone measurement: There are several considerations for achieving high-quality ozone measurement including the accuracy and response time of the ozone analyzer, the representativeness of ozone sampling across the duct cross section, and the design of the of the sampling system. Because of the importance of measuring low ozone concentrations, the standard requires a research grade ozone analyzer (defined as an accuracy of less than 2% or 2 ppb) and there are at least three US manufacturers who make a device that could work for the standard. In addition to the test duct itself, this will be a major budgetary item for anyone who wants to implement the standard.

To achieve a representative ozone sample, a sampling grid was designed. The sampling grid, illustrated in Figure 2.2, consists of three vertical stainless steel rods, 55 cm in length with a 6 mm outer diameter and 1.5 mm wall thickness. Five 1 mm diameter holes were drilled 12 cm apart on each of the three rods, to measure an average ozone concentration over the entire cross section of the duct. The three rods are spaced evenly across the duct with one inserted at the centerline of the duct and the other two 20 cm on either side of center. A Swagelok cap is attached to each rod on the end inside of the duct. The rods are each held in place within the duct with a Swagelok bulkhead union. The segments of the sampling grid outside of the duct are a combination of three short 6 mm vertical stainless steel rods and two horizontal pieces, connected by Swagelok unions. From the top of the sampling grid, 6 mm Teflon tubing connects the sampling grid to remainder of the sampling system.

Figure 2.2. Ozone sampling grid used to measure ozone upstream and downstream of air cleaner

One of the key considerations in a test method that involves two measurement points (for example, upstream and downstream ozone concentrations) is whether to require two measurement devices or a single device with switching valve. The standard allows both pathways (as long as certain qualification criteria can be met), but we assessed that the cost and added complexity of a second analyzer, especially when ozone concentrations are low, exceeded the benefits. In order to use a single monitor to analyze both the upstream and downstream ozone concentrations, two Omega 2-way General Purpose Solenoid Valves (Normally Closed Model No. SV125; Normally Open Model No. SV133) were used to enable switching back and forth between upstream and downstream sampling. An Omega Programmable Timing Controller (Model No. PTC-15) controls these valves, controlling whether the ozone monitor is analyzing upstream or downstream concentrations.

Airflow measurement: Many test standards that involve flow in a duct require ASME flow nozzles for flow measurement. This type of flow measurement approach presented two problems for the duct apparatus: the pressure drop of relevant flow nozzles are very large and would have further diminished maximum flow and there are very few flow nozzles that have high accuracy over the range of flows needed in the test apparatus. In the test apparatus, a flow station is located past the outlet of the second fan. The flow station (Shortridge Instruments, Inc., VelGrid) is a square, 16 point, face velocity grid. The pressure difference is measured through the velocity grid by using an Energy Conservatory DG-700 digital manometer. The flow station was calibrated with an Energy Conservatory TrueFlow Plate. If a more powerful fan was available in the system, a decision to use a flow nozzle (or multiple flow nozzles) may have been made as this approach would have higher flow measurement accuracy. However, the uncertainty in emission rate measurements for most devices tested in this project was driven by uncertainty in the ozone concentration measurement, not flow rate.

Other apparatus design considerations: The ease of changing air cleaners for testing is important for facilitating more rapid testing. The air cleaner test section had a 55 cm × 30 cm removable gasketed panel that could be replaced with a panel with a hole cut for each air cleaner. Thus, each air cleaner could be installed in a panel and bolted on to the air cleaner duct as needed for testing. Five panels were needed to accommodate the air cleaners tested in this report. Air leakage in the test duct could lead to ozone emission into the laboratory space and/or inaccurate emission rate results. All sections of the test duct were gasketed with neoprene gasketing and the duct gaps were also taped with foil tape such that the foil side of the tape was exposed to the airflow. For safety reasons, both fans had interlocks such that the fan would not energize if the air handler cabinet was open. An additional safety concern had to do with operator exposure to UV light from some of the air cleaners and for this reason, a pressure switch was placed on the door to the apparatus requiring it to be closed for the power to the air cleaner to be energized.

A schematic of the apparatus from the air cleaner access side (air flow is counter-clockwise) is shown below in Figure 2.3and a photograph of the fan access side (air flow is clockwise) is shown below in Figure 2.4.

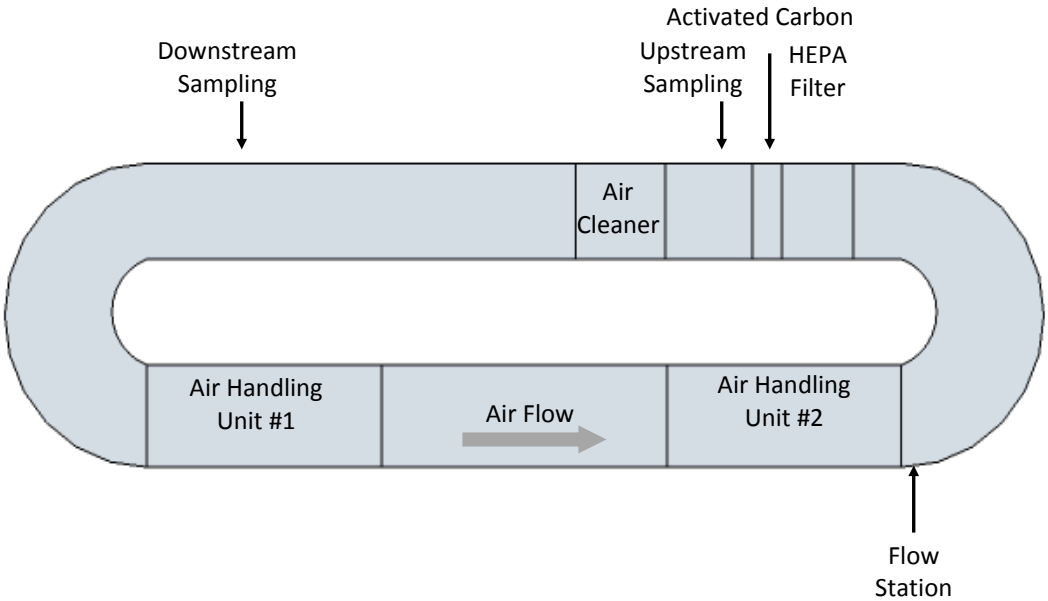


Figure 2.3. Schematic of test duct.

Figure 2.4. Photograph of test apparatus

2.2.2 Device testing

Once the standard was developed and preliminary testing complete, the final standard was used to test 12 air cleaning devices. Since the test standard was a major outcome of the project, it is shown in the Results section of this report. Note however, that the test standard is the *method* with which these devices were tested. The devices are shown below in Table 2.1 where the technology is as described by the manufacturer. Most of the devices generate ozone as a result of having an ultraviolet lamp, however, Air Cleaner 3 generates ozone as a result of a corona discharge.

Table 2.1. Air cleaning technologies tested in apparatus using the Standard Test Method

Air Cleaner	Product	Technology
1	Dust Free Bio Fighter Lightstick	Ultraviolet light
2a	Guardian Air by RGF #1	Photohydroionization
2b	Guardian Air by RGF #2	Photohydroionization
2c	Guardian Air by RGF #3	Photohydroionization
3	Honeywell F300 Electronic Air Cleaner	Electrostatic Precipitation
4	Lennox PureAir Air Purification System	Photocatalytic Oxidation
5a	activTek INDUCT 2000 #1	Ultraviolet light
5b	activTek INDUCT 2000 #2	Ultraviolet light
6a	Air-Zone Air Duct 2000 #1	Ozone generator
6b	Air-Zone Air Duct 2000 #2	Ozone generator
7	APCO Fresh-aire	UV / PCO / Carbon
8	HVAC UV 560	Ultraviolet light

The specific testing was oriented to address four main topics:

1. Ozone emission rates of electrically connected in-duct air cleaners (testing on all air cleaners in Table 2.1)
2. Influence of flow rate on ozone emission rate (most air cleaners in Table 2.1)
3. Influence of temperature and relative humidity on ozone emission rate (Air Cleaners 3 and 5b)
4. Repeatability of testing and impact of order of testing (Air Cleaners 5a and 5b)

To address topic 3, the temperature and relative humidity of the air were varied in the duct by adding steam and/or using an electrical heating element. The range of temperatures tested was 25 – 45 °C and the range of relative humidities was 25-75 %. To address topic 4, both units of air cleaner 5 were tested 3-4 times alternating between doing the testing in the order specified in the standard (low to high flow) and the reverse. This was done to explore any impact of air heating as the fan heats air in the test duct as well as hysteresis of the ozone analyzer (or more generally, the standard itself).

2.3 Field testing

In Task 3 and 4 of *In-duct air cleaning devices: Ozone emission rates and test methodology* the objective was to determine how much the ozone concentration can rise within building environments when an electrically connected in-duct air cleaner is operating. This can be accomplished by measuring the concentration in a building with the device on while accounting for the background ozone concentration. However, it is not possible to extrapolate this single result to make predictions for other homes, nor is it possible to use the concentration alone to make comparisons with laboratory measurements of ozone emission rates. This is because each building removes ozone at different rates, by air leakage and reactions with building

surface. Thus, to extrapolate to other building environments and make comparisons with laboratory results, the method developed for the field testing is based on collection of ozone and CO_2 tracer decay measurements that are then used to calculate air exchange rates (AER) and ozone decay rates (ODR). Combining these data with the incremental increase in the ozone concentration due to operation of the device allows for an estimate of the ozone emission rate (OER) of the device.

Field work consisted of measuring the increase in ozone concentrations due to devices installed in homes in California and in a commercial building. A vetted approach to developing field protocols included rigorous testing in a home in Tulsa, OK (home location of the co-principal investigator responsible for field research). Field sites in California were recruited through list-serves, contractors, distributors and other sources.

2.3.1 Tulsa test home selection

A survey of potential homes in the Tulsa area was conducted to establish a list of candidate homes based on the following criteria, focusing on homes in the style of typical small California homes.

Construction style. One story home with crawl space (pier & beam) or on grade slab foundation construction
Home size. 800 to 1800 ft^2 floor area.
Age of structure. List to include homes with construction dates from the 1920's to 2011 to provide a selection process to be reflective of oldest to newest homes.
Occupancy and availability. Consideration was given to occupied and unoccupied homes with higher ranking given to homes that were reflective of occupied structures. Model homes for rental groups and occupied structures rated higher than empty homes. Homes that were available to rent were also considered, however additional cost may have been incurred to rent furniture to put the homes in an "occupied-like" status. Availability of the home for the test period was also discussed to determine a time frame (up to 6 weeks) if required.
Interior surfaces. Homes were considered based on the type and style of floor covering, recent construction, remodeling or restoration activity and type and amount of furniture present in the home. Homes with updated windows and heating and cooling systems (in the past 5 years) were ranked above homes that had not been updated recently. Homes with new paint, floor surfacing or sealing and other restoration activity were rated lower than homes with these items in good condition that had time to release primary emissions of volatile gases, and also for these surfaces to become more oxidized (reducing ozone consumption).
Heating and cooling equipment. The type, location and access to the Forced Air System were considered in ranking the homes. Single forced air unit for the structure and no multiple units or zoned homes were preferred. Additionally, discussions with the owner/operator of the structure to were undertaken to ensure that modification of the duct system was permissible. Homes with limited access were noted on the survey form and ranked lower than homes with acceptable access.

Results of survey and selection of test house. The Tulsa University Indoor Air Program surveyed eleven potential Tulsa test homes in November 2011. Appendix 9.3 provides a summary of each home surveyed for Tulsa testing. The home that was selected for testing had new double-pane windows and an HVAC system installed in the summer of 2011. The HVAC had a single house return near the house center of the structure that would facilitate testing. The occupant was willing to participate in the testing and had the flexibility to easily vacate the house during the testing. Figure 2.5 is the floor plan of the Tulsa test house (not to scale) and shows location of sampling sites. The air handler with distribution plenum and furnace was mounted in the attic and accessed through the closet in the master bedroom; the unit was just to the right side (when facing front of house) of the attic entrance. The Tulsa test home was located on the 2200 block of East 12th Place in Tulsa Oklahoma.

Figure 2.5. Tulsa test house floor plan & sampling sites (not to scale).

2.3.2 Tulsa test house method

Field experiments were conducted in the Tulsa test house to develop and refine field test protocols for determination of air exchange rate (AER), ozone removal rate (ORR), ozone decay rate (ODR), and ozone emission rate (OER). Note that OER is the "effective" emission rate for the device/building system, not necessarily identical to the source emission rate *S*, and may influenced by phenomena not entirely accounted for using the ODR test. The Tulsa field tests addressed key issues such as ozone reactivity in an occupied house, practicality of identifying sources of high ozone removal surface-types, ozone reactive VOCs (e.g. terpenes), dynamics of air mixing that affect CO_2 and O_3 seeding for AER/ORR/ODR determination, installation of in-duct ozone generators in existing HVAC equipment, monitor locations and building sealing to reduce AER. Ultimately, the Tulsa field tests provided data and experience for conducting tests in California homes. Device testing results from the Tulsa test house can be combined with California field test results for a more complete picture of the impact of ozone generating in-duct devices. Testing was repeated several times with the protocol reviewed and revised between testing.

2.3.3 Test periods and lessons learned

February 20-24, 2012—this was the first testing period in which the house was tested for tightness, a licensed HVAC technician installed a test port for installing test devices in the distribution plenum after the air handler/HVAC unit, and sampling locations were identified. The ducts were not booted properly (seal was not tight) to the supply vents and one supply vent was blocked by a ceiling joist and the duct was taped on top of the joist about six inches away from the supply vent. The HVAC technician rebooted the ducts to the supply vents and relocated the supply vent that was bifurcated by the ceiling joist. During this initial test, considerations were given to locating monitoring equipment in an occupied home so it could be stored out of the occupants' way when testing would require multiple days. Two days of testing, February 22 & 23, were conducted to refine AER, ORR, and ODR measurement.

March 5-7, 2012—this testing focused on refining AER, ORR and ODR measurements and calculating a trial OER using the activTek INDUCT 2000 device. The testing indicated that the valve switching on the API ozone monitor to acquire alternating indoor and outdoor samples did not give a clear delineation of indoor and outdoor values at the time of the valve switch (switching was set at 4 minutes).

April 25-27, 2012—this test period focused on refining OER determination and testing three separate devices; Air Zone Air Duct 2000, activTek INDUCT 2000, and Air Guardian.

May 2-3, 2012—this test period focused on simplifying and improving the protocol by conducting AER and OER tests concurrently. During OER test setup, the house

was seeded with CO_2 to measure the decay of a conservative (non-reactive) species. The Air Guardian and Air Zone Air Duct 2000 were tested during this period.

November 1-3, 2012—this test period focused on the HVAC UV 560 device. Testing indicated this device to be the O_3 generator with the highest emission rate based on the increase in concentration of ozone in the home. Sampling within the duct distribution plenum, where the device was installed, revealed elevated O_3 concentrations (maximum for a 10 minute sampling period was 1466 ppb O_3).

Performing multiple test runs helped to identify ways to improve the protocol. The Tulsa field tests revealed several challenges which were noted and factored into final protocols developed for CA testing. Protocol modifications that resulted from the Tulsa test house field experiments included:

- Using a large ice-chest to secure reactive VOC contaminant sources like candles and air fresheners, instead of separately bagging each item. After March 5-7 testing, it was observed that removal of contaminant sources took considerable time and a more efficient method was needed.
- Dedicating an ozone monitor to outdoor measurement to minimize uncertainty rather than using a valve switch to take alternating indoor and outdoor sample intervals using one ozone monitor.
- Establishing a double check procedure of monitor operation and logging, and using household power to operate the monitors, instead of relying on batteries. During *March 5-7* testing data was lost because data logging was unsuccessful.
- Looping sampling tubes through supply and return grills to quickly and easily position the tubes without using tape which tended to release and pose a damage risk to finished surfaces in the home.
- Pulsing CO_2 seeding (turning on and off canister valve as canister is moved through house) to improve mixing and reduce monitor spiking (the upper limits of the CO_2 monitors is 8888 ppm).
- Using long extension cords for the mixing fans and ozone generators so that they could easily be moved about the house (room-to-room) to improve the efficiency of seeding/mixing for AER/ORR/ODR measurements.
- Running AER measurement concurrently with OER measurements, so that AER during testing of the in-duct device could be calculated. Air exchange in a home is influenced by outside weather conditions, such as wind, that alter pressure differentials between the indoor space and ambient air and affect AER.
- Running tests with HVAC system on, primarily. Stage 1 (HVAC fan on) and Stage 2 (HVAC fan off) measurements were developed to examine the home profile (e.g. air exchange rate, ODR, ORR) with fan off. This would show how fan operation affected air exchange and ozone decay. AER is significantly influenced by the HVAC fan. When the fan is on the air exchange rates can be twice as high as with the fan off; see February 22, 2012 Tulsa field test data (2 tests at 10 am and 4 pm with Fan On, and 1 test at 1 pm with Fan Off). However, the length of time needed to conduct both Stage 1 and 2 tests was

often not practical given the short periods of times that tests houses can be accessed. For this reason, Stage 2 (HVAC fan off) AER tests were only conducted when there was sufficient access time. As to the operation and examination of the impact of the in-duct ozone generating air cleaners, homes were operated with the HVAC fan in a fan "on" mode (or "auto" mode in some cases as time allowed or circumstances dictated). All test homes had forced air central heating and cooling systems that normally are operated in an "on" or "auto" mode (auto mode cycles the fan based on sensible load demand in the home).

- Measuring O_3 at both supply and return during OER testing. This would provide a more complete assessment of O_3 levels and an evaluation of the difference between concentrations at supply grills (before thorough mixing in indoor air) and at return (where assumed closer to "fully" mixed, whole house indoor air returned to the HVAC system). In the Tulsa field tests only 2 ozone monitors were available. However in the California field tests, four ozone monitors were used: one monitor was dedicated to outdoor measurements, one monitor to supply and room measurements (center of room, typically bedroom), one monitor to return and room measurements (center of room, typically living room or hallway), one monitor to room measurements (typically living or dining room area).

2.3.4 Recruiting, selection and description of California Homes

California homes were recruited in several ways. To identify homes with pre-installed electrically connected in-duct air cleaners, installers were contacted and asked to identify appropriate homes. Only one installer agreed to help identify homes (Sawyer Heating and Air, Modesto, CA). By this method three homes were identified, two of which had electronic air cleaners. These three homes were included in the first California field tests from May 22 to May 30, 2012.

Other homes were recruited via email requests from current and former colleagues at the California ARB and at UC Davis. By this mechanism, four houses were identified and used for testing that occurred from January 7 to January 14, 2013. Recruitment emails included the following information to narrow down homes to ones with desired characteristics.

- A small residence, not an apartment, in the Davis/Sacramento area (~800-1500 square feet or so)
- Preferably single-story
- Residence must have an air handler and standard recirculation throughout the house. An outdoor intake is not preferred.
- Overall the house should be in good shape and should be reasonably tight (not too leaky).
- Unoccupied for 5 to 7 days
- The project team will install a new device in the duct after the air handler. A licensed HVAC contractor will do all of the inspections, installation and de-

installation (Probably Sawyer Heating). They will return it to original condition.

The following are brief descriptions of test houses and one commercial test site in California. More information and images can be found in Appendix 9.5.1

Test House 1
Location: Davis, CA.
Testing conducted: May 22 and 23, 2012.
Device Tested: activTek INDUCT 2000
Description: House area is 150 m2 and volume is 377 m3. The house had a high vaulted ceiling, two floors, and an open stair case and balcony overlooking living room area. Living, kitchen, dining, and ½ bath areas located on the first floor. Three bedrooms and two bathrooms located on the second floor. The house had an attached two-car garage. HVAC was a forced air system accessed from the attic. The occupants owned a rabbit which commonly stayed indoors.

Test House 2
Location: Sacramento, CA.
Testing conducted: May 25, 2012.
Device tested: Trane Clean Effects
Description: House area is 218 m^2 and volume is 531 m^3, but the upper floor with 219 m^3 was sealed off during testing so that only 312 m^3 (downstairs, approximately 127 m^2) was involved in the testing. The 1st and 2nd floors had separate HVAC systems. The downstairs had two bathrooms, three bedrooms, a living room, a den, and a kitchen. The house had a fireplace that was sealed during testing. Attached to the house was a two-car garage. HVAC was forced air systems with a Trane Clean Effects EP installed on the 1st floor system. The HVAC system was accessed in a small 1st floor utility closet. The occupant used 2 Oreck Air Purifiers (table-top, room sized cleaners with EP and filtration); these devices were turned off during testing.

Test House 3
Location: Sacramento, CA.
Date of tests: May 30, 2012.
Device tested: AirZone Air Duct 2000
Description: House volume is 431 m^3 and area is 180 m^2. The house had split HVAC systems for 1st floor and 2nd floor; forced air HVAC system accessed from attic. It was not practical to seal off the 2nd floor of this house due to design of staircase. The upper floor had four bedrooms and two bathrooms, and a small storage room. The 1st floor had a kitchen, dining room, living room, and den. A two-car garage was attached to the house.

Test House 4
Location: Garden Valley, CA.
Date of tests: January 7-8, 2013.

Devices tested: HVAC UV 560 and activTek INDUCT 2000
Description: located approximately 30 minutes southeast of Sacramento in the Sierra Nevada foothills. The house is in a remote, rural location in the foothills. The volume is 196 m^3 and the floor area is 93 m^2. The home had non-standard ceiling heights in bedrooms and living room area; approximately 2.3 m rather than 2.44 m. It is a single story house with 2 bedrooms, 2 bathrooms, dining area, living room, and kitchen. The house was tightly sealed and had a forced air HVAC system that was easily accessed in the attic. The house was not constantly occupied, but was fully furnished. The occupant operated the HVAC in an energy saving mode with the thermostat set at 55° F. The house did not have a garage attached.

Test House 5
Location: Davis, CA.
Date of tests: January 9-10, 2013.
Device tested: HVAC UV 560
Description: The volume is 206 m^3 and the floor area is 92 m^2. The house had 2 bedrooms, open kitchen/dining/living room space, laundry room, and two bathrooms. The house was attached to houses on either side (a modern row house construction). The house had a low slope roof with the HVAC system roof mounted. The system was not easily accessed and installation of the HVAC UV 560 test device required placing the UV lamp fixture completely into the duct distribution plenum, rather than mounting the lamp fixture outside the plenum with the UV lamp penetrating into the duct space. The house had an attached single car garage. A dog and a cat regularly occupied the house. Test House 5 had a large master bedroom that was undergoing renovations and had the flooring removed to expose the concrete subfloor (house slab)

Test House 6
Location: Citrus Heights, CA.
Date of tests: January 11-13, 2013.
Device tested: Honeywell F300 Electrostatic precipitator
Description: The volume is 199 m^3 and the floor area is 94 m^2. Testing was conducted January 11 to 13, 2013. The house had three bedrooms, a living room, dining area, kitchen and one bathroom. A two-car garage attached to the house. The HVAC system was a forced air system accessed in the attic. A medium sized dog regularly occupied the house, but was not in house during testing.

The commercial system test site
Location: Sacramento, CA, Grant Union High School, Classroom B-12.
Date of tests: January 14, 2013.
Device tested: Trane TCACS
Description: The classroom was a large, traditional high school design with marker and chalkboards along three walls, a projection screen, classroom and office desks, and windows along the exterior wall. Ceilings were high; approximately 3 m and supply and return air were provided by ceiling mounted ducts. The room volume was 144 m^3 and the floor area is 48 m^2.

2.3.5 California residential test method

The following is the California residential test method (CRTM) that was developed based on the Tulsa field test experience.

2.3.5.1 Overview

One of the primary goals of field testing of electrically connected in-duct devices in CA is to determine how much the indoor ozone concentration rises when the device is operating in-situ (while installed in an operating central air system of a home or building). In addition to directly measuring the indoor concentration of ozone while the device is off and on, several other building related parameters were measured: air exchange rate (AER, indicates exchange of air through the building envelope) and ozone decay rates (ODR, surface reactions that remove ozone). Where possible, the additional measurements were used to provide an estimate of the "effective" ozone emission rate (OER) for the device while operating in situ, and help provide context for the measurements. For example, if a 10 ppb rise in ozone is observed due to device operation in a residence with relatively high ozone reactivity (a.k.a., ozone decay rate), we can expect the incremental increase of ozone in a residence with low reactivity to be larger, all else being equal. Checklists for device testing in California buildings are shown in Appendix 9.4 and 9.5.

CRTM 1. Measurement objectives

The incremental increase in indoor ozone concentration that results from operation of an in duct electronic air cleaner will be measured. Subsequently, the decay of ozone and CO_2 will be measured to help interpret the increased ozone concentration. These measurements will be converted into air exchange rate (AER) and ozone decay rate (ODR) values. From the incremental increase in ozone concentration, the AER and the ODR, the ozone emission rate is estimated.

CRTM 2. Basis

The AER method is based on ASTM standard E741-11 *Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution.* Throughout this method, specific sections of the E741-11 standard are noted as relevant. This method is specific to the *Concentration Decay Test Method*, Section 8 of ASTM E741-11. The ODR method follows many of the same procedures outlined in the *Concentration Decay Test Method*, but relies also on methods described in Lee et al., 1999, Ozone Decay Rates in Residences. *Air & Waste Management Association* 49: 1238-1244. Some details below are unique to the overall goals of the project, but do not deviate substantially from the two reference methods.

Monitoring site selection and preparation for AER, ODR, & OER Tests (Duration 15 minutes)

CRTM 2.1. If necessary, have licensed HVAC installer install in-duct device to be tested. Where possible, run in device for at least 4 hours prior to testing.

CRTM 2.2. For all AER/ODR/OER tests minimize length of sampling tubes to 2 meters or less.

CRTM 2.3. For AER/ODR tests, locate two indoor "*static monitoring"* sites for the O_3 monitors. The static monitoring sites should be located as feasible given space design and furnishings:

CRTM 2.3.1. In principal living/activity areas of the house such as living room, master bedroom, and/or kitchen/dining areas.

CRTM 2.3.2. Center of room.

CRTM 2.3.3. 0.5 meters from corners, windows and walls, and 0.5 meters from large vertical surfaces like partitions, cabinetry, or large furniture pieces.

CRTM 2.3.4. 2 meters from air supply and return vents, fans or other devices that move air.

CRTM 2.3.5. 2 meters from doorways.

CRTM 2.3.6. Away from direct sunlight.

CRTM 2.3.7. 1 to 1.5 meters above floor surface.

CRTM 2.3.8. Not in hallways, corridors, or small enclosed areas like closets and utility rooms.

CRTM 2.3.9. Have electrical power for ozone monitor.

CRTM 2.4. For outdoor readings to align with AER/ODR/OER tests, locate one outdoor "static monitoring" collection point:

CRTM 2.4.1. Within 2 meters of home.

CRTM 2.4.2. 1 to 1.5 meters above ground surface.

CRTM 2.4.3. Where possible, as far as possible from VOC emitting sources such as pine trees or other high-emitting plants.

CRTM 2.4.4. Away from separate ozone generating or sink source points.

CRTM 2.4.5. Sampling tube is expected to originate from an indoor sampling device. Tubing is to be routed through a window or other convenient outlet point from the home.

CRTM 2.5. For OER test, locate one downstream sampling collection point from the electrically connected in-duct device:

CRTM 2.5.1. Identify an air supply (downstream) monitoring site that has the shortest duct run from the test device, and locate a return (upstream) monitoring site that has the shortest duct run to the test device. If the supply and returns with the shortest duct runs from the device are within 2 meters, select an alternate supply or return with the next shortest duct run from the test device or locate return sampling tube a sufficient distance from the return towards center of room to obtain a minimum 2 meter distance between sampled supply and returns.

CRTM 2.5.2. Place the supply collection point in center of supply vent with tube just below vent or through vent into duct area. The sampling tube should draw airflow from the center of the supply.

CRTM 2.5.3. Place the return collection point in the center of the return vent with tube just below vent (10 to 20 cm).

CRTM 2.6. For OER test, locate one upstream sampling collection point from the electrically connected in-duct device:

CRTM 2.6.1. Use the air return vent nearest the device or near center of room, but at least 2 meters from a supply.

CRTM 2.6.2. Place the return collection point in the center of the return vent with tube just below vent (10 to 20 cm). The sampling tube should draw air flow from center of the return.

CRTM 2.7. Set-up ozone monitoring devices. For AER/ODR tests position ozone monitors at static and outdoor monitoring sites. For OER test position ozone monitors at downstream and upstream monitoring sites, and at outdoor monitoring site.

CRTM 2.7.1. Ozone monitoring devices must be turned on and allowed a warm-up period (minimum 30 minutes) until test cell temperature reaches manufacturer's specification (2B Tech 37 +/- 1 degrees C, API 52 +/- 0.5 degrees C).

CRTM 2.8. Set-up ozone monitor data logging computers and establish data connection with monitors. Test data connection to ensure data is received on computer.

CRTM 2.9. Set-up carbon dioxide monitoring devices within 1 meter of ozone sampling tubes.

CRTM 2.10. Set-up ozone generators and carbon dioxide canisters near monitoring sites. For carbon dioxide canister determine pathways for moving through house to seed carbon dioxide efficiently throughout house.

CRTM 2.11. Set-up mixing fans near monitoring sites. Use at least 2 box fans with long extension cords so fans be moved about house.

CRTM 3. Building preparation for AER, ODR and OER tests (Duration 30-60 min)

The following procedures should be implemented.

CRTM 3.1. Inspect the interior of the home to assure that all exterior windows are closed and locked or secured to prevent unplanned introduction of outdoor air.

CRTM 3.2. Select an egress door (use the door from the home to the garage if possible) and all other exterior doors will be closed and locked to prevent unplanned entry.

CRTM 3.3. Temporary signs should be placed on the doors that says "Do Not Enter," describes test, organization, contact information and test start and end times.

CRTM 3.4. Use air flow smoke tubes to detect any large air flows through house envelope such at floor furnace grates, around window air conditioning units, cracked or broken windows, and exterior doors with large air gaps.

CRTM 3.4.1. Seal any significant air leaks using quick-release painters tape and 4 mil or thicker polyethylene sheeting.

CRTM 3.5. Connecting doors should be opened to allow unobstructed internal air flow.

CRTM 3.6. Closet doors should be closed to reflect normal occupied conditions.

CRTM 3.7. Bathroom, kitchen or building exhaust fans are turned off.

CRTM 3.8. If possible, remove HVAC air filters to reduce potential O_3 reactions on filter surfaces. Ensure that HVAC system seals without filter.

CRTM 3.9. Where feasible, suspected O_3 reactive emission sources (e.g., air freshener, cleaning chemical, and combustion sources, such as candles, stove burners, portable gas heater, etc) must be turned off, removed or sealed in air tight containers prior to sampling effort.

CRTM 3.10. Identify potential O_3 emission sources in the home (electronic air cleaners, laser printers, copiers, etc.) and assure each is turned off or unplugged prior to conducting tests.

CRTM 4. General monitor parameters for AER, ODR, & OER tests (Duration 0.5 hours, concurrent with Building Preparation for AER, ODR, & OER Tests)

CRTM 4.1. Calibrate the air quality monitors with a certified calibration gas (CO_2) the day prior to testing.

CRTM 4.2. Ozone measurements will be logged internally or using an external data logging device (e.g. computer) with 2 minute or less intervals.

CRTM 4.3. CO_2, T and RH are logged at 60 second intervals.

CRTM 4.4. Check ozone monitors for correct operation and resolve fault errors. Check data logging and data cables.

CRTM 4.5. Log baseline indoor and outdoor ozone concentrations for 30 minutes after monitor cell temperatures are in correct range (warmed-up).

CRTM 4.6. Take pictures of the inside and outside of home to record conditions; include photographs of the 2 indoor and 1 outdoor static monitoring sites.

CRTM 5. Ozone concentration change Test (Duration 5 hours)

CRTM 5.1. Install ozone generating device in duct (done prior to test).

CRTM 5.1.1. A licensed HVAC technician must install the in-duct ozone generating device.

CRTM 5.1.2. The licensed HVAC technician will test the device to ensure is operating as specified by the manufacturer.

CRTM 5.1.3. Operate device for at least 4 hours if possible to run it in prior to starting experiment.

CRTM 5.2. Ozone concentration change Test Preparation (Duration 0.5 hours)

CRTM 5.2.1. The fan control switch will be placed in the "ON" position to assure the fan operates continuously for the test period.

CRTM 5.2.2. Attach supply and room (or return) sampling tubes to ozone monitors. Move monitors as necessary to connect with supply and room (or return) sampling tubes.

CRTM 5.2.3. Review ozone monitor conditions and resolve fault errors.

CRTM 5.2.4. Log indoor and outdoor baseline O3 concentration 30 minutes prior to starting measurement.

CRTM 5.3. Air Exchange Rate (AER) measurement (Duration 4.5 hours, simultaneous with CRTM 5.4. Ozone concentration change measurement)

CRTM 5.3.1. Measure air exchange rate using same procedure described in CRTM (6 and 7). Stage 1 (HVAC Fan On) AER & ODR CRTM 6.

CRTM 5.3.2. Estimate AER using early and later concentration values that are representative of decay.

CRTM 5.4. Ozone concentration change measurement (Duration 4.5 hours, simultaneous with CRTM 5.3. AER measurement)

CRTM 5.4.1. Start ozone and CO_2, T and RH monitor data logging.

CRTM 5.4.2. Confirm data connections to logging computer, and that monitors are operating at correct test cell temperatures.

CRTM 5.4.3. Record on checklist the start time, and indoor and outdoor CO_2, T, RH, and O_3 readings.

CRTM 5.4.4. The in-duct device is placed in the "ON" mode during study test run. If the device has level settings such as "low to high," set the device on the high setting to measure emission rate at highest output.

CRTM 5.4.5. The supply and return monitoring sites O_3 concentrations are logged at 2 minute or less intervals during the 4.5 hour test to establish ozone emission rate profile.

CRTM 5.4.6. At downstream and upstream monitoring sites CO_2, T and RH are logged at 60 second intervals during the 4.5 hours test.

CRTM 5.4.7. Turn off mixing fans, lock door and record egress time after CO2 concentrations at the downstream and upstream monitoring sites are within 10% of each other as described in 6. Stage 1 (HVAC Fan On) AER & ODR Test CRTM 6.7.

CRTM 5.4.8. After 3.5 hours return to test house, unlock door, and record ingress time.

CRTM 5.4.9. Turn off in-duct device and continue recording for 60 more minutes to obtain end-of-test background ozone concentration.

CRTM 5.4.10. Record end time, and indoor and outdoor CO_2, T, RH, and O_3 readings.

CRTM 5.4.11. Confirm successful data logging and that data is consistent with typical values.

CRTM 5.4.12. Download logged data to at least 2 external storage devices.

CRTM 5.4.13. Estimate AER and OER using early and later concentration values that are representative of actual CO_2 decay and stable ozone concentrations to determine if values are consistent with typical house values.

CRTM 6. Stage 1 (HVAC Fan On) AER & ODR Test (Duration 2 hours)

CRTM 6.1. Attach the 2 indoor static monitoring site sampling tubes to the ozone monitors. Move monitors as necessary.

CRTM 6.2. Start ozone and carbon dioxide monitor data logging. These should be ready from previous device testing.

CRTM 6.2.1. Confirm ozone monitor test cells are at correct test temperatures (warmed-up).

CRTM 6.2.2. Confirm logging and check connections.

CRTM 6.3. Start test by recording start time and beginning indoor (2 static monitoring sites) and outdoor T, RH, CO_2 and O_3 concentrations in the protocol checklist.

CRTM 6.4. Mixing fans (e.g., portable fans, ceiling fans, etc.) are turned on to circulate the air and allow O_3 and CO_2 gas mixing thoroughly within the home.

CRTM 6.5. HVAC system will be placed into operation with the fan selection set in the "on" position, so air is circulated in the house.

CRTM 6.6. O_3 gas will be introduced in a room adjacent to the ozone sample site via ozone generators to an average concentration approaching 100 ppb, but not to exceed 100 ppb.

CRTM 6.7. Simultaneous with O_3 generation release CO_2 (tracer gas) within the interior space of the home via compressed gas cylinder at several predetermined points within the home to assure a uniform interior CO_2 level in excess of 4,000 ppm is observed in all rooms.

CRTM 6.8. When CO_2 concentrations indoors differ by less than 10% of the average CO_2 concentrations (ASTM E471-11, 12.4.1) as measured at the 2 static monitoring sites, the mixing fans are turned off and the ODR and CO_2 tracer gas decay sampling process starts. Since ozone may react at different rates with surfaces in each room, it is not possible to ensure that ozone concentrations achieve the same concentration throughout the house. Since CO_2 and ozone are injected simultaneously, CO_2 uniformity will be used as a surrogate.

CRTM 6.9. O_3 concentrations will be monitored and recorded at 2 minute or fewer intervals for a minimum of 90 minutes to establish decay rate profiles.

CRTM 6.10. Indoor T, RH, and CO_2 concentrations will be data logged at 1 minute intervals at the static monitoring sites during the 90 minute test to determine decay rate profiles.

CRTM 6.11. The outdoor T, RH, CO, and CO_2 concentrations will be observed and recorded at 1 minute intervals during the 90 minute test to ensure necessary air exchange rate data are collected and thermal conditions are characterized.

CRTM 6.12. No occupants or researchers will remain in the home during the AER & ODR measurement to minimize exposure.

CRTM 6.13. Lock doors and record egress time.

CRTM 6.14. After 90 minutes return to test house, unlock doors, and record ingress time.

CRTM 6.15. At the end of the test, the end time and final indoor and outdoor T, RH, CO_2 and O_3 concentration will be observed and recorded in the protocol checklist.

CRTM 6.16. Confirm successful data logging and that data appears is consistent with typical values.

CRTM 6.17. Download logged data to 2 external storage devices.

CRTM 6.18. Estimate AER and ODR using early and later concentration values that are representative of decay to determine if values are consistent with values typical of the type of building tested.

CRTM 7. Stage 2 (HVAC Fan Off) AER & ODR Test (Duration 2 hours)

Conduct the Stage 2 AER & ODR test, if sufficient time of test house occupancy remains to complete the test, move test equipment and materials

from the house and restore house to original conditions (i.e., unseal windows and doors, put back sealed emission sources like candles, and reinstall HVAC air filters). Stage 2 results will improve ozone emission rate estimates, but test can be eliminated based on available time in test house.

CRTM 7.1. Log indoor and outdoor baseline O3 concentration 30 minutes prior to starting Stage 2 AER & ODR measurement. Logging will begin immediately after finishing OER measurement.

CRTM 7.2. Ensure indoor O_3 and CO_2 has stabilized to 30% of background concentrations from OER measurement. If necessary, open windows and doors, and use mixing fans to increase air exchange to bring down concentrations.

CRTM 7.3. Start ozone and carbon dioxide monitor data logging.

CRTM 7.3.1. Confirm ozone monitor test cells are at correct test temperatures (warmed-up).

CRTM 7.3.2. Confirm logging and check connections.

CRTM 7.4. Start test by recording start time and beginning indoor (2 static monitoring sites) and outdoor T, RH, CO_2 and O_3 concentrations in the protocol checklist.

CRTM 7.5. Mixing fans (e.g., portable fans, ceiling fans, etc.) are turned on to circulate the air and allow O_3 and CO_2 gas mixing thoroughly within the home.

CRTM 7.6. HVAC system will be turned off (fan in auto position, and heat/cool switch in "off" position to ensure no operation of the unit during the test period) so air is not circulated in the house by the system.

CRTM 7.7. O_3 gas will be introduced in home via ozone generators to an average concentration approaching 100 ppb, but not to exceed 100 ppb.

CRTM 7.8. Simultaneous with O_3 generation release CO_2 (tracer gas) within the interior space of the home via compressed gas cylinder at several predetermined points within the home to assure a uniform interior CO_2 level in excess of 4000 ppm is observed in all rooms.

CRTM 7.9. When CO_2 concentrations indoors differ by less than 10% of the average CO_2 concentrations (ASTM E471-11, 12.4.1) as measured at the 2 static monitoring sites, the mixing fans are turned off and the ODR and CO_2 tracer gas decay sampling process starts.

CRTM 7.10. O_3 concentrations will be monitored and recorded at 2 minute or fewer intervals for a minimum of 90 minutes to establish decay rate profiles.

CRTM 7.11. Indoor T, RH, and CO_2 concentrations will be data logged at 1 minute intervals at the static monitoring sites during the 90 minute test to determine decay rate profiles.

CRTM 7.12. The outdoor T, RH, CO, and CO_2 concentrations will be observed and recorded at 1 minute intervals during the 90 minute test.

CRTM 7.13. No occupants or researchers will remain in the home during the AER & ODR measurement to minimize exposure.

CRTM 7.14. Lock doors and record egress time.

CRTM 7.15. After 90 minutes return to test house, unlock doors, and record ingress time.

CRTM 7.16. At the end of the tests, the end time and final indoor and outdoor T, RH, CO_2 and O_3 concentration will be observed and recorded in the protocol checklist.

CRTM 7.17. Confirm successful data logging and that data are consistent with typical values.

CRTM 7.18. Download logged data to 2 external storage devices.

CRTM 7.19. Estimate AER and ODR using early and later concentration values that are representative of decay, and are constituent with typical values for the type of building tested.

CRTM 8. AER & ODR Data analysis

CRTM 8.1. In field data analysis will consist of separate Stage 1(HVAC fan on) and Stage 2 (HVAC fan off, if test is conducted) estimates of house air exchange rates, ozone removal rates due to decay and indoor/outdoor air exchange, and ozone decay rates. Record data analysis in the following table (shown with example inputs):

Example of data recording in field.

House ID	Stage 1 HVAC On			Stage 2 HVAC Off		
	Air Exchange Rate (Result Eq. 1) (1/hr)	Ozone Removal Rate (Result Eq. 2) (1/hr)	Ozone Decay Rate (Result Eq. 3) (1/hr)	Air Exchange Rate (Result Eq. 1) (1/hr)	Ozone Removal Rate (Result Eq. 2) (1/hr)	Ozone Decay Rate (Result Eq. 3) (1/hr)
1	0.42	1.32	0.90			
2						
…						

CRTM 8.2. Calculation of ozone AER, ORR and ODR

CRTM 8.2.1. Field estimates of air exchange rates are calculated using the two-point decay equation below [Eq. 1]. Final AER measurement is determined from linear regression the natural log of the CO_2 concentration difference (subtracting out background CO_2) vs time (slope = AER) of the full decay data series.

$$AER = [\ln (C_{t2} - C_0) - \ln (C_{t1} - C_0)] / (t_2 - t_1) \qquad \text{[CRTM Eq. 1]}$$

Where:

AER = air exchange rate , (h^{-1})

C_0 = background carbon dioxide concentration (ppm)

C_t = carbon dioxide concentration at time, t (ppm)

CRTM 8.2.2. Field estimates of the first order ozone removal rates are calculated using the two-point decay equation below [Eq. 2]. Final ORR is the slope of a linear regression the natural log of the ozone difference (subtracting out background ozone) of full decay data series.

$$ORR = [\ln (C_{t2}-Co) - \ln (Ct_1-Co)] / (t_2 - t_1) \quad \text{[CRTM Eq. 2]}$$

Where:

ORR = ozone removal rate (h^{-1})
C_{t1} = ozone concentration at time 1 (ppb)
C_{t2} = ozone concentration at time 2 (ppb)
C_o = background indoor ozone concentration (ppb)
t = time (h)

CRTM 8.2.3. The ozone decay rate is estimated by subtracting the air exchange rate (AER) from the estimated ozone removal rate (ORR).

$$ODR=ORR-AER \quad \text{[CRTM Eq. 3]}$$

CRTM 9. Incremental increase in ozone concentration and ozone emission rate analysis

CRTM 9.1. The incremental increase in the ozone concentration (estimated from field data) is the average ozone concentration measured in the room (or return) with the device on MINUS the average ozone concentration measured in the room (or return) with the device off taking into account time for mixing and approach to steady-state conditions.

CRTM 9.1.1. Note also the increase in the average concentration at the supply with the device on versus with the device off.

CRTM 9.2. The effective ozone emission rate is estimated using two methods, both based on a mass-balance of ozone within the building shell:

$$OER1= V[(C_{O3})(AER+ODR)-P(AER)\ C_{O3,out}] \quad \text{[CRTM Eq. 4]}$$

And

$$OER2 = (C_{O3}-C_{O3,o})(AER+ODR)V \quad \text{[CRTM Eq. 5]}$$

where,

C_{O3}= steady state indoor ozone concentration with device on (mg m^{-3})
$C_{O3,o}$= steady state indoor ozone concentration with device off (mg m^{-3})
$C_{O3,out}$= average outdoor ozone concentration (mg m^{-3})
AER=air exchange rate measured by CO_2 decay rate (h^{-1})
ODR = first-order decay rate (h^{-1})

P=penetration (using 0.8 as a central value)
V = volume of test house (m^3)

2.4 Building simulations

In Task 5 of *In-duct air cleaning devices: Ozone emission rates and test methodology*, indoor ozone concentrations resulting from the use of electrically connected in-duct devices are simulated using standard mass balance models of air in buildings typical of the California residential building stock.

In this task, the team applied a steady-state single zone model and a dynamic, multizone model. Each has its advantages in revealing the influence on ozone concentrations of underlying parameters and phenomena. The single-zone steady state model assumes a well-mixed home where parameters such as volume, air exchange rate, building and building shell reactivity, and source strength can be varied over ranges typical of residences in California. The dynamic, multi-zone model focuses on a specific small house of a set size but allows for spatial differences among rooms to develop, perhaps due to wind impinging on the side of the house. It also accounts for time-dependent ozone concentrations, especially as they are influenced by on-off cycles of the central air system.

2.4.1 Single zone model

It is generally accepted that the following dynamic mass-balance model incorporates the most important factors that influence ozone levels in residences and other indoor spaces that are well mixed internally (Nazaroff, 1986; Weschler et al., 1989; Weschler, 2000; Zhao et al., 2006; Carslaw, 2007). The rate of change of ozone within the environment is,

$$\frac{dC}{dt} = \lambda C_o P_b + \frac{S'}{V} - \lambda C - \sum_{i=1}^{n} \frac{k_i C_i}{V} C - \sum_{j=1}^{m} v_{d,j} \frac{A_j}{V} C - (1 - P_r)\lambda_r C \qquad (1)$$

Term: *1* *2* *3* *4* *5* *6*

Where, C is the indoor concentration of ozone (μg m^{-3}) at all locations within the room, or residence depending on simulation volume of interest. Each term after the equality represents an input or output from the system. Variables are defined below and in Section 8.

Term *1* represents the rate at which outdoor ozone enters the building by ventilation or infiltration. The air exchange rate, λ, (h^{-1}) is the volumetric ventilation + infiltration rate divided by the volume, V, of the building. A typical North American air exchange rate for closed residences is ~0.5 h^{-1} (Murray and Burmaster, 1995), meaning that it takes about 2 hours for a volume, V, of outdoor air to enter and exit the building. Contemporary measurements of air exchange rates for US and California homes are available (e.g. Offermann, 2009). The outdoor ozone concentration, C_o (μg m^{-3}), is time dependent and varies diurnally because its

formation is driven by sunlight photolysis. The building shell may partially filter out ozone due to reactions with building shell materials (concrete, wood, insulation). To account for this phenomenon, a unitless building-shell penetration factor, P_b, ranging from 0 to 1, has been added to newer indoor air quality models.

Term *2* represents source emissions of ozone into the occupied space (not directly from an in-duct device itself). The source emission factor, S' (μg h^{-1}), is itself dependent upon the emission rate of the in-duct device and attenuation phenomena within the ductwork. To be more specific, S' is a function of the source emission rate of the device, S, the surface reactivity of the duct-work and the device itself, flowrates, turbulence, and any gas-phase reactions that may be fast enough to significantly decrease the ozone concentration. To provide an analysis that focuses on the more important influences in indoor ozone concentrations, S is not integrated directly into the model because this creates a much more complicated system which requires many more inputs (e.g. lengths and surface reactivity of each supply duct). Instead, the effect of duct reactivity on recirculated ozone removal is integrated into term 6. In general, S is larger than S', but in most cases, the difference is predicted to be small. Thus, S' is treated as the device emission rate throughout and recognition of the difference is discussed in the results section.

Term *3* is the rate at which ozone is removed from the building by air exchange.

Term *4* represents the rate at which ozone is depleted due to its reaction with chemicals in the air of the occupied space. Examples include ozone reactions with nitric oxide (generated by gas burners on stoves) and terpenes (fragrance chemicals released by personal care products and cleaners). Each chemical, i, reacts at a rate characterized by a second-order rate constant, k_i. The summation accounts for ozone depletion by all gas-phase reactions.

Term *5* represents ozone depletion due to its reaction with indoor surfaces of the occupied space (not ductwork). Each surface, j, reacts at different rates with ozone. This rate depends on the chemical composition of the surface or its coating, and the fluid mechanical rate of ozone transport to each surface. The deposition velocity, $v_{d,j}$ (m h^{-1}), is a parameter that combines both phenomena and A_j is the area of the surface j The summation accounts for ozone depletion by all surface reactions.

Term *6* represents ozone depletion within a building's recirculation system. This includes return ductwork not considered in Term *2*. Ozone can react with dust, duct material and filters; thus air delivered to a room at a supply vent may have a somewhat lower ozone concentration than the air drawn in by the return vent. The recirculation system penetration factor, P_r, combines all removal mechanisms within the mechanical recirculation system. The recirculation air exchange rate, λ_r (h^{-1}), is the volumetric flowrate through the system divided by the building volume. Generally, recirculation is a periodic, on-demand, phenomenon. Measured ozone loss on in-duct filters (Zhao et al., 2006) and models of ozone loss within ductwork

(Morrison et al. 1998) will be applied here. Duct leakage is not included in this calculation. Note that terms 4, 5 and 6 can be combined as an overall ozone removal rate, recognizing that there may be differences in the removal rate when the recirculation system is operating.

Indoor air concentrations are dynamic, changing substantially over a day's time. But over short intervals, such as one hour, ozone levels tend to change by modest amounts. For assessing the influence of one variable over another, or for assessing the impact of a control strategy, steady-state analysis proves useful and even acceptably accurate for short averaging time periods. Steady-state analysis requires that none of the variables vary over the time-interval of interest. This requires that dC/dt = 0. The estimated ozone concentration in the occupied space, *C,* can then be solved directly,

$$C = \frac{S' + V\lambda C_o P_b}{\left(\lambda + \sum_{i=1}^{n} \frac{k_i C_i}{V} + \sum_{j=1}^{m} v_{d,j} \frac{A_j}{V} + (1 - P_r)\lambda_r\right) V} \qquad (2)$$

Thus, if all independent parameters are known for an individual building (V, A_j, k_i, C_i, $v_{d,j}$, λ, λ_r, C_o, P_b, P_r) an estimate of the indoor concentration can be determined. See glossary of parameters in section 8.

2.4.2 Parameters

Equation (2) includes a large number of parameters that influence indoor concentrations. Many parameters have been measured in field or laboratory studies or have been predicted based on mathematical models. A nominal, average or median value of each parameter will be chosen to represent a Standard House. Round values towards the edges of parameter distributions, that maximize indoor ozone concentrations that result from indoor sources, will be chosen to represent an At Risk House.

2.4.2.1 Source emission rate.

The effective source emission rate (S'), assuming an HVAC duty cycle of 100%, in equation(2) could range from zero to greater than 2000 mg h^{-1}. Bowser (1999) studied 15 homes with in-duct "electronic air cleaners" (type not specified, but probably plate-and-wire electrostatic precipitators) and observed ozone emission rates ranging from 13 to 62 mg h^{-1}. They observed indoor concentrations of ozone, but were not able to ascribe what fractional increase was due to device emissions. Hanley et al. (1995) measured an emission rate at 10 mg h^{-1} for a single electrostatic precipitator. Viner et al. (1992) studied three commercial in-duct electrostatic precipitators and observed ozone emission rates ranging from 20-30 mg h^{-1}. A 25 mg h^{-1} emission rate is equivalent to infiltration of outdoor ozone at the federal regulatory limit (75 ppb) in a typical house (300 m^3) with a typical air exchange rate (0.56). Therefore, an in-duct air cleaner can contribute substantially to indoor ozone concentration of a typical home. Emmerich and Nabinger et al. (2000) used two in-duct air cleaners (electrostatic precipitators) in a full scale "test house". The resulting indoor concentration from use of one device as recommended rose as high

as 200 ppb at an air exchange rate of 0.2 h^{-1} with an outdoor concentration equal to 50 ppb. A second device tested did not generate measurable emissions of ozone but also exhibited very low particle filtration efficiency. In a single home, use of an electronic air cleaner (plate and wire electrostatic precipitator) increased indoor concentrations of ozone by approximately 10 ppb over normal background levels (CMHC, 2003). They did not report an emission rate. The current ARB study found ozone emission rates ranging from undetectable to over 350 mg h^{-1}. At least one manufacturer of ozone generators designed explicitly for insertion into air ducts claims an ozone emission rate as high as 2000 mg h^{-1}.

For simulations, the influence of *S'* on indoor concentration is shown by varying from zero to 300 mg h^{-1}. Unlike other building related parameters, there is no obvious "nominal" value as new devices that generate ozone are always being marketed. Nevertheless, we chose 100 mg h^{-1} as a base-case value that results in the indoor concentration rising to 27 ppb in the Standard House (about half the 50 ppb standard) and 50 mg h^{-1} in the At Risk House which raises the concentration indoors to well over 50 ppb.

2.4.2.2 Air exchange rates

Air exchange rates have been measured in a large number of homes across the US. The largest compilations (Murray and Burmaster, 1995; Pandian et al., 1998) of U.S. residential air exchange rate measurements were based on over 4000 measurements by Brookhaven National Laboratory between 1982 and 1987. These data were segregated by four regions and four seasons, although some seasons in some regions had small data sets. Region 4 of this data set was dominated by data from southern California. Note that results from Murray and Burmaster (1995) are nearly identical to that reported by Pandian (1998) because the data sets are largely overlapping. Wilson et al. (1996) reported on California specific air exchange rate measurements for over 500 homes from 1984 to 1985 and nearly 300 homes during the winter of 1991-1992. Yamamoto et al. (2010) reported on over 500 air exchange rate measurements for three locations (Elizabeth, NJ; Houston, TX; Los Angeles County, CA) as part of the Relationship Among Indoor, Outdoor and Personal Air Study (RIOPA) that took place from 1999 to 2001. To capture a cross-section of newer buildings, Offermann (2009) measured air exchange rates (and other parameters) in 107 "single‐family detached homes built after January 2002" in California. In a modeling study, Persily et al. (2010) calculated distributions of air exchange rates for 209 model homes based on seasonal environmental conditions and the types of houses in regions across the United States. A condensation of the 5th percentile, median and 95th percentile air exchange rates from these studies, with a particular focus on California specific data, are shown in Table 2.2.

Based on the results of national and California specific measurements, we chose to simulate indoor air concentrations within a range of 0.1 to 3 air changes per hour, with a middle value of 0.5 h^{-1}. We chose air exchange rates for the Standard and At Risk Houses as 0.5 and 0.1 h^{-1}.

Table 2.2. Air exchange rates for residential buildings (h^{-1}).

Study	# samples	5%	50%	95%
Murray and Burmaster, 1995				
• National (all seasons)	2844	0.15	0.51	2.19
• Region 4 (dominated by southern Cal)	1549	0.21	0.65	2.82
Pandian et al., 1998				
• National (all seasons)	2971	0.16	0.50	2.21
• Region 4	1482	0.22	0.67	2.87
Wilson et al., 1996 (Winter 1991-1992 data)				
• Northern California	128	0.16	0.41	1.0
• Los Angeles	75	0.21	0.64	2.0
• San Diego	85	0.21	0.46	1.2
Yamamoto et al., 2010 (all seasons)				
• Los Angeles County	182	0.2	0.87	4.0
Offermann, 2009				
• California	107	0.09[a]	0.26	1.1[a]
Persily et al., 2010 (modeled infiltration rates)				
• National	209[b]	0.1	0.44	1.21
• Pacific	209[b]	0.14	0.4	0.97

[a] estimated from reported geometric mean and standard deviation
[b]Number of types of homes in simulation. Much larger number of simulated conditions were used to generate results

2.4.2.3 Building Volume

Residence volumes vary widely; a compilation is shown in Table 2.3. The American Housing Survey (2011) found that Pacific State and National median volume of ~ 380 m^3 (extrapolated from data available). Individual metropolitan areas in California have characteristics similar to the national results with volumes ranging from below 100 m3 to greater than 900 m^3 and a median of 347 to 407 (based on interpolation of data reported for each area). Median values from small studies directed to air quality or air exchange rate measurements reflect some selection bias. For example, Offermann (2009) chose only houses newer than 2002, resulting in a high median volume of 718 m^3. The RIOPA sample of houses tended towards smaller volumes (156 m^3 for Los Angeles County; Yamamoto et al., 2010) although the Los Angeles sample had the highest fraction of newer homes. Persily et al. (2006) developed a suite of 206 model homes for model estimates of heating, cooling, air exchange and air pollution phenomena based on the 1999 American Housing Survey (HUD 1999) and the Department of Energy's Residential Energy Consumption Survey (RECS) (DOE 1999) with a median estimated volume (based on 2.6 m ceiling height) of 460 m^3. For the current study, we chose a range of

volumes from 75 m^3 to 900 m^3 with a central volume of 350 m^3. We chose volumes for the Standard and At Risk Houses as 350 m^3 and 150 m^3 respectively.

Table 2.3. Residential building volumes (m^3).

Study	# samples	5%	50%	95%
American Housing Survey (2011)				
• National	80,950,000	167	379	853
• Pacific	10,623,000	173	369	826
• Anaheim	1,054	211	407	845
• Los Angeles		151	347	845
• Oakland		169	363	845
• Riverside		184	376	818
• San Diego		165	377	826
• San Francisco		186	385	873
• San Jose		215	376	845
Wilson et al., 1996 (Winter 1991-1992 data)				
• All California	293		283	
Yamamoto et al., 2010 (all seasons)				
• Los Angeles County	182		156	
RIOPA raw data				
• Los Angeles County		73	149	278
Offermann, 2009				
• California	107		718	
Persily et al., 2006, 2010				
• National (attached and detached homes)	209		460	

2.4.2.4 Penetration (building shell)

The building shell penetration factor, P_b, parameterizes the fraction of outdoor ozone that remains after reactions with the building shell remove ozone from infiltrated air. Liu and Nazaroff (2001) modeled penetration through cracks, wall cavities and insulation. They concluded that penetration through large cracks and low reactivity surfaces would be high (P approaches 1), but could be very small for small, reactive cracks (P approaches 0). Because information about the distribution of cracks, dimensions and reactivity were not readily available, they could only conclude that penetration for a house could range from very low to very high. However, they felt that it would tend toward the high side under many conditions. Stephens et al. (2012) measured penetration factors in eight homes by inducing a controlled "infiltration" flowrate through cracks in a house. They found penetration to range from 0.62 to 1.02 with a mean of 0.79 ± 0.13. With this limited amount of model predictions and measurements, we chose a middle value of penetration as 0.8 and a range from 0.6 to 1.

2.4.2.5 Ozone decay rates

The overall decay rate (minus the air exchange rate) is represented by Terms 4, 5 and 6 normalized by the concentration, C, in Equation (1) $\left(\sum_{i=1}^{n}\frac{k_i C_i}{V} - \sum_{j=1}^{m} v_{d,j}\frac{A_j}{V} - (1-P_r)\lambda_r\right)$1. Different measurements of decay rate have been performed using a variety of methods, some representing Terms 4 and 5 (without recirculation operating), some including all three terms (with recirculation operating). To complicate things further, some measurements were performed with fans used to improve mixing. Therefore, these measurements span a range of wide range of decay rates. The most comprehensive single study in residences, using the same methods throughout, was by Lee et al. (1999) for 43 residences in Southern California. The raw data was analyzed by (USEPA, 2007) and a log-normal distribution was found to provide a good fit to this data. They report a geometric mean of 2.5 and a geometric standard deviation of 1.5 and a minimum and maximum of 0.95 and 8.05 h^{-1}. This range is consistent with decay rate measurements performed in other indoor settings (see Weschler, 2000 for review; excluding Lee et al. data, values range from 2.5 to 7.6 h^{-1}). For use in predicting indoor ozone concentrations, there may be weaknesses in the data and in the approach that Lee et al. used. Lee et al. determined ozone decay rates by subtracting the AER from an overall decay measurement, just as was done in the field research described in section 2.3. But they did not measure AER directly; instead they estimate the AER from blower-door measurements. They performed all ozone decay rate measurements in sealed homes, with the recirculation system off (if present) and window opening effects on decay were not included. This may bias the distribution to lower values due to reduced air mixing and reduced deposition velocities (v_d). Stephens et al. (2012) used ozone decay in eight homes ranging from 3.6 to 16.8 h^{-1} with a mean of 11.6 ± 0.6 h^{-1} while operating the HVAC system and using mixing fans. Stephens et al. note that their values may be somewhat higher than normal because of higher mixing rates. For the 7 homes tested in this research (with no mixing fans, but with the HVAC system operating), the decay rate ranged from 1.6 to 11.0 h^{-1} with a mean value of 5.2 h^{-1}. Note that in this research and the Stephens et al. research, the decay is due to both the building volume decay rate and any losses associated with the recirculation system (filters, duct surfaces, duct leakage,etc.). In general, it is anticipated that building volume decay rates will increase with HVAC operation due to increased air velocities (Mueller et al., 1973; Morrison et al., 2003) and duct leakage.

For the purpose of separating simulation terms, we chose "ozone decay" to be equal to terms 4 and 5 in equation 1 ($k_d = \left(\sum_{i=1}^{n}\frac{k_i C_i}{V} - \sum_{j=1}^{m} v_{d,j}\frac{A_j}{V}\right)$. Term 6 is separated out to probe the influence of removal taking place in the HVAC system. Existing measurements are the result of a range of methods and conditions that may, or may not, be indicative of "typical" operation. Nonetheless, we choose a range to cover most conditions (1 to 12 h^{-1}). Since the HVAC system fan will normally be operating when the electronic air cleaner is on, some enhanced mixing would be expected. Thus we chose a middle value (Standard House) of 4 h^{-1} that falls between the low

geometric mean value (2.5 h^{-1}) of the 43 homes in Lee et al. (1999) with the HVAC system off, and the higher mean values (~5 to 11 h^{-1}) observed in other studies. For the At Risk House, we chose 1.5 h^{-1} as representing a low, but not unreasonably low, value observed in field studies.

2.4.2.6 Effective exchange rate, λ_r in residential air recirculation systems

The recirculation airflow in residential air distribution systems is commonly normalized by the cooling capacity (tons or kW) of the air conditioner. Typical airflow rates recommended by manufacturers range from 169 to 193 $m^3\ h^{-1}\ kW^{-1}$. The cooling capacity specified depends on the building size, climate and other characteristics. Stephens et al. (2011) measured airflow rates and recirculation air exchange rates in 17 homes in Austin, TX. The median recirculation rate was 6 h^{-1} with a mean of 7.6 h^{-1} and a standard deviation of 6.7 h^{-1}. Excluding two small buildings that were < 100 m^3, the results were slightly lower (median = 5.7 h^{-1}, mean = 5.8 h^{-1}, standard deviation = 1.4 h^{-1}. Low, middle and high values were chosen as 2, 5.7 and 9 h^{-1} for the Standard House and 2 h^{-1} for the At Risk House.

2.4.2.7 Penetration of ozone in residential air recirculation systems, P_r

The overall ozone penetration, P_r, of HVAC/recirculation system is the result of losses to duct and grill surfaces, air handler surfaces (e.g. coils, fan, etc.) and the filter itself. The penetration can be separated into its components for sequential removal. Assuming no duct leakage and that there is a single return and multiple (but identical) supply ducts, overall penetration is simply the product of the individual penetration values for each sequential component (return grill, RG; return duct, RD; air handler, AH; filter, F; supply duct, SD; supply grill, SG).

$$P_r = P_{RG} P_{RD} P_{AH} P_F P_{SD} P_{SG} \qquad (3)$$

Measurements and model predictions are available for ozone penetration through some, but not all, of these components. To our knowledge, no comprehensive measurements of penetration through grills or through air handlers have been reported.

Penetration of ozone through ducts was modeled by Morrison et al. (1998) and predictions based on duct reactivity, duct dimensions and flowrates were provided. For large commercial systems, ozone penetration through ductwork was estimated to be high (>0.96) due to short residence times and modest to low reactivity of duct walls. For residential systems, smaller ducts or lower velocities could reduce penetration. To apply the Morrison et al. methods, the range of residential duct hydraulic diameter, duct lengths, air velocity and surface reactivity are required. Recommended air velocities, u, are 700-900 ft/min (3.5-4.5 m/s). Residential ducts can be rectangular, circular or ovoid with hydraulic diameters ranging from 4" to about 24" (0.1 to 0.6 m) and run lengths, L, from a <0.1 m to 10 or more meters.. Thus, the length to hydraulic diameter (L/D_h) ranges from 0 to ~100 and Reynolds numbers ($u\ D_h/\nu$; ν is the kinematic viscosity) ranging from ~<50,000 to >300,000. The surface reactivity is characterized by a "reaction probability" that has been

measured to range from < 10^{-8} to > 10^{-4} for surfaces that line commercial ducts. The exposed inner surface of residential ducts (before extensive use) is commonly galvanized steel or vinyl. Both of these have very low reaction probabilities of less than 10^{-6}. Indoor surfaces, on average, tend to have reaction probabilities in the range of 10^{-5}, and it has been suggested that this value may be a natural background value due to low-level replenishment of surfaces with reactive materials such as oils (Nazaroff et al., 1987). The inner surfaces of ducts rapidly become soiled with dust and therefore, are likely to have a higher reactivity than the original exposed nylon or galvanized steel, similar perhaps to the average indoor surface value.

Predicted duct penetration values for a range of duct characteristics are shown in Figure 2.6. For any duct with surface reaction probabilities < 10^{-6}, as would be the case for clean ducts, penetration values are greater than 0.99. For ducts with a surface reaction probability equal to 10^{-5}, penetration is greater than 0.92 and typically greater than 0.95. Only for very reactive ducts do penetration values sink below 0.9; a long, reactive, small diameter duct with low velocity could have penetration values as low as 0.6. These results suggest that ducts are likely to have a small impact on ozone removal under most circumstances, with typical penetration ($P_{RD}P_{SD}$) of the order 0.95 or greater.

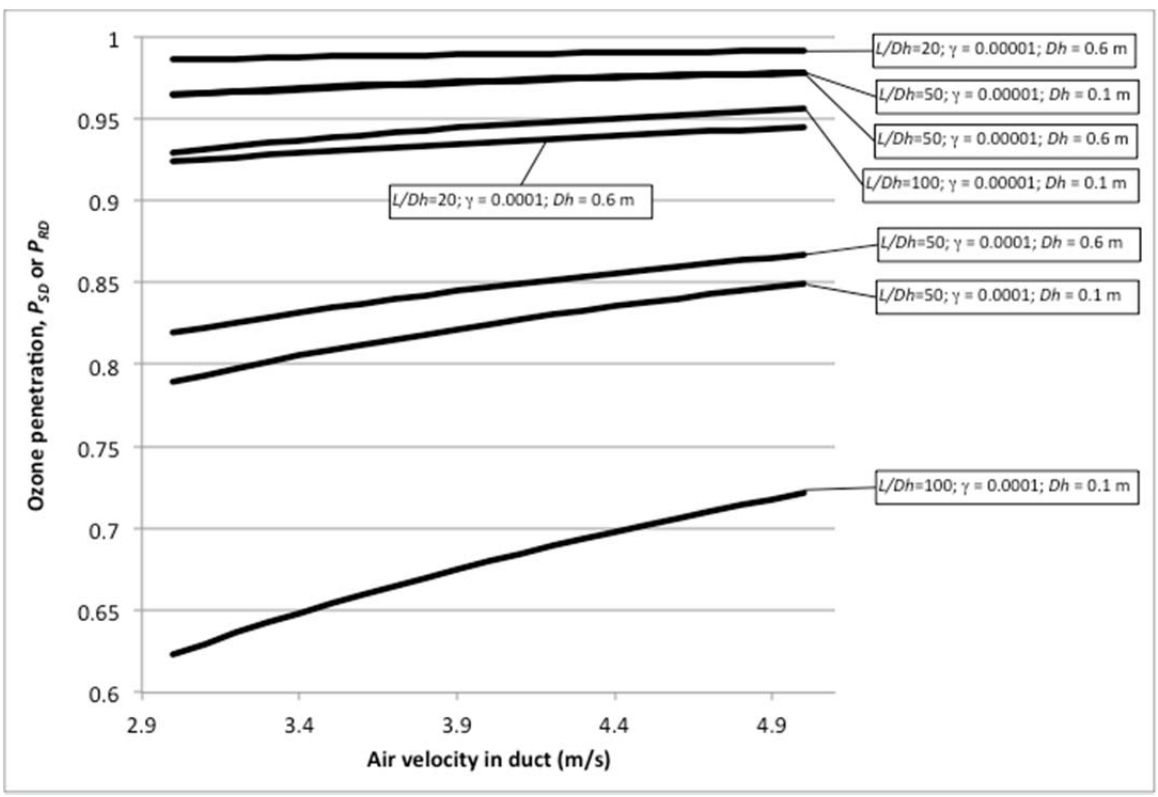


Figure 2.6. Ozone penetration predicted for residential HVAC systems.

Ozone penetration through filters has been studied by several groups. Zhao et al. (2007) measured ozone removal efficiency for 22 filters, some new and unused, some that had been installed in field locations for 4 to 12 weeks. Of these, 16 were

residential filters. MERV ratings ranged from <4 to 8. They found that clean, new filters had penetration values, after several hours of exposure, which ranged from 0.92 to 1.0. Residential filters that had been installed for > 4 weeks had somewhat lower penetration values ranging from 0.7 to 0.9, but mostly above 0.8. Lower penetration was ascribed to reactions with dust that had accumulated on the filters. They observed higher removal efficiencies (lower penetration) through soiled commercial filters. Hyttinen et al. (2006) observed similar ozone removal through clean and soiled commercial filters. For residential filters that are expected to be coated with some dust during most of their operational life, penetration is likely to be in the range of 0.8-0.9.

Combining duct and filter penetration estimates and measurements, we anticipate that overall residential penetration through the air recirculation and distribution system to range from about 0.75 to 0.95, with a middle value of 0.85.

2.4.3 Review of parameters used in single zone model

In Table 2.4 are the parameters used in the single zone model, along with parameters chosen to reflect a typical house (Standard House) and an At Risk House.

Table 2.4. Major parameter values used in single zone model.

	Low	Middle	High	Standard House	At Risk House
Source emission rate (S'), mg h^{-1}	0	100	300	100	50
Air exchange rate (λ), h^{-1}	0.1	0.5	3	0.5	0.1
Volume (V), m^3	75	350	900	350	150
Penetration (P)	0.6	0.8	1.0	0.8	1.0
Decay rate (k_d), h^{-1}	1	4	12	4	1.5
Recirculation air exchange (λ_r), h^{-1}	2	5.7	9	5.7	2
HVAC penetration (P_r)	0.75	0.85	0.95	0.85	1
Outdoor concentration (C_o), ppb	0	60	140	0	0

2.4.4 Multizone model: CONTAM simulations

The model discussed so far accounts for a single "compartment". This either assumes that analysis is for a single well-mixed room, or that the entire building is well mixed over the time scales of interest. However, non-uniform indoor air concentrations may result from low inter-room air exchange (Batterman et al., 2006). This could result in ozone concentrations that are higher in some rooms than would be anticipated based on a whole-house model. Therefore, nominal simulations were also performed using a dynamic, compartment-based model (CONTAM 3.0) to identify phenomena that could enhance indoor concentrations in some rooms (e.g. wind direction) or at some times (e.g. when the air handler initially turns on after ozone has built up in the duct due to a continuously operating ozone-generating device). CONTAM 3.0 was chosen as it is freely available, meets all

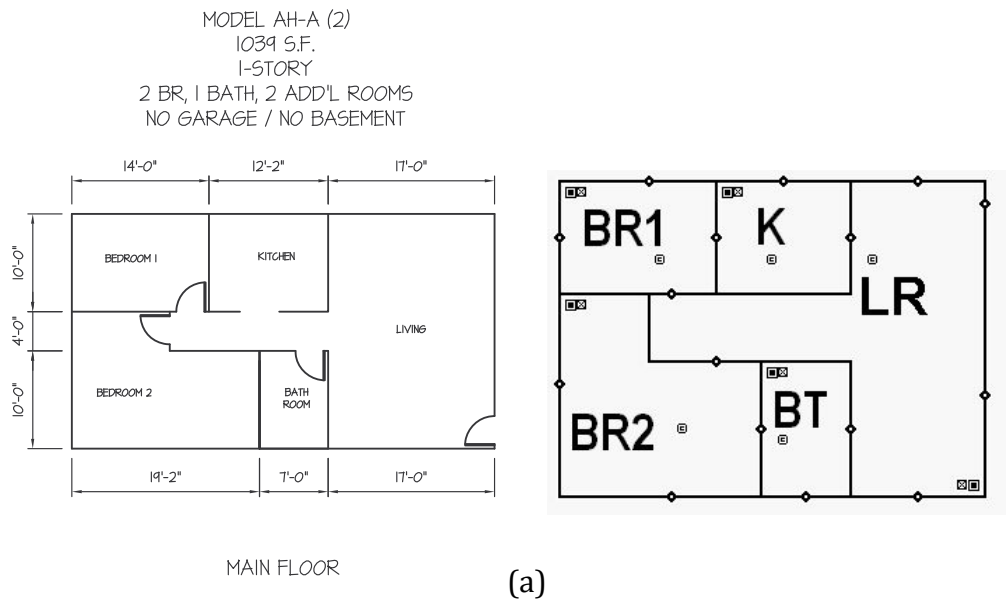
needs described here and has a large number of preformatted residential input files that are typical of the US housing stock (Persily et al., 2006).

CONTAM 3.0 is a multizone modeling program that accounts for the air movement among rooms or other compartments in a building. Fundamental mass and energy conservation concepts underlie the model in a manner similar to (but much more comprehensive than) the mass balance model of equation (2). CONTAM includes the capability of modeling transport, formation, reactive chemistry and deposition of contaminants. Details of the model framework and program can be found at (www.bfrl.nist.gov/IAQanalysis).

Since the objective was to probe the possibility of temporal or spatial "peaks" in ozone within a building, we focused on a single residence and applied a focused set of conditions that would help identify these non-uniform conditions. We did not generate simulations for all types of California homes, or all possible conditions. An example project file is shown in Appendix 9.8. The project file includes all environmental conditions, ambient concentration profiles, schedules of HVAC operation, source and sink parameters, building information and so forth in a format that CONTAM can read and execute.

Building: Persily et al. (2006) generated a set of 209 model building plans for the CONTAM software platform that are representative of US homes. In consultation with the project advisory board and ARB, we chose building AH-14. This 5 room, 1039 ft^2 floor-area home plan is shown in Figure 2.7. The small size is representative of older California homes and indoor ozone concentrations resulting from indoor sources will tend to be higher in smaller homes, all else being equal. Some modifications to the stock parameters were made to 1) allow for the inclusion of an in-duct ozone generating device and 2) to address the goal of probing non-uniform concentrations.

CONTAM does not have a native capability of including an ozone source within ductwork or an air handler. Instead, a separate zone (attic) through which all recirculated air must pass was created. This zone is not shown in Figure 2.7 as it is a separate floor that overlays (above) the main floor. The supply and return registers (☒) connect the source zone with the main floor. The ozone source is placed within this separate zone; note that each zone is well-mixed in this version of CONTAM and location of a source, sink, supply or return within a zone does not influence the results. Ozone removal within the duct is included by including a deposition sink within the attic source zone. The attic source zone is small and the volume and surface area are similar to what you would find in a ducted ventilation system. The ductwork and air handler only move air among compartments; they do not participate in ozone formation or removal. To emphasize spatial differences that may develop among compartments, the open doors shown in Figure 2.7 were closed. Building specific parameters are shown in Table 2.5.



(a) (b)

Figure 2.7. Floor plan of building AH-14 (a) and CONTAM 3.0 representation (b) of building with a main floor and an attic. Diamonds (◇) represent leakage across inner (doors) or outer walls (windows), ☒ represents supply (BR1, BR2, K, BT) or return (LR) registers, © represents ozone sinks and ▣is a place-holder symbol for zone information.

Table 2.5. Selected parameters used in CONTAM simulation using building AH-14. See section 9.9 for input files with details of other input parameters.

Parameter				
Exterior wall leakage area	0.25	in^2/ft^2	17.4	cm^2/m^2
Interior wall leakage area	0.5	in^2/ft^2	34.7	cm^2/m^2
Total AHU flowrate	1243	cfm	2113	m^3/h
Floor area	1039	ft^2	96.5	m^2
Volume	8282	ft^3	25.0	m^3
Interior surface area	4736	ft^2	440	m^2
Ambient temperature	68	F	20	C
Absolute pressure	14.7	psi	101325	Pa

Simulations were separated into *steady-state* and *dynamic simulations*. Steady-state simulations include variable wind direction, different indoor surface reactivity and the possibility for the air handling unit (AHU) to be fully on (100% duty cycle) or off (0% duty cycle). Dynamic simulations include periodic on-off operation of the AHU (e.g. 50% duty cycle), different indoor surface reactivity and non-zero outdoor air concentrations.

AHU and source duty cycle: Duty cycle is the percent time that an air handling unit is on. The AHU duty cycle was chosen, for most simulations to be either 0, 20, 50 or

100%. At 0% duty cycle, the AHU is off. If the ozone source is integrated into the on-off state of the AHU, then the ozone source would be off at all times. Thus no ozone from the in-duct air cleaner would enter the home (not a worthwhile simulation). However, some in-duct devices are independent of the AHU and are likely to be on at all times, regardless of the AHU duty cycle. Pressure gradients in the house can slowly move air through the source zone, injecting ozone into main-floor rooms. At 50% duty cycle, the air handler is on 50% of the time; the on-time can vary. Again, the air cleaner may, or may not, match the AHU duty cycle.

Ozone source zone. The ozone source is located in the "attic", a model compartment that is connected to each room on the main floor via air leakage points (CONTAM simulation of a "hole", required in this case for air return to the AHU). As noted earlier, this simulates having the source inside an HVAC system since CONTAM does not have a mechanism for doing this directly. For all simulations, the ozone source is set to 100 mg h^{-1}. Within the sources zone, some ozone is lost due to reactions with walls. In Figure 2.6, we show that removal of ozone within the duct is likely to be modest. For these simulations, the deposition velocity is set to 0.36 m h^{-1}, which results in a volumetric ozone removal rate of 28.8 m^3 h^{-1}. The flow through the source zone (i.e. duct) is not a constant in these simulations. However, for a nominal return flowrate of 2110 m^3 h^{-1}, approximately 98% of the ozone generated will penetrate the duct and be delivered into rooms. For simulations in which wind-induced pressure gradients slowly drives air through the source zone, penetration of ozone is much lower.

Main floor ozone sinks: All ozone removal on the main floor is modeled as deposition to floors, walls and ceilings with equal deposition velocities associated with each surface. For equal room-specific air exchange rates, a room with a larger surface area to volume ratio, such as the bathroom, will tend to have lower ozone concentrations than the living room. The model is run at two different deposition velocities, representing a "lower-reactivity" and "higher-reactivity" house. The lower-reactivity house has a deposition velocity that is on the low-end of observations for materials tested either in the laboratory or in the field. For example, well-aged paint is a typical low-to-moderate ozone sink and typical has a deposition velocity in the 1 m/h range or less (Wang and Morrison, 2006; Wang and Morrison, 2009). Thus, for the low reactivity house, we chose a deposition velocity equal to 0.72 m/h. In this house, the estimated decay rate (surface area*deposition velocity/volume) would be about 1.3 h^{-1}, consistent with the low end of decay measurements by Lee et al., (1999). The deposition velocity for the higher reactivity house is specified as 2 m h^{-1} which corresponds to a decay rate of 3.7 h^{-1}. This is about middle-range for field measured decay rates but on the higher-end of those measured by Lee et al. (1999).

Weather: Wind directions included 0°, 90°, 135°, 180° and 270°, where 0° is directly from the top of Figure 2.7. In other words, 0° impinges directly on the wall with the kitchen and 90° impinges on the right-hand wall of the living room. Wind speeds

were varied from 2 to 8 m/s based on the range of average wind speeds in California (<1 m/s to 8 m/s; WRCC, 2013).

Ambient ozone concentrations: Based on conversations with staff at ARB, the ambient ozone concentrations for a 24 hour period were generated by averaging the hourly concentrations reported from four monitoring stations in Sacramento, August 30, 2011 (Elk Grove-Bruceville Road, Folsom-Natoma St.,, North Highlans-Blackfoot Way, Sacramento-Del Paso Manor). The ozone concentration (ppm) vs time is shown in Figure 2.8. This single day was used for any dynamic simulations that included non-zero ambient ozone concentrations.

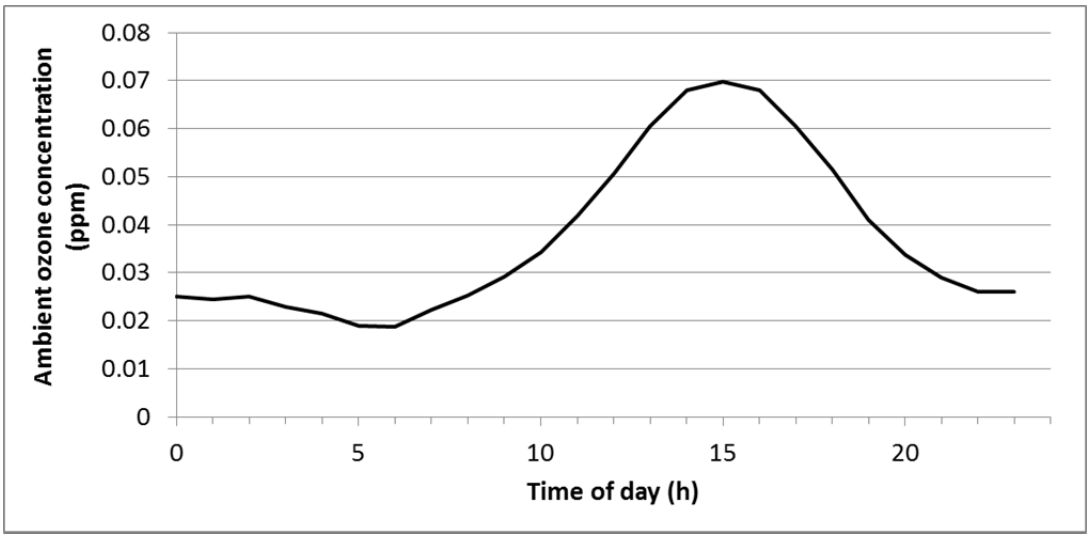


Figure 2.8. Ambient ozone concentration vs time for single-day, dynamic CONTAM 3.0 simulations.

Table 2.6 shows the primary parameters that were applied to steady-state or dynamic simulations.

Table 2.6. Simulation parameters applied to steady-state and dynamic simulations. BASE case values are bold.

	Wind angle (degrees)					Wind Speed (m/s)			Ambient ozone	Deposition Velocity (m/h)		AHU duty Cycle (%)			
	0	90	135	180	270	2	**5**	8		**0.72**	2.0	0	20	50	**100**
Steady State	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓
Dynam-ic	✓						✓		✓	✓	✓	✓	✓	✓	✓

3 Results

3.1 Candidate device survey

Task 1 of *In-duct air cleaning devices: Ozone emission rates and test methodology* required the development of a list of in-duct electronic air cleaners that may emit ozone and are likely (or potentially) installed in California buildings. The analysis was performed through direct contact (phone and email) with manufacturers, distributors and installers, as well as other means where possible (internet searches).

3.1.1 Devices and technologies identified

Based on internet searches and discussions with manufacturers, we developed general classes of in-duct electronic air cleaners and manufacturers. The following companies provided responses to an e-mail or phone inquiry (a total of 13 were contacted): StrionAir, Lennox, DustFree. A great deal of valuable information was provided by Peter McKinney of StrionAir, and some of his responses are shown in the results section in quotes. It was not always possible to identify the precise technology used given limited product information available.

Electrostatic precipitator (EP) air cleaners. Particles are charged in an electrostatic field surrounding a wire or "point" held at a high voltage relative to ground potential. The charged particles are then attracted to an oppositely charged, or grounded, plates, grids or other media. Ozone can be generated in the strong electrostatic field through a reaction sequence involving electrons, free radicals and oxygen. Some devices, typically called ionizers, are similar but have no oppositely charged plates. Instead removal of particles is due to enhanced deposition of charged particles to duct and building surfaces.

Electronically enhanced filters(EEF). In this category are filter media that is actively polarized (requiring electronics to supply a voltage). Particles are naturally charged, slightly, and will be attracted to oppositely charged surfaces. The purported advantage is that, for a relatively low operating cost, polarizing filter media can enhance the removal efficiency without increasing pressure drop.

The following manufacturers (or re-packagers) sell EP and/or EEF style air cleaners; some may be hybrid devices that incorporate other "technologies": Honeywell, Aprilaire, American Standard, Carrier, Bryant, Trane, Rheem, York, AspenAir, Goodman, Ruud, Coleman, Dynamic Air Quality Solutions, Trion, Bel-Aire, Emerson, White-Rogers. Carrier now owns Strionair which manufactures air purifiers for Carrier, Bryant, and Honeywell. According to McKinney "The major competitor to the StrionAir products in the residential whole-house electrically enhanced media filter category is the AprilAire 5000 by Research Products".

Although the packaging appears different among the other companies, it is likely that devices are made by a limited number of OEM manufacturers.

Ultraviolet light bulbs. Without a catalyst (see PCO next), ultraviolet lights are intended to inactivate microorganisms in air and on HVAC surfaces to reduce pathogen transmission and limit growth of microorganisms (e.g. mold, bacteria) on filters, coils and other surfaces. Germicidal lamps that emit UV light with a wavelength of 254 and below can generate ozone through photolysis of oxygen and further reaction ($3O_2 \rightarrow$photolysis$\rightarrow 2O_3$). Both UV-A (long wave, low ozone production) and UV-C (short wave, higher ozone production) are used in HVAC systems. UV lamps are sold to be directly inserted into the duct (e.g. Rheem) or are incorporated into hybrid systems. Honeywell, Lennox, Rheem, York, DustFree and activTek all sell devices that incorporate UV lamps. Some manufacturers, such as Sterile-Aire, use lamp coatings intended to inhibit ozone production.

Photocatalytic Oxidation (PCO). Photocatalytic oxidation systems oxidize molecules at the surface of a semi-conductor catalyst (usually TiO_2). To generate the required "electron-hole" pairs on the surface of the catalyst, it must be illuminated by light. While some visible-light catalysts have been developed, it is unlikely any have made it into the residential PCO market and UV lights are used instead. Lennox, Dynamic Air Quality Solutions sell PCO systems for the residential market.

Dedicated ozone, hydroxyl or hydroperoxide generators. Rather than remove pollutants within the HVAC system, these devices intentionally generate ozone or other oxidants intended to decontaminate the occupied spaces of a building. Manufacturers may use other terms to sell the product (tri-valent oxygen, activated oxygen, hydroxyl generator, ion generator, plasma). Sellers promote its "fresh scent", that it is germicidal and that it chemically purifies the air and surfaces. Ozone generators can use strong electrostatic fields to generate ozone (as in an electrostatic precipitator), electric discharge/plasma, or UV lights. The "technology" behind newer hydroxyl and hydroperoxide generators is more obscure. Based on discussions with Catherine Noakes of Leeds University (who tests these devices for germicidal properties), early versions combined ozone with limonene to generate hydroxyl radicals. The resulting output WAS germicidal according to Noakes. Based on the description of the technology, limonene was in excess and no ozone was emitted. Since hydroxyl radicals have a very short lifetime, the devices probably do not generate these, but instead release reactive intermediates of the limonene-ozone reaction which themselves are germicidal. Newer versions do not use limonene and (according to Noakes) are not germicidal. Hydroperoxide radicals are also relatively short-lived and their efficacy seems questionable. In some cases it is difficult to determine what the device does based just on marketing. Manufacturers that target HVAC applications include Plasma Air (plasma), RGF (hydroperoxide, plasma), Air-zone (ozone), activTek (ion/plasma), IAQ Products (explicit ozone generator), Odorox (hydroxyl) and O3 Ozone Allergy Purifiers LLC (ozone). Note: Odorox is a major hydroxyl generator manufacturer, but does not appear to make a device for in-duct use.

Hybrid systems. Manufacturers are developing air cleaning systems that combine multiple technologies to remove contaminants in duct air. For example, Trane markets the Trane Catalytic Air Cleaning System (TCACS) in the commercial market that combines UV, PCO and high efficiency filtration (MERV 13). Extensive product development of hybrid systems for the residential market may be limited due to equipment and operating costs.

3.1.2 Candidate device survey in California residences

To generate a reasonable estimate of the types of devices installed in California we contacted 72 HVAC installers in Bakersfield, Fresno, Los Angeles, Riverside, Sacramento, San Diego, San Jose and Stockton. Of the 72, we were able to get a manager or installer at 34 companies to answer some of our questions regarding the types of devices installed.

- We identified ourselves and requested that they share the following information with us:
    - Verify that they do residential installation of air cleaning equipment
        - If only commercial continue with survey
    - Do they install electronic in-duct air cleaners
    - What brands do they sell
    - Which model/brands are most popular or that are most likely to install based on their experience.
    - Which distributors they work with

In many cases, we were unable to obtain answers to all questions. However, most provided an answer to the primary question: what electronic air cleaner(s) are they likely to install. The following are raw results from the survey. Manufacturer and model names and were taken "as is" and several do not correspond to our definition of electronic air cleaners or in some cases to real manufacturers. Note that some installers named more than one manufacturer as "preferred".

Table 3.1. Preferred manufacturers: responses from California installers.

Manufacturer	Responses	Style
Honeywell	12	EP, EEF and UV
Aprilaire	10	EP, EEF
Carrier	7	EP, EEF, UV
American Standard	6	EP, EEF
Bryant	5	EP, EEF, UV
Lennox	4	UV, PCO
Trane	4	EP, EEF
Rheem	3	EP, UV lights in duct
York	3	EP + UV lights
AspenAir	3	EP or EEF (power grid)
Flanders[1]	2	Airia 1400 & 2000 Electronic Air Cleaners
Respicare[2]	2	1" 24 volt electronic, this may refer to home care provider
activTek	2	EP with "corona discharge air freshener;" also unit with UV
Air Scrubber[2]	1	PCO & UV
Aller-pure[2]	1	Electrostatic filter
Allergy Gold Filter	1	Electrostatic filter
Dust Free - Dust Fighter 85	1	Electrostatic filter
Electromaze Lifetime Filters[1]	1	Electrostatic filter
Goodman	1	EEF
Rotobrush[1]	1	Resale of various electrostatic filters
Ruud	1	EP
Source 1[1]	1	Accordion type deep pleat (not electronic)
Sta-Med[2]	1	The Sta-Med Electronic Air Cleaner uses a principle known as "Electronic Polarization". 1" 24 volt electronic; EEF type unit
Coleman	1	EP
SaniBulb™ Air Sanitizer	1	Not in-duct system, replacement CFL bulb for standard light fixtures and claims photocatalytic effect.

[1] Does not sell electronic air cleaners
[2] Could not identify manufacturer
[3] Carrier Corporation is also the manufacturer of Bryant, Payne, and Day & Night Heating and Cooling Systems as well as Arcoaire, Comfortmaker, Day & Night Heil, KeepRite, Lincoln, and Tempstar brands
[4] Trane and American Standard have the same manufacturer

Models and device styles. Several specific models were indicated in the survey. Many manufacturers identified sell only one electronic air cleaner model. In order of popularity, with non-electronic devices removed from list:

Table 3.2. Popular electronic air cleaners

Manufacturer and model	Style
Honeywell S300, S500	EP
American Standard Accuclean	EP
Lennox Pure Air	PCO
April Air 5000	EP
Honeywell UV Lights	UV
Trane Clean Air Effects	EP
Aspenaire Filter Grill Models	EEF for return duct grill
PCO	probably indicates a photocatalytic oxidation system, but no manufacturer
Rheem Electronic filter with UV light	EP
activTek Induct2000	UV
Respicare DG1000 "Electronic Polarization". 1" Filter 24 volt electronic Very similar to Sta-Med filters	EEF type

***Summary of installer survey*.** The top manufacturers, in order of responses, were StrionAir (Carrier, Honeywell, Bryant), Aprilaire, American Standard, Lennox, Trane, Rheem, York, AspenAir. The top device styles were Electrostatic precipitators. It is interesting to note that electronically enhanced filter media as drop-in replacements for filters, were not mentioned by installers.

3.1.3 Contact with agencies

We contacted agencies that we felt would have already spent some time considering in-duct devices and would have already developed opinions on what kinds of devices they would like tested. The following are the results of that survey.

Underwriters Laboratory: actively interested in the devices and indicated that they were putting together recommendations with their staff. A representative of UL did mention (verbally) an interest in devices by Trane. We received no further information.

***Consumer product safety commission*:** No specific recommendations

Environmental Protection Agency: No specific recommendations

- Hydroxyl generators (specifically Odorox)
- Activated oxygen generators (ozone generator, specifically EMO_3)
- Negative of bi-polarization technologies (plasma, specifically Plasma Air)
- UV-C technologies (none specifically indicated)
- Any combination of the above

3.1.4 Recommendations for device testing

Given that the project relied heavily on donated devices, we designated preferred styles and manufacturers rather than specific models. In consideration of all information collected in this survey, Electrostatic Precipitators from StrionAir, Aprilaire and possibly American Standard or Trane were preferred. Since many manufacturers carry these, we felt that at least one electronically enhanced air filter and UV light/hybrid from major manufacturers should be tested. Pending availability and remaining test "slots" PCO, and a "generator" of some sort can be included. , Small market devices were of interest if they had a high ozone emission rate. To capture both "popular" devices and small market, potentially high-emitting devices, we initially suggested the following list of devices for testing,

Table 3.3. Initial list of devices to be tested using laboratory ozone emissions test method.

Test	Technology	Manufacturer
Include	Electrostatic precipitators	StrionAir, Aprilaire, Honeywell
Include	Ozone generator	Air-Zone or other
Include	UV-C light, in duct	Dust Free, Rheem, York or Honeywell
Include	Photocatalytic oxidation	Lennox or Dynamic Air Quality Solutions
Include	Oxidant/ion generator	activTek or similar
Include	Oxidant/Ion generator	RGF or similar
If possible	EEF	Major Manufacturer

3.1.5 Devices actually acquired for testing

The project budget limited purchases of all desired devices or specific manufacturers for testing. However, most of the desired technologies were included in testing:

Table 3.4. Devices tested. See Appendix 9.1 for descriptions and details of each device. For laboratory testing, devices were numbered as shown in Table 3.3.

Manufacturer	Model	Style	Devices tested	Devices tested in field location
Dust Free	Bio-Fighter Lightstick	UV	1	--
RGF	Guardian Air	Oxid. Gen/UV	3	1
Honeywell	F300 Electronic Air Cleaner	EP	1	1
Lennox	PureAir	PCO	1	--
activTek	INDUCT 2000	Oxidant Gen/UV	2	2
Air-Zone	Air Duct 2000	O_3 Gen/UV	2	1
APCO	Fresh-aire	Oxidant Gen/PCO	1	--
unknown	HVAC UV 560	O_3 Gen/UV	1	1
Trane	Clean Effects	EP	*	2
Trane	TCACS (commercial)	EP	**	1

* Trane Clean Effects electrostatic precipitators were tested in field locations as they had been installed originally for homeowner. No device of this model was available for lab testing.
** The only field test on a commercial installation of an in-duct air cleaner was that for a Trane TCACS system in a school classroom. This system is too large to be tested in the current standard test apparatus.

3.2 Laboratory test method development and device testing

3.2.1 Test method development

The standard appears in the section that follows this one. It generally follows the format of other test standards used in the HVAC and indoor air quality industry and is divided into each of 10 major sections as shown in Table 3.5. Although the contents of most of these sections should be easy to understand, there are several sub-sections that benefit from further explanation than is explicitly written in the standard. These are described below

Table 3.5. Major Sections in Standard Test Method.

Section	Contents
STM 1	Purpose
STM 2	Scope
STM 3	Definitions and Acronyms
STM 4	Background
STM 5	Test Apparatus
STM 6	Measurement Equipment
STM 7	Apparatus Qualification Testing
STM 8	Test Method
STM 9	Reporting Results
STM 10	Calculated Values

Subsection STM 4.1: The ozone mass emission rate for any air cleaner is the product of the average ozone mass concentration rise across the air cleaner and its volumetric flow rate. This is the fundamental basis for the standard in that both flow rate and ozone concentrations have to be measured accurately and both measurements are challenging in in-duct systems because flow is typically non-uniform and the concentration increase across a device can be very low.

Subsection STM 4.2: Ozone emission rates for portable air cleaners are typically measured with a dynamic rise to steady-state method (i.e. UL 867). This is an appropriate methodology for a low-flow system but does not work for most in-duct applications because very high flows dilute the ozone rise below measurable levels. Said differently, a seemingly small rise in ozone can result from a very high ozone emission rate, and significant increase in indoor ozone concentrations, if the airflow rate is sufficiently high.

Subsection STM 5.2: The apparatus requirements are designed to be sufficiently flexible to allow the use of existing test ducts. This was done to broaden the potential eventual use of the standard. As examples, ASHRAE Standard 52.2 and 52.1 ducts, EN 779 ducts, and several other test apparatuses could be easily modified for the test standard.

Section STM 7: The qualification testing is designed to minimize the impact of the test duct design on the ozone emission results.

Subsection STM 8.1: Given the importance of flow rate and the diversity of flows in residential HVAC systems, the goal of this part of the method was to allow for a variety of flow rates and accommodate most of the in-duct air cleaners in the market, but still result in high accuracy emission rate data. A further purpose of specifying flow rate range was to investigate any dependence between ozone emission rate and air flow rate.

Subsection STM 8.2g: The duration of sampling is of critical importance and it depends on several apparatus specific factors (e.g., length of sampling tubing, sampling valve travel time, response time of ozone analyzer). For all tests completed as part of this research, two minutes was a sufficient sampling time. However, a final sampling duration of 4 minutes was selected to be conservative and allow for other apparatuses with longer response time. The language in Subsection STM 8.2h is complicated, but stems from the desire to make the standard accessible to different apparatus with potentially longer response times as well as applicable to ozone emitting air cleaners that cycle ozone production. There is more information on the impact of sample interval in the Results section.

Subsection STM 10.5: The inclusion of the method of quantitation limit (MQL) is to allow for an assessment of the lowest emission rate that can be accurately measured with an apparatus. It should be noted that some in-duct air cleaners do not emit ozone at a constant rate (see above) and so future iterations of this standard might have to explicitly account for this possibility.

3.2.2 Standard Test Method (STM) for measuring ozone emission rates from electrically connected in-duct air cleaners

STM 1. Purpose.

STM 1.1. This standard establishes a test procedure for evaluating the ozone generation from electrically-connected in-duct air cleaning devices.

STM 2. Scope.

STM 2.1. This standard describes a method of laboratory testing to measure the ozone emission rate of electrically-connected in-duct air cleaning devices.

STM 2.2. This standard establishes performance specifications for the equipment required to conduct tests and defines methods of calculating and reporting the results obtained from the test data.

STM 3. Definitions and Acronyms.

AHU: Air handling unit, a device that consists of a fan and often conditioning equipment that is used to move air through the air cleaning device in this test method.
CFM: Cubic feet per minute, a measurement of volumetric flow rate.
COV: Coefficient of variance, arithmetic mean divided by the standard deviation.
HEPA: High efficiency particle arresting, a type of filter defined by IEST-RP-CC001.5.
IEST: Institute of Environmental Sciences and Technology, Arlington Heights, IL.

MQL: Method quantitation limit, defined for this test method in Section 10.5
UL: Underwriter's Laboratory, Northbrook, IL.

STM 4. Background

STM 4.1. The fundamental approach utilized in this standard is to measure two parameters for the test air cleaner: the air flow through the device and the ozone concentration rise across the device. The product of these two parameters is the ozone emission rate (as defined in Section 10). The apparatus and methodology described in this test standard are designed to result in high-quality measurements of these two parameters.

STM 4.2. The approach described in Section 4.1 is very different from the dynamic rise to steady-state approach that is utilized in ozone emission test methods and standards for portable air cleaners. The dynamic rise can be considerably more accurate, but it is also creates test conditions that are unrealistic for in-duct air cleaners, especially the condition of very low or no air flow through the device.

STM 4.3. The general approach of the standard is to first describe the criteria for the test apparatus (Section 5.2) and then provide an example of an apparatus that meets these criteria (Section 5.3). Details about instrumentation are defined in Sections 6 and apparatus qualification testing in Section 7. The test procedure is in Section 8, with reporting and required calculations in Sections 9 and 10.

STM 5. Test Apparatus.

STM 5.1. The general requirements for a test apparatus are described in Section 5.2 and an example of a test apparatus is described in Section 5.3.

STM 5.1.1. All critical dimensions and arrangements of the test apparatus are shown in the figures of this section. Units are shown in inches and millimeters (in parentheses) unless otherwise indicated.

STM 5.2. General requirements

STM 5.2.1. The test apparatus may be an open-loop or closed-loop system, meaning that return air may be exhausted or recirculated. If it is open-loop, exhaust air should be treated for ozone removal before release to a laboratory or indoor environment.

STM 5.2.2. The apparatus consists of four major sections/functions: the test section where the air cleaner is located and where ozone is measured; the treatment section where incoming or recirculated air is cleaned of ozone and particles before entering the apparatus, the flow generation

section where airflow is generated (usually with variable speed fans), and an additional section, the contaminant and environmental variation section, can be considered optional, where ozone, dust, moisture, and conditioning are controlled for specific optional tests. Note that these sections are not necessarily contiguous unless otherwise required below. Each section is described below.

STM 5.2.3. The test section that will contain the air cleaner must be large enough to accommodate most electrically-connected in-duct air cleaners without modification. A minimum cross section of 24 inches (610 mm) square is recommended. The length of the test section should be at least six diameters in length (where the diameter is defined as the length of one side of the square of the test section). No penetrations are allowed into the test section with the exception of accommodation for the ozone sampling apparatus (described in Section 5.2.5). The test section should have a gasketed and mechanically fastened entry door for test air cleaners

STM 5.2.4. The test section inner duct material must be contiguous (other than the opening for the air cleaner, any required sensors, and necessary structural and access connections) and constructed of stainless steel with smooth interior finish or a material similarly non-reactive with ozone. Other parts of the apparatus can be constructed of galvanized steel or other material, but materials that are reactive with ozone (e.g., wood) must be avoided.

STM 5.2.5. Ozone sampling should occur between 1 and 2 diameters upstream of the air cleaner installation penetration and between 5 and 7 diameters downstream of the air cleaner installation penetration. Each ozone sample should be a representative ozone concentration from the entire cross-section of the duct (specific qualification criteria are described below in Section 7). All ozone sampling apparatuses should be installed in gasketed and mechanically fastened sampling penetrations. Sampling lines from the upstream and downstream sampling points should be the same length and contain the same valving, fittings, and other sources of ozone loss.

STM 5.2.6. Temperature and relative humidity sampling should be conducted at least one diameter upstream of the upstream ozone-sampling grid. Any additional sampling (i.e. particles, dust, VOCs) should also be located at least one diameter upstream of the ozone sampling grid.

STM 5.2.7. Prior to reaching the test section, the air must be cleaned of particles using a high efficiency particle arresting (HEPA) filter and an activated carbon filter. The HEPA filter must be installed with no bypass so that the air stream entering the test section will have fewer than 100 0.02 – 1

μm particles/cm^3. (3270 0.02 – 1 μm particles/in^3) The activated carbon should achieve a concentration of <3 ppb of ozone at the upstream ozone sampling point at all times. These filters do not need to be in the same location in the duct as long as the above performance is met at the beginning of the test section.

STM 5.2.8. Variable speed fan or fans should be able to provide between 300 and 1200 CFM (509-2037 m^3 h^{-1}) of airflow when all components are installed in the duct.

STM 5.2.9. Flow measurement should occur as close to the test section as possible, but be located upstream of any sensors or optional equipment described in Section 5.2.10.

STM 5.2.10. Optional equipment might include heat exchangers to control the temperature and relative humidity in the duct, dust spreaders to artificially load air cleaners with test dust, and ozone generators to create ozone to measure ozone removal by air cleaners or by the test duct itself. Such equipment should be installed as far away from the test section as possible, in such a manner that it does not generate leaks out of or into the duct, and in such a manner that it generates a uniform concentration of moisture/contaminant/temperature throughout the duct cross section in the test section.

STM 5.3. Example Apparatus.

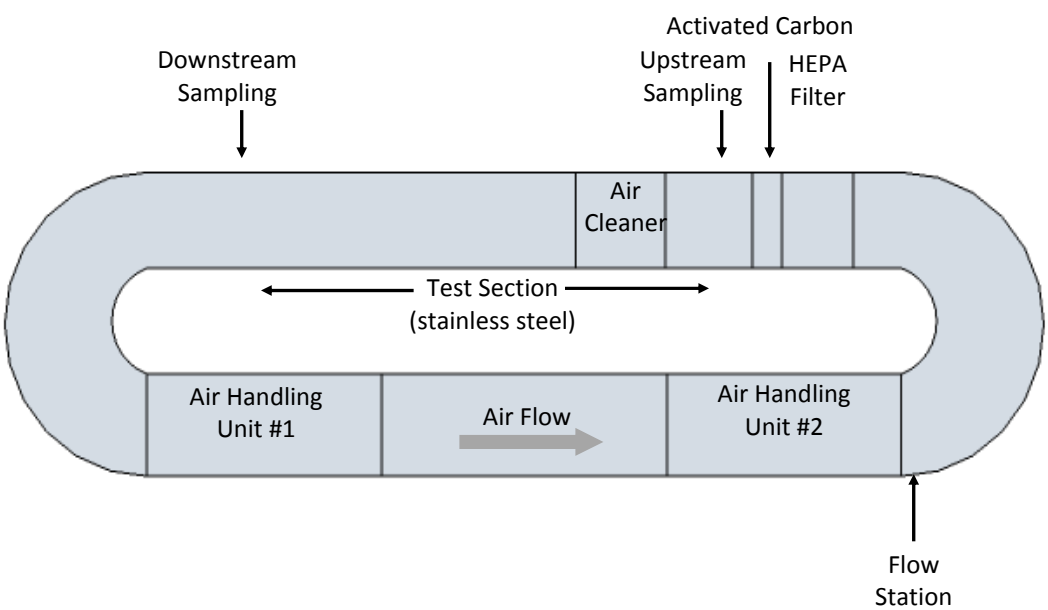


Figure STM 1. Example of an apparatus configuration, which follows the guidelines set in Section STM 5.2.

STM 5.3.1. The apparatus is a closed-loop system, meaning that return air is recirculated. The air flow direction is counter-clockwise based on the representation shown in fig STM1.

STM 5.3.2. The test section is located in the top portion of the duct, the air treatment section is also located in the top section, immediately prior to the test section. The flow control section consists of two air handling units, each with a variable speed fan, in the bottom portion of the loop.

STM 5.3.3. The test section is 24 inches (610 mm) square and 144 inches (3660 mm) long. The test section includes a 24 inch (610 mm) air cleaner installation section with a gasketed plate that supports the air cleaner.

STM 5.3.4. The entire upper portion of the duct, including the test section, is constructed of stainless steel with smooth interior finish. The sides and the bottom portion of the loop are constructed of galvanized steel.

STM 5.3.5. The ozone sampling grids are located 6 inches (150 mm) upstream of the upstream edge of the air cleaner installation section and 114 inches (2900 mm) downstream of the downstream edge of the air cleaner installation section. The sampling grids consist of three 24 inch (610 mm) long 0.5 inch (12.7 mm) ID stainless steel tubing that are perforated with 0.0625 inch (1.5 mm) holes every 1 inch (25.4 mm) of their length. The three tubes are installed vertically with the holes facing upstream at depths of 4 inch (102 mm), 12 inch (305 mm), and 20 inch (508 mm) across the cross section. The three tubes are connected with sealed fittings and horizontal stainless steel tubing to the PTFE tubing that connects to the valve that then connects to the ozone analyzer.

STM 5.3.6. Temperature and relative humidity sampling are located 30 inches (760 mm) upstream of the upstream ozone-sampling grid.

STM 5.3.7. The HEPA filter is located 62 inches (1570 mm) upstream of the upstream edge of the air cleaner installation section in a gasketed and sealed filter rack. The activated carbon filter is 46 inches (1170 mm) upstream of the upstream edge of the air cleaner installation section.

STM 5.3.8. Two variable speed fans provide between 300 and 1200 CFM (509-2037 m^3/hr) of airflow when all components are installed in the duct.

STM 5.3.9. Flow measurement is done with a calibrated flow station located at the downstream edge of Air Handling Unit #2.

STM 6. Measurement equipment

STM 6.1. Ozone concentrations

STM 6.1.1. The ozone analyzer used for ozone concentration sampling upstream and downstream of the analyzer should have a stated accuracy of, at most, 2 ppb (absolute) or 2% (relative). Any ozone analyzer used in this apparatus should be calibrated at least every six months.

STM 6.1.2. The ozone sampling system should provide a sealed connection from the sampling grids (defined in Section 5.2.5) to a valving system that can allow for upstream or downstream sampling. The ozone sampling system should pass qualification testing as described in Section 7.

STM 6.2. Volumetric air flow rate measurement

STM 6.2.1. Flow measurement can be by any device with an absolute uncertainty of <10%, should work for the entire range of flow specified in Section 5.2.8, and should be calibrated at least yearly.

STM 6.2.2. It is acceptable to calibrate the flow measurement device with a non-permanent flow measurement calibration procedure, provided that the calibration is done in the test apparatus.

STM 6.3. Temperature and relative humidity measurement

STM 6.3.1. Temperature measurement should have an accuracy of 0.1 ºC or better over the range of 0 to 50 ºC.

STM 6.3.2. Relative humidity measurement should have an accuracy of 5% (absolute) or better over the range of 25 – 75%.

STM 6.4. Electrical power measurement

STM 6.4.1. Voltage should be measured with a device that is ±0.5 V or better at the air cleaners operating voltage.

STM 6.4.2. Electrical should be measured with a device that is ±5% or better at the air cleaners operating current.

STM 6.4.3. Electrical power draw should be measured with a device that is accurate to ±1W or better.

STM 6.5. Additional measurements Additional measurements that are used for duct qualification or for optional tests should be selected to be appropriate for their intended purpose and their accuracy and calibration should be reported on any test or apparatus documentation.

STM 7. **Apparatus Qualification Testing.**

Apparatus qualification tests shall verify quantitatively that the test rig and sampling procedures are capable of providing reliable flow and ozone concentration measurements. Qualification tests should be conducted every six months or any time after changes in laboratory or apparatus conditions or maintenance activities warrant such testing.

STM 7.1. The following general qualification areas shall be addressed:

(a) Uniform air velocity in the test section
(b) Uniform ozone concentration in the test duct and representativeness of the ozone sampling system
  (1.) Minimal and equivalent ozone loss in sampling system
(c) Minimal ozone losses in the test section
(d) Minimal duct leakage
(e) Ozone and particle removal prior to test section

Criteria and test methods for each are described below

STM 7.1.1. Uniform air velocity in the test section is defined from a nine-point equal area Pitot tube traverse at the entry and exit of the test section described in Section 5.2.3. The test section should be free of an air cleaner and properly sealed. Average velocity at entry and exit should be within measurement uncertainty (typically 1%) of each other. For both entry and exit, the coefficient of variation (COV) of velocity should be <20%.

STM 7.1.2. Uniform ozone concentration qualification

STM 7.1.2.1. Uniform ozone concentrations are tested by installing an air cleaner that emits at least 5 mg h^{-1} of ozone (as defined in Section 10.3) in the test section, setting the system airflow to 300 CFM (509 m^3 h^{-1}), and allowing the system to come to steady state, defined as the ozone concentration COV for 10 consecutive 10 s measurements being less than 10%.

STM 7.1.2.2. Uniform ozone concentration at the upstream sampling location is defined from a nine-point equal area ozone concentration traverse at the upstream ozone measurement location. The equal area traverse should be conducted by connecting the ozone analyzer to a clean stainless steel sampling tube and sampling in the center of the nine equal areas of the cross-section of the duct. For example, a 24 inch square cross section duct has nine 8 inch square areas and so sampling should occur at the nine intersections of lines at 4, 12, and 20 inches from the top and side edge of the duct. All nine values should be below 3 ppb.

STM 7.1.2.3. Uniform ozone concentration at the downstream sampling location is defined from a nine-point equal area ozone concentration measurement at the downstream location should have a coefficient of variation of <20%.

STM 7.1.2.4. For measurements completed in both Section STM 7.1.2.2 and STM 7.1.2.3, the results should be compared to the ozone concentration recorded by the analyzer connected directly to the sampling grids with as less than 12 inch (305 mm) PTFE or similarly non-reactive tubing. The difference between the value measured with the nine-point equal area method and the sampling grid should be less than the larger of 10% or the ozone analyzer uncertainty

STM 7.1.3. Losses in Sampling System

As an additional check on the sampling system losses, the ozone concentrations measured in Section 7.1.2.3 should be compared to the ozone concentration measured with the ozone grids connected to analyzer through the entire sampling and valve system as described in Section 6.1.2. The difference between the ozone concentration with and without sampling system should be less than the larger of 10% or the ozone analyzer uncertainty.

STM 7.1.4. **Ozone losses in test section.**

This test will first be performed, without the air cleaner in the apparatus, to ensure there are no losses in the test section between sampling grids. The penetration for the air cleaner should be sealed such that there is no leakage. An ozone generating device that can generate at least 5 mg h^{-1} of ozone will be installed at least two duct diameters upstream of the upstream sampling point. The HEPA and activated carbon filters may be removed to achieve injection two duct diameters upstream of the test section. The ozone generating device should create an approximately uniform concentration of ozone across the test-duct cross section. The lowest flow of the apparatus should be used to capture the longest residence time, and the test should generally follow the test procedure described in Section 8. The concentration readings at both the upstream and downstream sampling grids shall be compared and should be within the largest of 5% or the ozone analyzer uncertainty of each other.

STM 7.1.5. Test duct leakage

STM 7.1.5.1. The static pressure difference between the inside and the outside of the duct at the air cleaner installation point should be measured with a digital manometer (±1% reading or better accuracy) and a static pressure tap when no air cleaner is installed and the variable speed fans are set to the greater of 1200 CFM or the maximum test flow in the apparatus.

STM 7.1.5.2. With the fans turned off, air leakage from the test duct shall be conducted with a calibrated fan connected as close to the entry to the test section as possible, and set to pressurize the duct. Air should be carefully metered into the duct by the calibrated fan until the static pressure measured at the location described in Section 7.1.5.1 matches that measured in Section 7.1.5.1 with respect to air outside the duct. The maximum allowable leakage is 10% of the total airflow rate used in Section 7.1.5.1. If the calibrated fan is not able to achieve the pressure measured in 7.1.5.1, it is acceptable to test at a lower static pressure, but the allowable leakage is 5% of flow that corresponds to the maximum flow that can be achieved with the calibrated fan.

STM 7.1.5.3. While the duct pressurization test is taking place, additional care should be focused on locating and sealing the negative static pressure portions of the apparatus, particularly those at or near the test section.

STM 7.1.6. Particle and Ozone Filtration

Prior to reaching the test section, the air must be cleaned of particles using a high efficiency particle arresting (HEPA) filter and an activated carbon filter. The qualification criteria are described in Section 5.2.7.

STM 8. **Test Method**

STM 8.1. **Airflow Rates for Tests.** Tests shall be run and reports generated for airflow rates as specified in Section 8.1.1 - 8.1.3.

STM 8.1.1. The air cleaner shall be first tested at 300 CFM (509 $m^3 h^{-1}$). If 300 CFM (509 $m^3 h^{-1}$) is too high to detect a 5 ppb difference between upstream and downstream measurements, use of the test duct should be reconsidered. It might be more appropriate to test in a static chamber (i.e., UL 867 Section 40, or similar). If the device has a flow switch which prevents testing at this low of flow, then the lowest flow that the switch will allow shall be used.

STM 8.1.2. The maximum flow rate tested should be the lesser of the following a) the maximum flow rate that can achieve a 5 ppb concentration difference between the upstream and downstream sampling point, b) the maximum flow achievable in the duct with the air cleaner installed, and c)the manufacturers maximum recommended flow rate, or d)2000 CFM (3393 $m^3 h^{-1}$).

STM 8.1.3. At least three additional flow rates should be tested, spaced equally over the flow range described by 8.1.1 and 8.1.2.

STM 8.2. **Test Procedure.** The following steps shall be taken to ensure a complete test for one air cleaning device.

STM 8.2.1. Insert air cleaning device into the test section of the test apparatus. Secure device and enclosure of test apparatus.

STM 8.2.2. If the device has multiple modes of operation, set it to the setting that is anticipated to produce the most ozone (usually the highest setting).

STM 8.2.3. If the device has a flow switch, the switch may be disabled or bypassed, but caution should be exercised when doing so.

STM 8.2.4. Set the fans of the AHUs to desired flow rate (Section STM 8.1.1).

STM 8.2.5. Confirm that environmental conditions are within 15-25 °C (59 – 88 ºF) and 35-65% relative humidity.

STM 8.2.6. Turn on the air cleaning device and ozone monitor. Allow operation of both devices for at least 30 minutes. This step can be omitted after the first flow rate in a test in a set of flow rates.

STM 8.2.7. Start the test procedure. The automated valves will switch back and forth between upstream and downstream measurements at equal intervals. Intervals shall be four minutes and a test shall consist of at least four intervals.

STM 8.2.8. Omit the first 45 s of each interval, because the system will need time to stabilize for accurate readings. Data recorded after the first 45 s of the interval should be compared to the last 60 s of the interval in 10s increments. If the data is within 95% of the concentration from the last 60 s, then the interval is considered in steady state. If the ozone concentration does not reach a steady state (i.e., COV >20% over the 10 measurements) increase the length of the test interval in two-minute increments until the interval is in steady state for at least 60 s. Some air cleaners do not emit ozone at a consistent rate. This behavior should be noted and the interval length selected that results in maximum emission.

STM 8.2.9. Measure and record all information for the test report (Section 9)

STM 8.2.10. Repeat steps STM 8.2.4-8.2.9, excluding step STM 8.2.6, for the next flow rate until the maximum test flow rate (Section STM 8.1.2) is achieved.

STM 9. Reporting Results

STM 9.1. Test results shall be reported using the test report format shown in this standard. The attached spreadsheet shows the complete test report.

STM 9.2. The summary section of the performance report shall include the following information:

(a) Name and location of the test laboratory
(b) Date of the test
(c) Test operator's name(s)
(d) Electrically connected air-cleaner
    (1.) Manufacturer, brand, and model
    (2.) Marketing organization, if different from the manufacturer
    (3.) How the sample was obtained

(4.) Description of the test air cleaner including:
(i.) Physical description of construction
(ii.) Face dimensions and depth
(iii.) Type of air cleaning technology
(iv.) Any other pertinent descriptive attributes
(5.) Manufacturers recommended air flow rate (or range), if applicable

(e) Ozone analyzer
(1.) Manufacturer and model
(2.) Uncertainty
(3.) Date of last calibration and corresponding calibration values

(f) Flow measurement device
(i.) Manufacturer and model
(ii.) Uncertainty
(iii.) Date of last calibration

(g) Temperature measurement device
(i.) Manufacturer and model
(ii.) Uncertainty
(iii.) Date of last calibration

(h) Relative Humidity measurement device
(i.) Manufacturer and model
(ii.) Uncertainty
(iii.) Date of last calibration

(i) Electrical power measurement device
(i.) Manufacturer and model
(ii.) Uncertainty
(iii.) Date of last calibration

(j) Test data for measurement intervals
(i.) Test air temperature and relative humidity
(ii.) Voltage, current, and power draw
(iii.) Air flow
(iv.) Location of ozone measurement (upstream or downstream)
(v.) Average upstream ozone concentration and standard deviation from last 100 s (10 data points) in interval, or average downstream ozone concentration and standard deviation from last 100 seconds (10 data points) in interval

(k) Calculated values from Section 10
(i.) Average ozone concentration difference (10.1)
(ii.) Average air flow rate (10.2)
(iii.) Ozone emission rate (10.3)
(iv.) Uncertainty in emission rate (10.4)
(v.) Apparatus method of quantification limit (MQL) (section 10.5)

(l) Comments or notes from testing

STM 10. Calculated Values

STM 10.1. The average ozone concentration difference is calculated as the mean of the upstream concentration, $\overline{C}_{up}$, from at least two intervals that meet the criterion in section STM 8.2.7 minus the mean of the downstream concentration, $\overline{C}_{down}$, from at least two intervals that meet the criterion in Section 8.2.h. This value should be reported in both ppb and μg m^{-3}. Absent a calculated conversion value from the ideal gas law at actual test conditions, a conversion value of 1.96 μg m^{-3} ppb^{-1} should be used.

$$\Delta C = \overline{C}_{down} - \overline{C}_{up}$$

[Eq. STM 1]

STM 10.2. The average air flow rate is calculated as the mean flow rate for all intervals used in Section STM 10.1. The flow rate shall be reported in m^3/hr and can also be reported in CFM. Absent a calculated conversion value from the ideal gas law at actual test conditions, a conversion value of 1.699 m^3 h^{-1} CFM^{-1} should be used.

STM 10.3. The ozone emission rate, *E*, is calculated as the product of the mean ozone concentration difference in μg m^{-3} from Section STM 10.1 and the mean flow rate, $\overline{Q}$, in m^3 h^{-1} multiplied by a conversion factor of 1000 μg mg^{-1}.

$$E = \overline{Q}\Delta C$$

[Eq. STM 2]

STM 10.4. The uncertainty in the emission rate, *e*, should be calculated from the absolute uncertainty of the ozone analyzer, *c*, (Section STM 9.2.d.2) and the absolute uncertainty of the air flow measurement device, *q*, (Section 9.2.e.2).

$$e = E\sqrt{\left(\frac{q}{Q}\right)^2 + \left(\frac{\left(\sqrt{2}c\right)}{\Delta C}\right)^2}$$

[Eq. STM 3]

STM 10.5. The method of quantitation limit, MQL, of the apparatus is calculated by conduction at least 10 separate tests on a low-emitting air cleaner with a non-zero emission rate. A low-emitting air cleaner is defined as an air cleaner that emits less than 5 mg h^{-1} of ozone (as calculated with Section STM 10.3). A non-zero emitting rate is defined as an air cleaner that emits more than the uncertainty in the emission rate as defined by Section STM 10.4. If no air cleaner can be found that meets these criteria, the MQL tests can be done on the air cleaner with the smallest emission rate that still has a non-zero emission rate. Once this air cleaner is

selected, at least 10 tests as defined in Section 9 should be conducted. The MQL is defined as six times the standard deviation from those tests.

3.2.3 Standard test method qualification and determination of quantification limit

The qualification testing followed Section 7 in the Standard Test Method and was repeated at least every six months of apparatus use. The most recent qualification testing was completed in Summer 2012 and the results are shown in Table 3.6. In Table 3.6 and in the test-method, the coefficient of variation (COV) is defined as the standard deviation divided by the mean.

Table 3.6. Qualification results for test apparatus, Summer 2012.

Qualification	Subsection STM	Criterion	Value
Upstream uniform air velocity	7.1.1	COV <20%	COV= 14%
Downstream uniform air velocity	7.1.1	COV <20%	COV= 9%
Air flow rate difference	7.1.1	<1% or uncertainty	0.5%
Uniform upstream ozone concentration	7.1.2.2	<3 ppb	1.8 ppb
Uniform downstream ozone concentration	7.1.2.3	COV<20%	COV = 10%
Upstream sampling grid	7.1.2.4	<10% difference[a]	1.6 ppb (10%)
Downstream sampling grid	7.1.2.4	<10% difference	2%
Ozone losses in upstream sampling system	7.1.3	<10% difference[a]	0.4 ppb (50%)
Ozone losses in downstream sampling system	7.1.3	<10% difference	1.6 ppb (5%)
Ozone losses in test section	7.1.4	<5% difference	<2%
Apparatus leakage	7.1.5.2	<45 CFM[b]	30 CFM
Upstream ozone concentration	7.1.6 (5.2.7)	<3ppb	varies[c]
Upstream particle concentration	7.1.6 (5.2.7)	100 particles cm^{-3}	85 particles cm^{-3}

[a]actual criterion based on ozone analyzer uncertainty for upstream tests because ozone concentration was near zero
[b]criterion based on 900 CFM maximum flow achieved with duct pressurization tester
[c]activated carbon filter changed when criterion exceeded

The acceptable duration of each measurement period (STM 8.2.7) determined by operating an air cleaner and measuring the emission rate that would result with different length of intervals of measurement at the upstream and downstream locations. We did substantial amounts of this exploration during preliminary testing (see below) and more formally for Air Cleaner 5b (see Table 2.1 in Methods). Figure 3.1 shows the results following the standard (four minute intervals) and following every aspect of the standard except for Section STM 8.2.7 and instead using two minute intervals. The results show good correspondence between these two interval lengths and a t-test showed no significant difference between the two tests, however we ultimately decided to require four minute intervals in order to account for slower responding apparatuses.

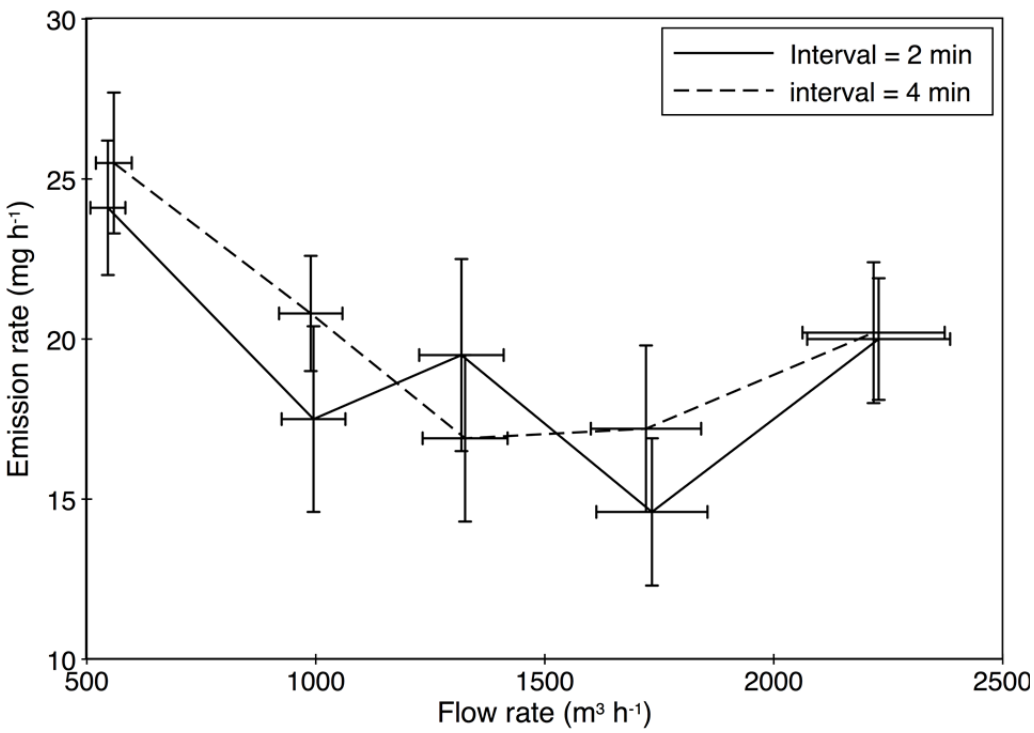


Figure 3.1. Testing at different interval lengths for AC 5b.

The method of quantitation limit testing (Section STM 10.5) was completed on Air Cleaner 1 (see Table 2.1 in Methods) because it had the lowest emission rate that was quantifiable above background noise. Air Cleaner 1 had a mean emission rate of 2.12 mg h^{-1} and a standard deviation of 0.39 mg h^{-1} over the 10 tests. This resulted in an MQL of 2.3 mg h^{-1}. Figure 3.2shows these results.

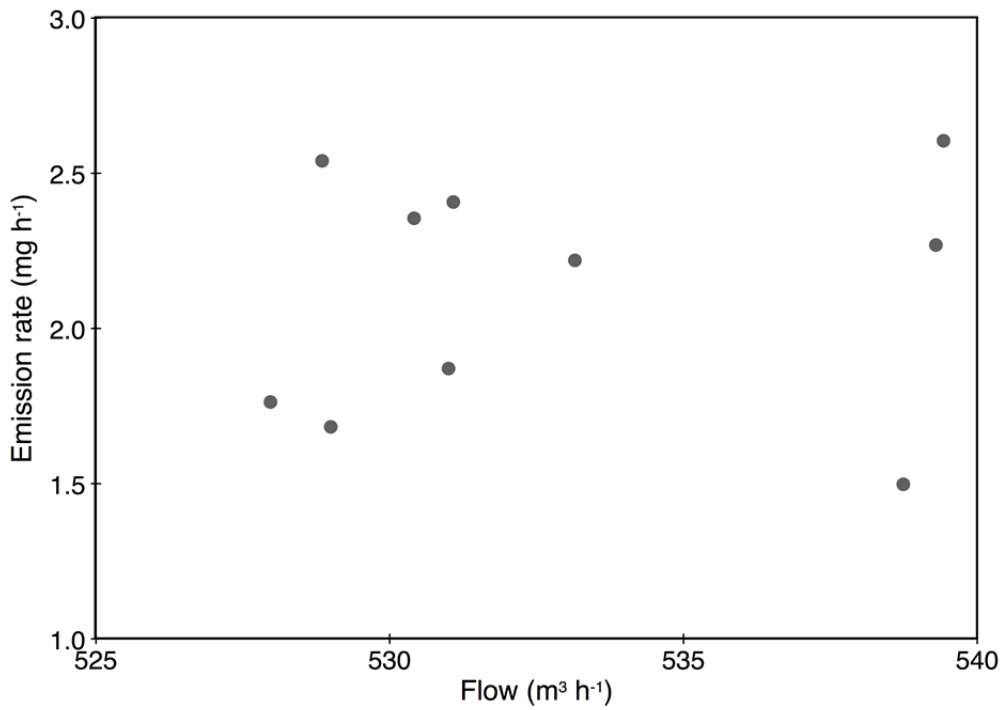


Figure 3.2. Emission rate measurements for 10 replicate tests on Air Cleaner 1 for the purposes of MQL assessment (Section STM 10.5). Uncertainty not shown for graph clarity.

3.2.4 Ozone emission rates from electrically connected in-duct devices

This section reports on the central ozone emission rate results for electrically connected in-duct devices. Detailed tabular results can be found in Appendix 9.2.

3.2.4.1 Preliminary test results

Figure 3.3 below shows the results of preliminary testing of eight air cleaners. These tests generally do not adhere strictly to the standard and were done during exploratory efforts to create and refine the standard. For this reason, the results should be interpreted with caution, although they are generally consistent with results that follow from applying the standard. Each air cleaner (excluding ACs 5b, 6b, 7 and 8 which were not yet available when preliminary testing was completed) had 20-30 tests conducted on it during this preliminary period, where each test was completed at a single flow rate. Because flow rate can impact emission rate (discussed below), Figure 3.4 shows the distribution of flow rates that were used for the preliminary tests on each air cleaner.

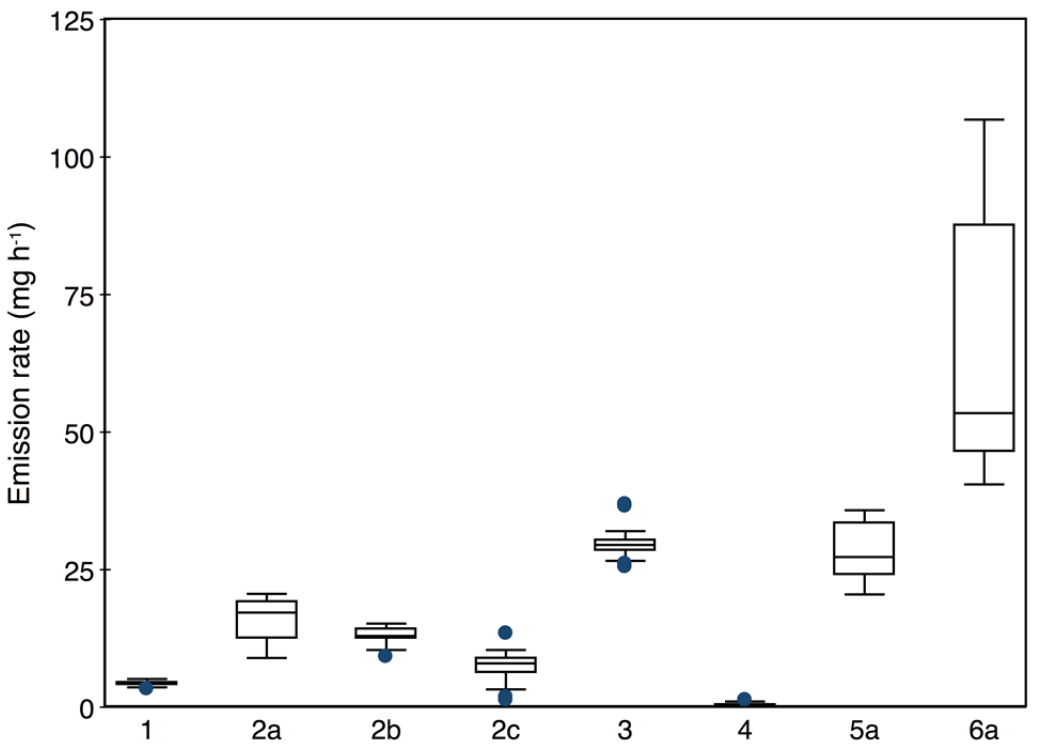


Figure 3.3. Emission rates for eight air cleaners from preliminary testing. The bottom of the box indicates the 25th percentile, the horizontal line indicates the median and the top of the box the 75th percentile. The whiskers indicate the data range within 1.5 times the interquartile range of the 25th and 75th percentile. Filled circles are outliers.

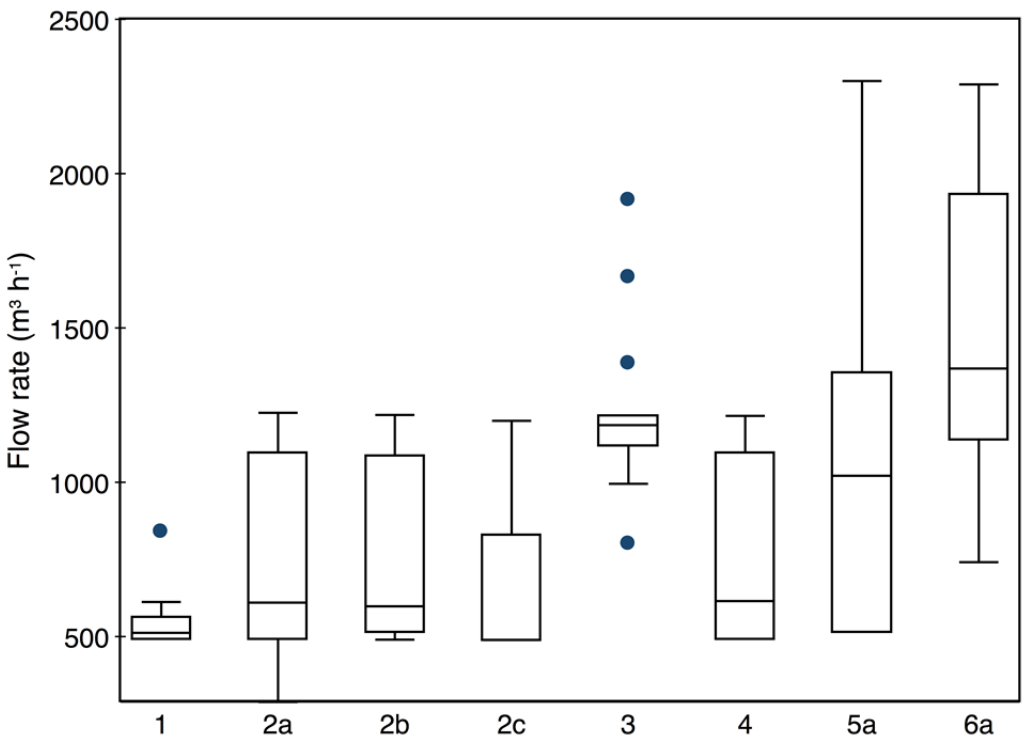


Figure 3.4. Flow rates corresponding to emission rate tests in Figure 3.3. The bottom of the box indicates the 25th percentile, the horizontal line indicates the median and the top of the box the 75th percentile. The whiskers indicate the data range within 1.5 times the interquartile range of the 25th and 75th percentile. Filled circles are outliers.

3.2.4.2 Application of standard to measure emission rates of in-duct air cleaners.

Figure 3.5 shows the Standard Test Method emission rates of all 12 tested air cleaners (see Table 2.1 in Methods for air cleaner designations). Note that results from air cleaner 8 are shown in the inset because the emission rates were much higher than other air cleaners. This figure must be read with care because all air cleaners were tested at different flow rates and some air cleaners had an emission rate that varied with flow (discussed below). To aid in interpretation, Figure 3.6 shows the flow ranges that corresponding to the testing in Figure 3.5. The bottom of the box indicates the 25th percentile, the horizontal line indicates the median and the top of the box the 75th percentile. The whiskers indicate the data range within 1.5 times the interquartile range of the 25th and 75th percentile. Filled circles are outliers.

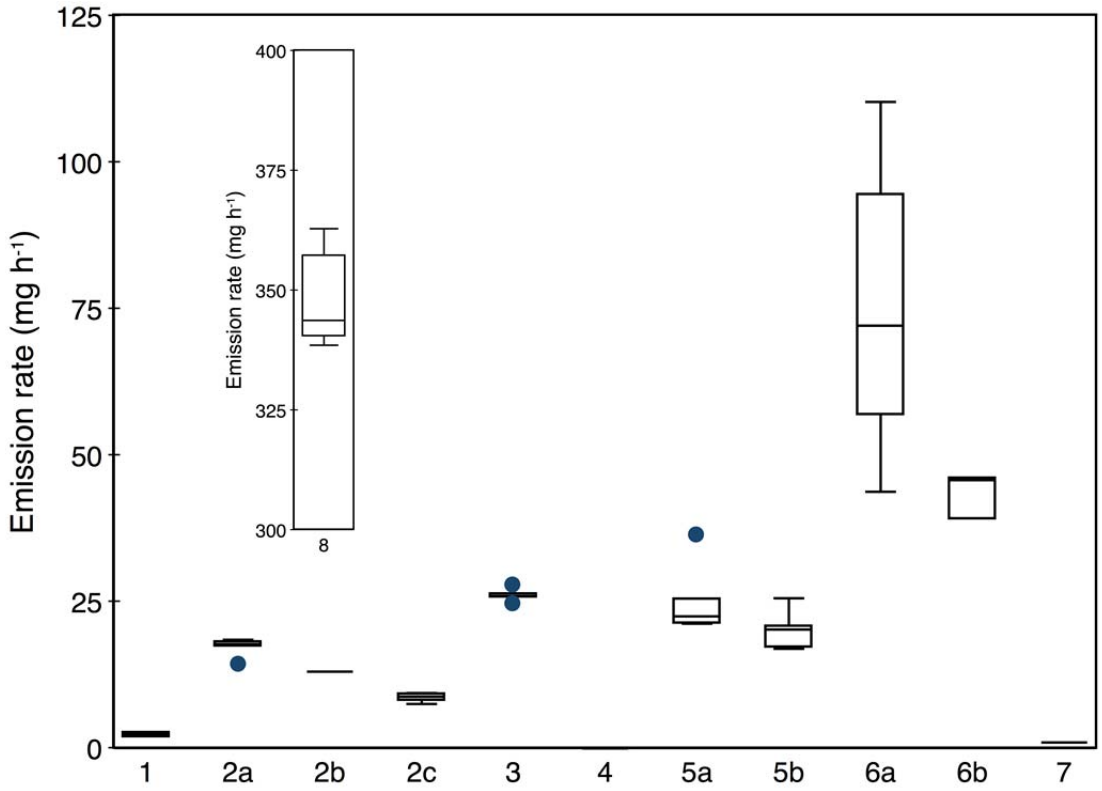


Figure 3.5. Emission rates for 12 air cleaners. Air cleaner 2b results from preliminary testing. Results from air cleaner 8 are shown in the inset because the emission rates are much higher than all other air cleaners. The bottom of the box indicates the 25th percentile, the horizontal line indicates the median and the top of the box the 75th percentile. The whiskers indicate the data range within 1.5 times the interquartile range of the 25th and 75th percentile. Filled circles are outliers.

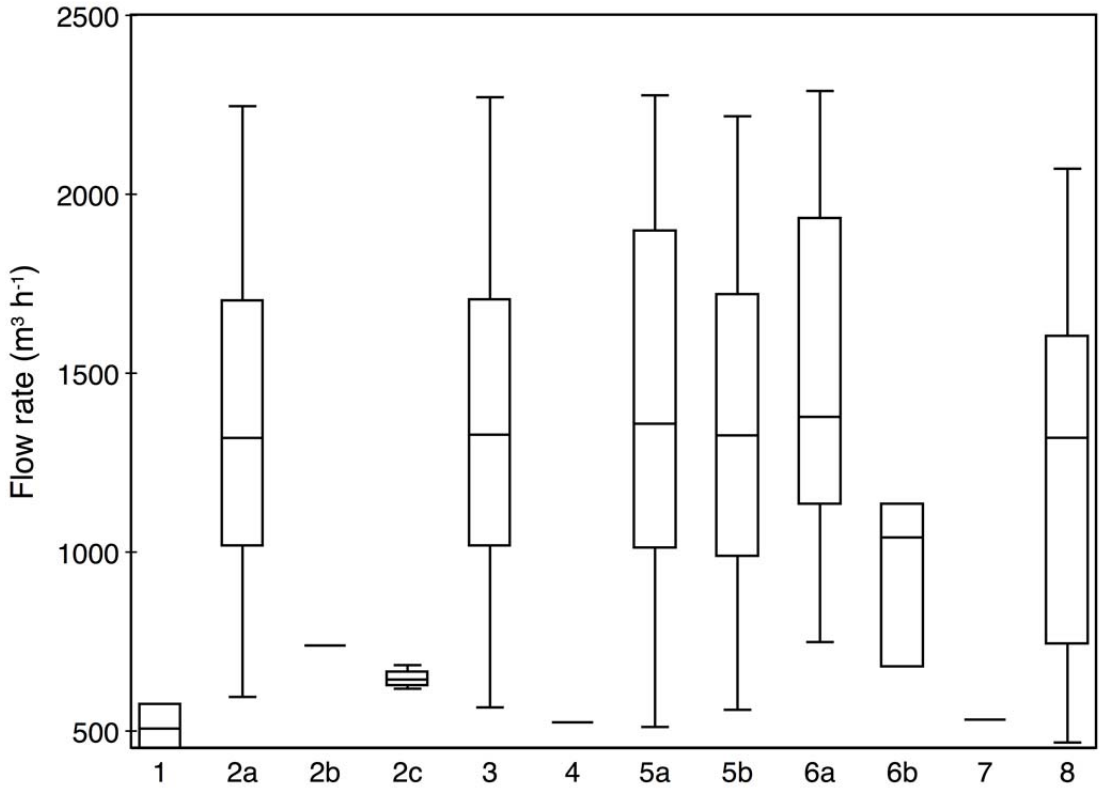


Figure 3.6. Flow rates corresponding to emission rate tests in Figure 3.5. The bottom of the box indicates the 25th percentile, the horizontal line indicates the median and the top of the box the 75th percentile. The whiskers indicate the data range within 1.5 times the interquartile range of the 25th and 75th percentile.

Figure 3.7 shows the emission rate at the lowest tested flow rate for each air cleaner. The tested flow rate (m^3 h^{-1}) appears above each bar. The uncertainty was calculated as defined in the standard. For both Figure 3.5 and Figure 3.7, the *preliminary testing* results for Air Cleaner 2b (the same model as Air Cleaners 2a and 2c) are included since the air cleaner was being used for field experiments during the standard application period. We found that the preliminary test results for other air cleaners were in good agreement (within emission rate uncertainty) with the standard test results for the same air cleaners (see Figure 3.4). This suggests that preliminary test methods provided similar results and inclusion of the preliminary results from Air Cleaner 2b is reasonable. Air cleaner 8 was included late in the project and the tests were performed with minor deviations from the Standard Test Method, none of which would affect the results. All other tests shown in Figure 3.5 through Figure 3.7 were completed in compliance with the test method.

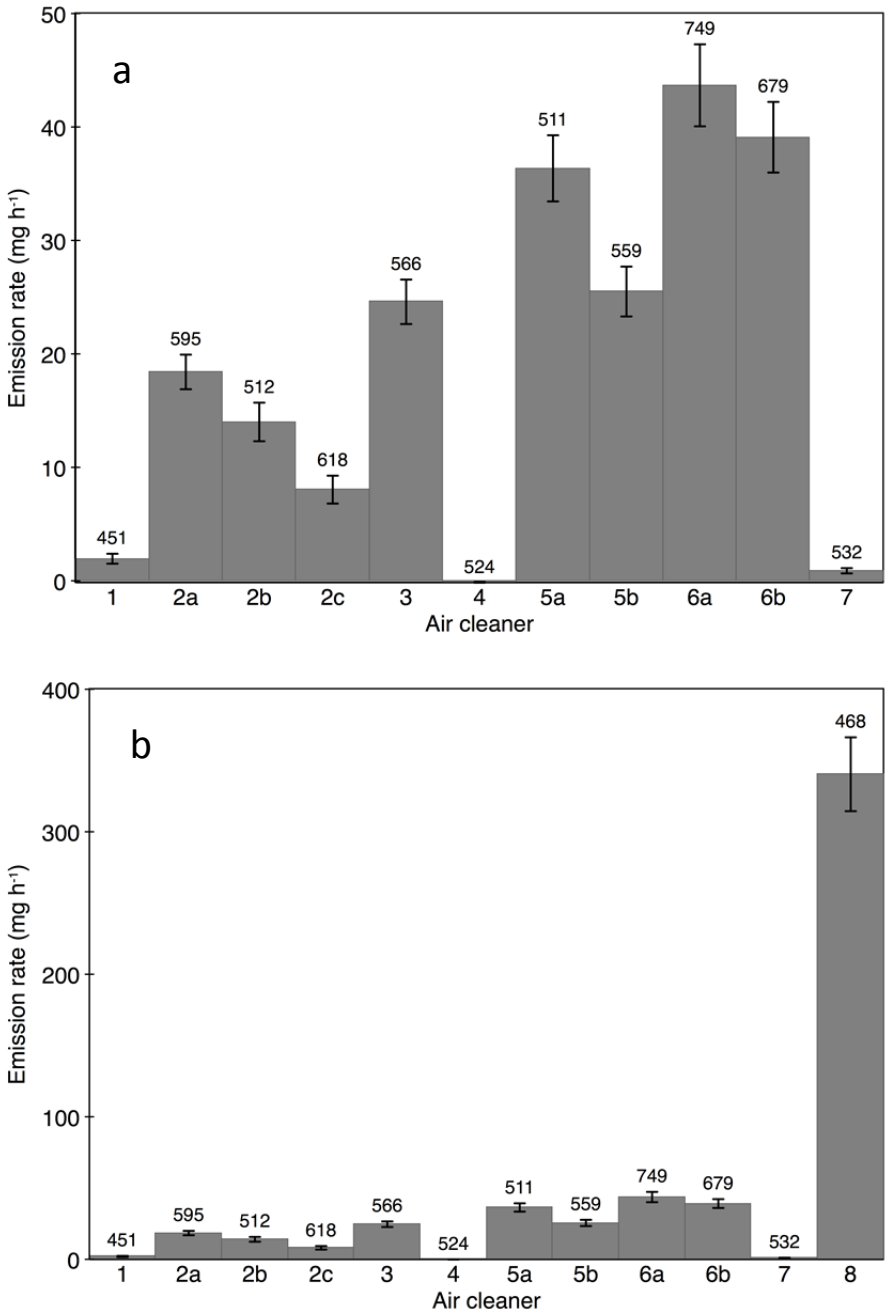


Figure 3.7. Ozone emission rate at lowest tested flow. Figure 3.7a includes air cleaners 1-7 only for clarity; Figure 3.7b shows the same results, but also includes air cleaner 8 which had a much higher emission rate than air cleaners 1-7. Corresponding flow rate appears above bars (m^3 h^{-1}). See notes in text about deviations from standard when testing Air Cleaner 2b.

The results suggest that some air cleaners (4 and 7) emit almost no ozone. Both of these air cleaners have an ozone removal component (a catalyst for Air Cleaner 4 and activated carbon for Air Cleaner 7). Attempts were made to test these units

without these removal devices, but both air cleaners had interlocks that prevented normal operation when the protective devices were removed. Air cleaner 1 emitted 2-3 mg h^{-1} of ozone, which is near the limit of quantitation for the apparatus. Air Cleaners 2a-2c (all the same model) emitted between 8 and 17 mg h^{-1}. This variation between seemingly identical units is not uncommon in portable air cleaner ozone emission rates and is likely caused by variation in electronic components and manufacturing tolerances. Air Cleaner 3 was the only tested air cleaner that used a corona wire (rather than a UV lamp) to generate ozone. It generated 24.6 mg h^{-1} of ozone at the lowest tested flow rate. Air Cleaners 5a and 5b (same model) generated 25.4 and 36.5 mg h^{-1} of ozone, respectively suggesting similar unit to unit variation as was seen for Air Cleaners 2-4. Air Cleaners 6a and 6b (same model) were dedicated ozone generating devices and yet only produced 39-44 mg h^{-1} at the lowest tested flow rate. Air cleaner 8, an ultraviolet light device, had the highest emission rate of 349 mg h^{-1}.

3.2.4.3 Influence of flow rate on ozone emission rate

Figure 3.8 shows ozone emission rate as a function of flow rate for all tested air cleaners. Most of the tested air cleaners do not exhibit a strong relationship between flow and emission rate. The strongest relationship between flow and emission rate was seen for Air Cleaner 6a, a dedicated ozone generator that showed a potentially linear relationship between flow and emission rate. At the lowest tested flow rate, the emission rate was 44 mg h^{-1} and at the highest flow rate, the emission rate was 102 mg h^{-1}. This behavior was not anticipated as the mechanisms for generating ozone (UV or corona) are not thought to be very sensitive to air velocity. For example, the photolysis rate of oxygen by UV light, and subsequent ozone formation, depends primarily on photon flux (light intensity). An increase in air velocity would not, by itself, change ozone generation rates. Air Cleaner 8 is an example of a UV bulb device that exhibited little dependence on flowrate. In the case of Air Cleaner 6a, air velocity could change the temperature of the bulb, and thus change the light intensity. There are several hypotheses that may explain the flow rate dependent behavior of Air Cleaner 6a, including:

- This air cleaner has emission rate limiting electronics that consist of an ozone sensor or a flow sensor. The unit does have a flow measurement device that only allows the unit to power on if it senses sufficient air flow.
- The electronics may, unintentionally, be sensitive to flow due to cooling of components that generate heat.
- The air cleaner has an ozone output switch that was set to maximum for all testing shown in Figure 3.5. This dial may have been faulty and this might have had an interaction with the control logic of the device.

Subsequent testing that involved trying different settings on the output dial did not modulate the ozone output or the dependence on flow rate suggesting that it may have been faulty, but this fault doesn't fully explain the variation with flow rate.
To further explore these hypotheses, Air Cleaner 6b (same model as Air Cleaner 6a) was tested. Note that these tests were abbreviated in order to get the air cleaner to the field, but testing according to the standard (including at higher flow rates that

are not included in Figure 3.5 because of minor deviations from the standard test procedure) suggested that the ozone emission rate was not significantly flow sensitive. Therefore, this testing was inconclusive. Similarly inconsistent performance was seen in the field testing with these units. This suggests substantial sample-to-sample variation and performance inconsistencies with this model.

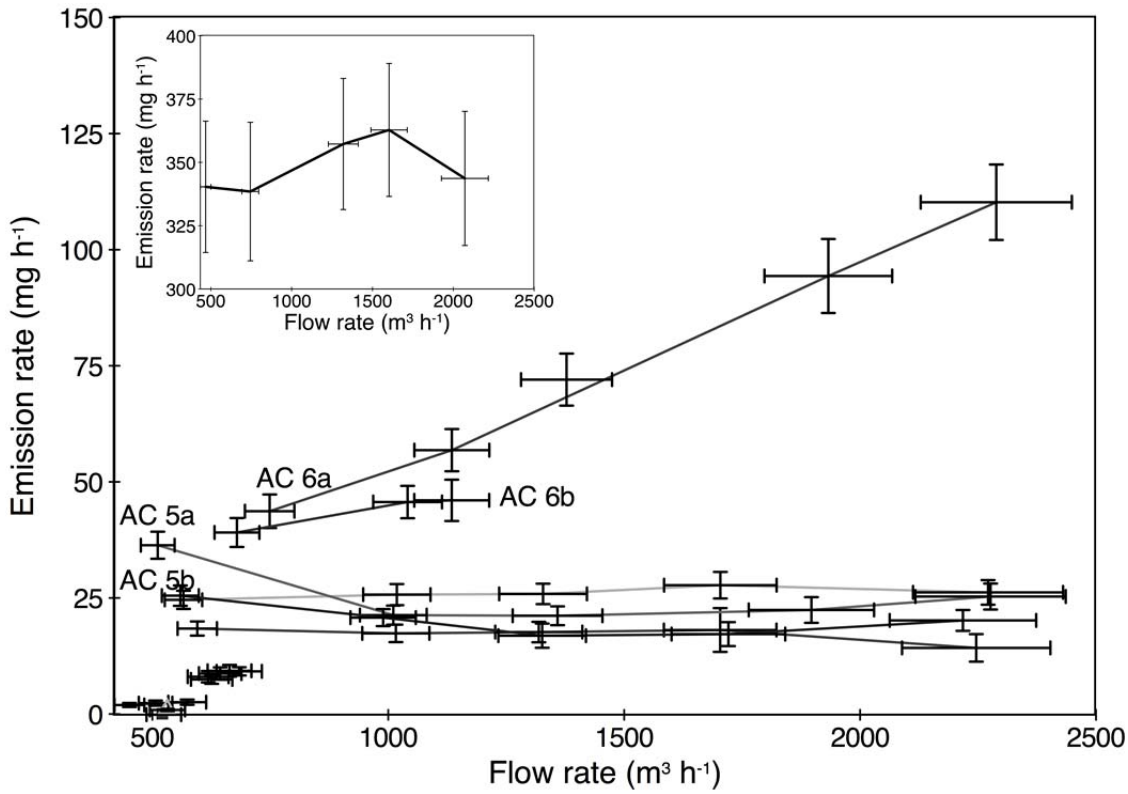


Figure 3.8. Ozone emission rate as a function of flow rate for all tested air cleaners. Results for air cleaner 8 are shown in the inset because the emission rate is much higher than other air cleaners.

Another air cleaner that exhibited a dependence on flow was Air Cleaner 5 (both tested units). Air Cleaners 5a and 5b had a higher emission rate at the lowest flow. This trend was originally assumed to be due to a non-uniformity of ozone downstream from the test section. This hypothesis was investigated using the qualification procedure in the test method (Section 7.1.2.3). However, the ozone concentration variation met the criterion in the standard and was not significantly different at the different flow rates. Figure 3.13 and Figure 3.14 below, show this data in more detail in the context of repetition testing

3.2.4.4 Influence of temperature and relative humidity on ozone emission rate

In order to explore the role of temperature and humidity variation on ozone emission rate, two air cleaners (Air Cleaners 3 and 5b) were tested at four conditions (standard test conditions (conforming to standard), high relative

humidity conditions (created by adding steam to duct), high temperature and high relative humidity conditions (created by adding heat and steam into duct), and high temperature conditions (adding heat but not steam to duct)). Only some of this testing could be completed at all five flow conditions as the high humidity conditions cause condensation in the ozone analyzer and sampling tubes and high temperature stressed the ozone analyzer and led to erratic readings.

The results of varying temperature for Air Cleaner 3 are shown in Figure 3.9. The results suggest a dependence on temperature with higher temperature leading to lower ozone emission rates for this air cleaner. A clear trend was not seen for varying relative humidity (Figure 3.10). However, these plots are potentially confusing because they do not show interactive effects of temperature, humidity, and flow. Figure 3.11 shows all results for the different conditions for Air Cleaner 3 and Figure 3.21 shows the same sort of results for Air Cleaner 5b. Performing t-tests between the different conditions for Air Cleaner 3 suggested a significant difference between high and low temperature conditions. Air Cleaner 5b shows no obvious pattern with either temperature or relative humidity and t-tests revealed no statistical difference in the emission rate between any of the conditions.

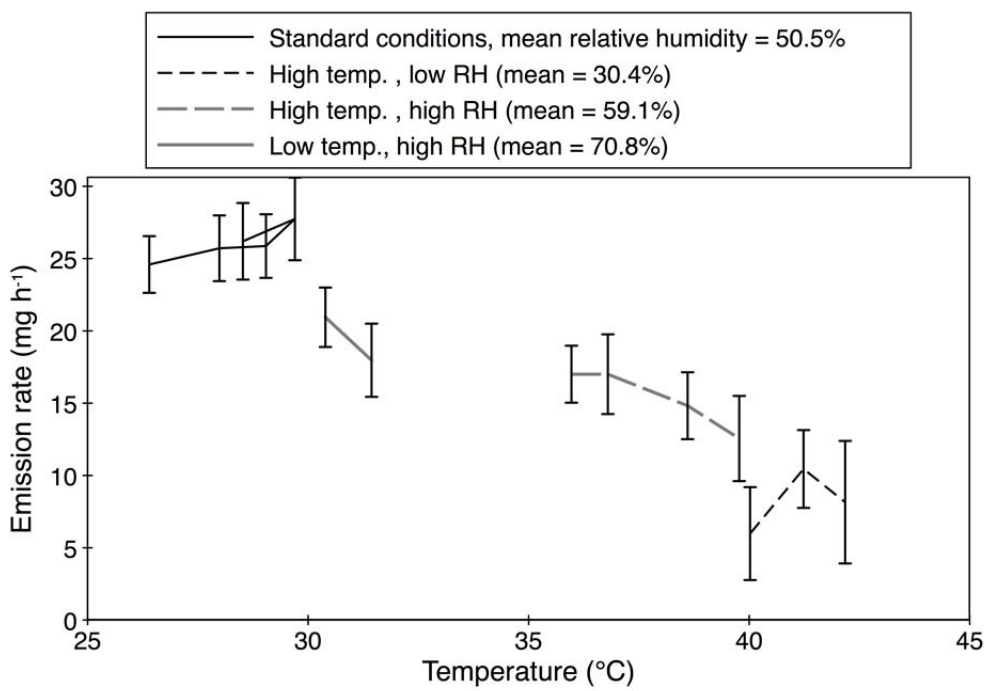


Figure 3.9. Ozone emission rate as a function of temperature for Air Cleaner 3.

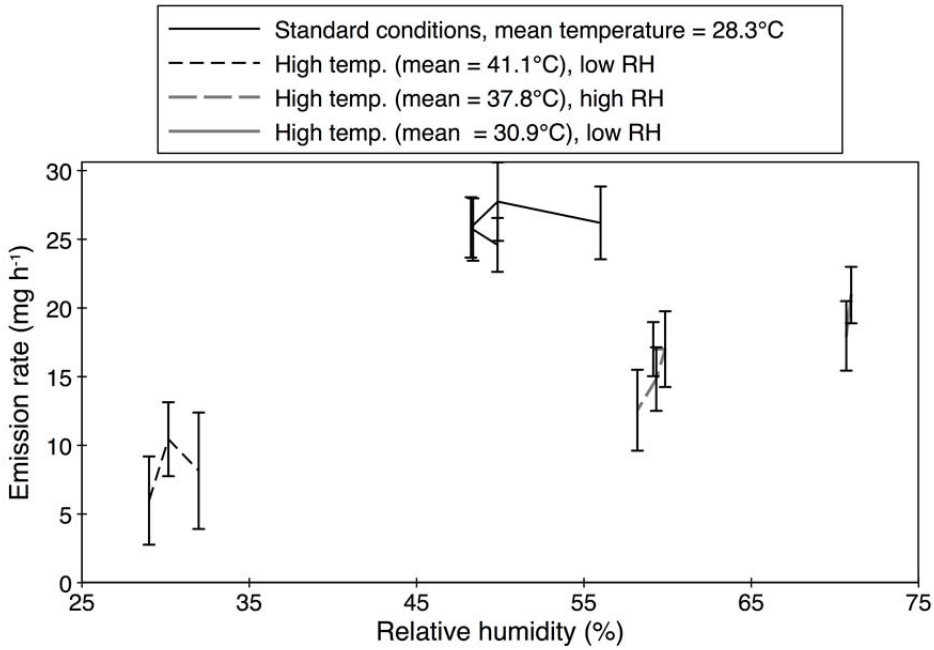


Figure 3.10. Ozone emission rate as a function of relative humidity for Air Cleaner 3.

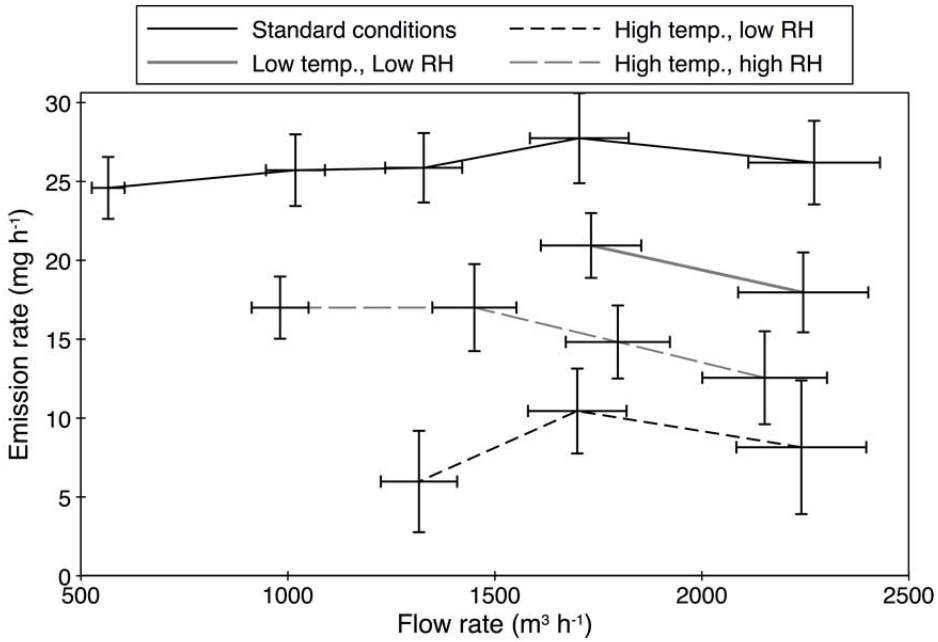


Figure 3.11. Ozone emission rate as a function of flow rate and different environmental conditions for Air Cleaner 3.

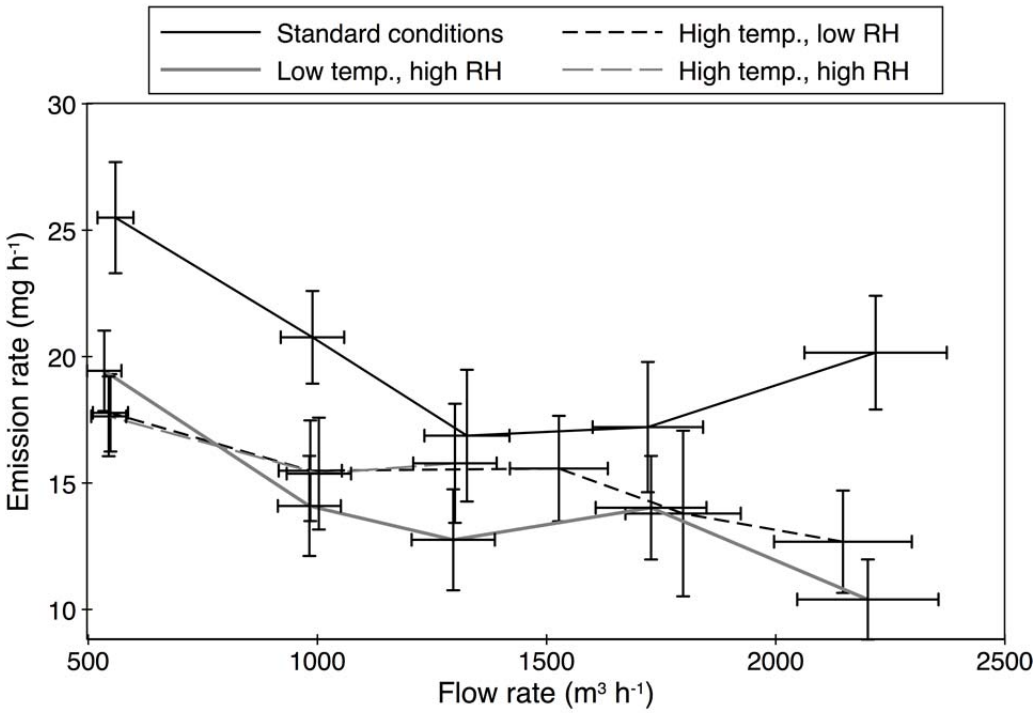


Figure 3.12. Ozone emission rate as a function of flow rate and different environmental conditions for Air Cleaner 5b.

3.2.4.5 Repeatability of testing and impact of order of testing

Given the potential for temperature to affect some air cleaners (such as Air Cleaner 3), there was some concern that the order of testing (both for different flows for a particular air cleaner as well as testing of one air cleaner immediately after another air cleaner) could affect test results. It was noted that temperature increased over time, depending on fan speed, because the fan motors added heat to the air stream. To explore this further, testing on Air Cleaners 5a and 5b was done in different orders (i.e., both from low to high flow as well as from high to low flow. Three or four tests were completed on each air cleaner with half of the tests starting at the high flow and half starting at the low flow and the results are in Figure 3.13 and Figure 3.14. t-tests showed no significant difference between any of the tests suggesting that the test method is repeatable and the order of testing is unimportant. One limitation of this exploration is that Air Cleaner 5b was not shown to be temperature dependent and so we had hoped to complete this testing on Air Cleaner 3 as well, but it was not available because it was in the field during testing, but given the results discussed above we added the temperature range required in Section STM 8.2.5 of the standard.

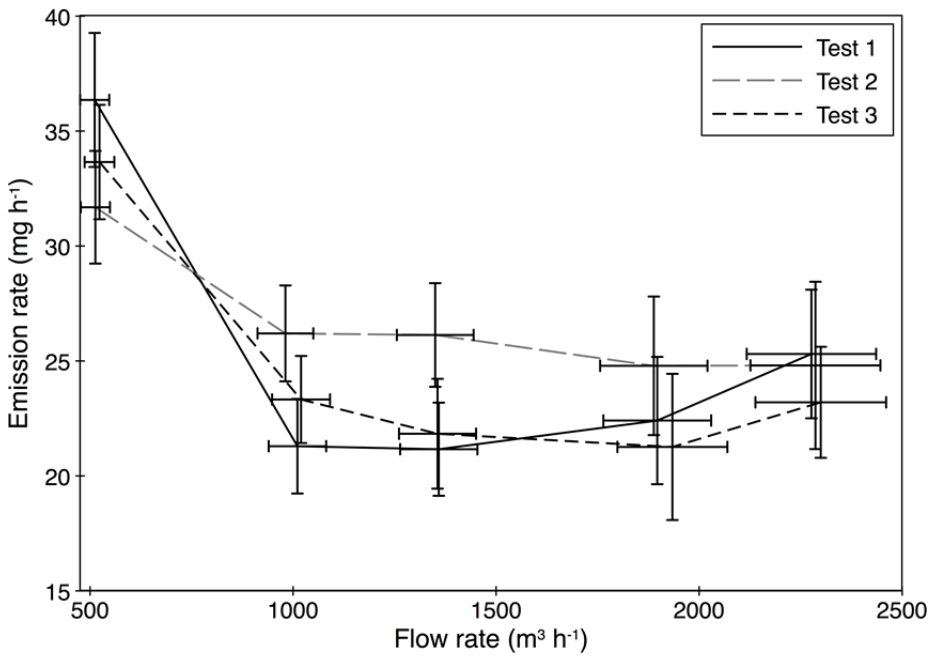


Figure 3.13. Emission rate for repeated tests on Air Cleaner 5a. Test 2 started at the high flow rate.

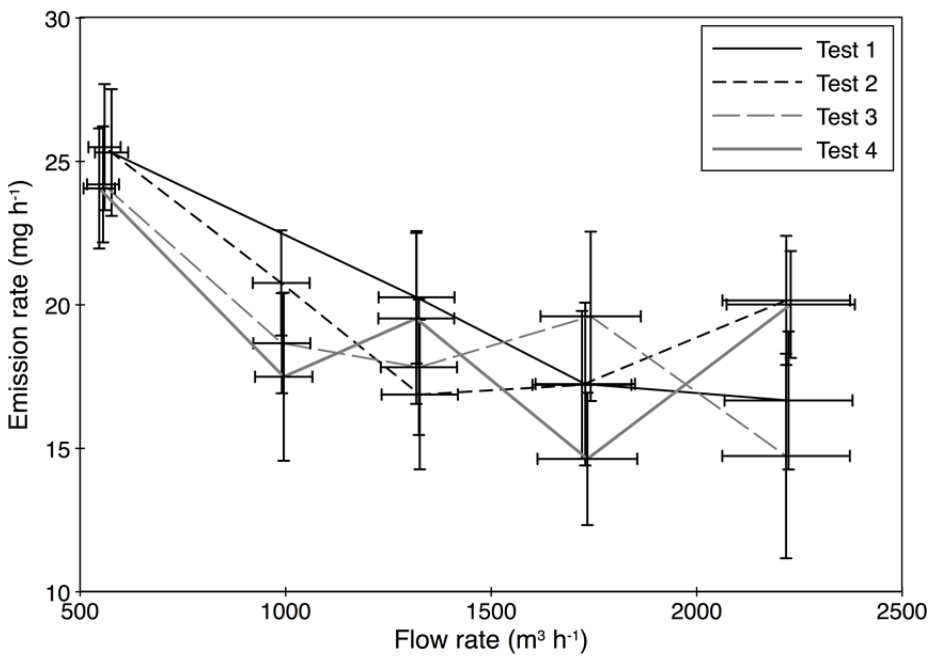


Figure 3.14. Emission rate for repeated tests on Air Cleaner 5b. Tests 2 and 4 started at the high flow rate. One data point excluded from Test 1 because of a valve timing error with the apparatus.

3.3 **Field testing**

Field tests were initiated in the Tulsa field test house, then moved on to California test houses. The Tulsa field tests served as series of trial tests to develop and refine the field test method applied in the California Field tests. The Tulsa field tests occurred periodically (see Table 3.7) from February through November of 2012. The data collected during these tests provide useful findings for evaluating in-duct ozone generating devices. The Tulsa test house represented a typical detached single family home with normal occupancy that provided a "real world" setting for determining how in-duct ozone generating devices perform in residential applications. The in-duct ozone generating devices tested in Tulsa all utilized UV lamps. Devices tested at the Tulsa house were the Guardian Air (#2a), activTek Induct 2000 (#5a), Air Zone Air Duct 2000 (#6b) and the HVAC UV 560 (#8). In California test houses, the activTek INDUCT 2000 (#5b), Air Zone Air Duct 2000 (#6b), HVAC UV 560 (#9), Trane Clean Effects (#9) and Honeywell F300 (#3) were tested. In a California classroom, the Trane TCACS commercial system (#10) was tested. See Table 9.1 for devices and number designations. Note that devices 9 and 10 were tested in the field, but not in the laboratory.

The composite Tulsa and California field testing results for AER, ORR, ODR, OER1 and OER2 are reported in Table 3.7 to Table 3.9. Estimates are developed using equations shown in the California Field Test Method. Also shown are maximum (at supply) and steady-state (at return) ozone concentrations. A detailed summary table of all tests is provided in Section 9.6. To help compare results visually, the incremental increase in the indoor ozone concentration, OERs, air exchange rates and ozone decay rates are shown in Figure 3.15-Figure 3.19.

Table 3.7. Major results from Tulsa test house

Date & Start Time	HVAC Status	Test & In-Duct Device Tested	Air Exchange Rate (1/hr)	Ozone Removal Rate (1/hr)	Ozone Decay Rate (1/hr)	Max Conc.[1] (ppb)	Steady state[1] conc.(ppb)	OER1[6], mg/hr	OER2[6] mg/hr
2/22/12 10:00	Stage 1 HVAC Fan On	AER/ODR	0.55±0.02	9.3±0.9	8.8±0.9	NA	NA	NA	NA
2/22/12 16:00		AER/ODR	0.42±0.01	3.6±1.9	3.2±1.9	NA	NA	NA	NA
4/25/12 14:00		AER/ODR	0.5±0.02	7.0±1.8	6.5±1.8	NA	NA	NA	NA
4/27/12 15:00		AER/ODR	0.79±0.21	8.4±0.2	7.7±0.3	NA	NA	NA	NA
2/22/12 13:00	Stage 2 HVAC Fan Off	AER/ODR	0.14±0.01	2.9±1.4	2.8±1.4	NA	NA	NA	NA
2/23/12 9:00		AER/ODR	0.20±0.01	5.1±3.5	4.9±3.5	NA	NA	NA	NA
5/3/12 14:00		AER/ODR	0.43±0.01	7.1±0.335	6.7±0.3	NA	NA	NA	NA
3/7/2012 11:00	HVAC Fan On, System Off	OER Air Zone Air Duct 2000	0.55±0.02[2]	11.5±2.6	11.0±2.6	103.6±1.5	99.6±5.3	436±145	414±105.2
5/3/2012 9:00		OER Air Zone Air Duct 2000	0.57±0.02	7.1±0.3	6.6±0.3	60±1.5	58.7±6.6	146.5±40.1	141.9±23.2
4/27/2012 15:00		OER Air Zone Air Duct 2000	0.79±0.21	8.4±0.2	7.7±0.3	78.9±1.5	51.6±1.0	163.1±58.5	151.3±15.9
4/25/2012 16:00		Air Guardian	0.5±0.02[3]	7.0±1.8[3]	6.5±1.8[3]	3.3±1.5	1.7±1.8	0.6±2.3	4.4±5.4
5/2/2012 13:00		Air Guardian	0.72±0.2	8.4±0.2	7.7±0.2	23.4±1.5	3.2±1.6	5±2.7	-2.3±8.6[7]
4/26/2012 11:00	HVAC Fan On	OER activTek INDUCT 2000	0.5±0.02[3]	6.7±1.8[3]	6.5±1.8[3]	4.5±1.5	2.7±1.2	-2.9±1.7[8]	0.8±0.6
3/7/2012 15:00		OER activTek INDUCT 2000	0.55±0.02[2]	11.5±2.6[4]	11±2.6[4]	30.6±1.5	27.6±2.9	111.6±41.6	95.7±29.1
11/1/2012 11:28		OER HVAC UV 560	0.76±0.02[5]	7.0±1.2[5]	6.3±1.2[5]	145±1.5	142±3.24[8, 9]	NA	NA
11/2/2012 10:00		OER HVAC UV 560	0.76±0.02[5]	7.0±1.22[5]	6.3±1.2[5]	137±1.5	133.6±5.2	357.2±106.7[9]	332.4±68.3
11/5/2012 10:00		OER HVAC UV 560	0.76±0.02[5]	7.0±1.2[5]	6.3±1.2[5]	508±1.5	495±12.2[8, 9]	NA	NA

Date & Start Time	HVAC Status	Test & In-Duct Device Tested	Air Exchange Rate (1/hr)	Ozone Removal Rate (1/hr)	Ozone Decay Rate (1/hr)	Max Conc.[1] (ppb)	Steady state[1] conc.(ppb)	OER1[6], mg/hr	OER2[6] mg/hr
11/21/2012 10:00		OER HVAC UV 560	0.77±0.01	2.9±2.4	2.1±2.4	99.1±1.5	105.9±7.4	101.3±26.6	98.1±16.9
10/21 to 22/2012 19:22		OER HVAC UV 560	0.59±0.01	2.9±2.4	2.3±2.4	104.1±1.5	101.5±2.6	99.8±25.5	87.9±11.9
4/26/2012 16:00	HVAC Fan Off	OER activTek INDUCT 2000	0.5±0.02[3]	7.0±1.8[3]	6.5±1.8[3]	5.3±1.5	2.1±2.4	-2.5±3[10]	-12.6±8[10]

[1] Maximum concentration uncertainty is determined by the ozone monitor accuracy of ±1.5 ppb. Max and steady-state collected at HVAC return.
[2] AER is from 2/22/2010 10 am test.
[3] AER/ORR/ODR is from 2/25/2012 2 pm test.
[4] ORR and ODR estimates are from 3/7/2012 11 am test.
[5] AER/ORR/ODR is average from System Off, Fan On AER/ORR/ODR tests.
[6] OER1 and OER 2 are estimated using the equations from the California Test Method, 10.
[7] Low house steady state concentration relative to house background concentration resulted in negative OER estimate that is reported as zero OER.
[8] HVAC UV 560 tests on 11/1 and 11/5 measured steady state at supply (living room and master bedroom supplies respectively) and are not a house steady state concentration; no OER estimates reported because ozone is measured at supply. 11/5.
[9] HVAC UV 560 operated in shock mode that increases ozone emissions. The shock mode is intended for occasional decontamination or powerful odor control needs and not daily or routine use. During these tests, the steady state concentration was measured at the supply which did not allow for OER1 or OER2 determination.
[10] High outdoor ozone concentrations relative to steady state concentration, and low steady state concentrations resulted in negative OER estimates.

Table 3.8. Major results from California test houses 1-3

Date & Start Time	HVAC Status	Test House, Test & In-Duct Device Tested	Air Exchange Rate (1/hr)	Ozone Removal Rate (1/hr)	Ozone Decay Rate (1/hr)	Max Conc.[1] (ppb)	Steady State[1] Conc. (ppb)	OER1[2], mg h^{-1}	OER2[3], mg h^{-1}
5/22/12 10:30	Stage 1 Fan On	**Test House 1** AER/ODR	0.34±0.01	6.4±0.2	6.0±0.27	NA	NA	NA	NA
5/22/12 13:26		**Test House 1** activTek INDUCT 2000	0.27±0.01	6.4±0.2	6.1±0.2	5.1±1.5	4.4±0.9	13.6±11.8	10.0±6.1
5/23/12 12:20		**Test House 1** activTek INDUCT 2000	0.31±0.01	3.5±0.2	3.1±0.2	6.8±1.5	5.8±0.8	5.5±1.5	8.8±4.3
5/25/12 15:25		**Test House 2** AER/ODR	0.26±0.01	1.9±0.1	1.6±0.1	NA	NA	NA	NA
5/25/12 10:16		**Test House 2** Trane Clean Effects EP	0.31±0.01	1.9±0.1	1.6±0.1	10.4±1.5	7.1±2.4	2.7±1.1	3.7±4.8
5/30/12 14:03	Stage 1 Fan On	**Test House 3** AER/ODR	0.69±0.02	4.4±0.3	3.7±0.3	NA	NA	NA	NA
5/30/12 9:00	Stage 1 Fan On	**Test House 3** Air Zone Air Duct 2000	0.73±0.02	4.4±0.3	3.6±0.3	10.8±1.5	25.2±2.4	61.3±16.2	71.1±17.5
5/23/12 10:20	Stage 2 Fan Off	**Test House 1** AER/ODR	0.19±0.01	3.5±0.2	3.3±0.2	NA	NA	NA	NA

[1] Maximum concentration uncertainty is determined by the ozone monitor accuracy of ±1.5 ppb. Max and steady-state collected at HVAC return.
[2] OER1 and OER 2 are estimated using the equations from the California Test Method, 10.

Table 3.9. Major results from California test houses 4-6

Date & Start Time	HVAC Status	Test House, Device	Air Exchange Rate (1/hr)	Ozone Removal Rate (1/hr)	Ozone Decay Rate (1/hr)	Max Conc.[1] (ppb)	Steady State[1] Conc. (ppb)	OER1[2], mg h^{-1}	OER2[2], mg h^{-1}
1/7 to 1/8/13 15:48	System On, Fan On	**Test House 4** HVAC UV 560	0.91±0.04	4.7±0.1	3.8±0.1	169±1.5	159±32	266.5±62	227±50
1/8/13 17:10	System On, Fan On	**Test House 4** activTek INDUCT 2000	0.57±0.01	3.99±0.1	3.43±0.1	19.8±1.5	17.8±1.3	23.6±4.7	22±6.6
1/10/13 9:21	System off, Fan Auto	**Test House 5** HVAC UV 560	0.44±0.01	6.2±0.5	5.8±0.5	93±1.5	103.2±3.7	239±32.6	234±33
1/11/13 9:02	System On, Fan On	**Test House 5** HVAC UV 560	0.52±0.01	6.2±0.5	5.7±0.5	109.3±1.5	118.8±22.4	280±64.3	272±64
1/12/13 9:34	System Off, Fan On	**Test House 6** A Honeywell EP	0.74±0.01	7.3±0.3	6.5±0.3	27.6±1.5	18.7±0.9	48±5.8	44±5.8
1/12/ to 1/13/13 20:00	System On, Fan Off	**Test House 6** Honeywell EP	0.79±0.01	8.1±0.7	7.3±0.7	21.8±1.5	9.2±3.5	22.6±18.6	21±11
1/13 /13 10:17	System On, Fan On	**Test House 6** Honeywell EP	0.77±0.01	3.7±0.1	2.9±0.1	35.8±1.5	26.9±1.9	39±15.4	33±4.4
1/14/13 9:35	System On, Fan On	**Commercial Test** Trane TCACS	0.75±0.16	5.7±0.2	5.0±0.2	21.6±1.5	14.4±6.3	18.0±9.9	17.2±11.5[4]

[1] Maximum concentration uncertainty is determined by the ozone monitor accuracy of ±1.5 ppb. Max and steady-state collected at HVAC return.
[2] OER1 and OER 2 are estimated using the equations from the California Test Method, 10.
[3] Outdoor ozone concentration was high relative to steady state concentration in classroom that resulted in a negative estimate for OER2

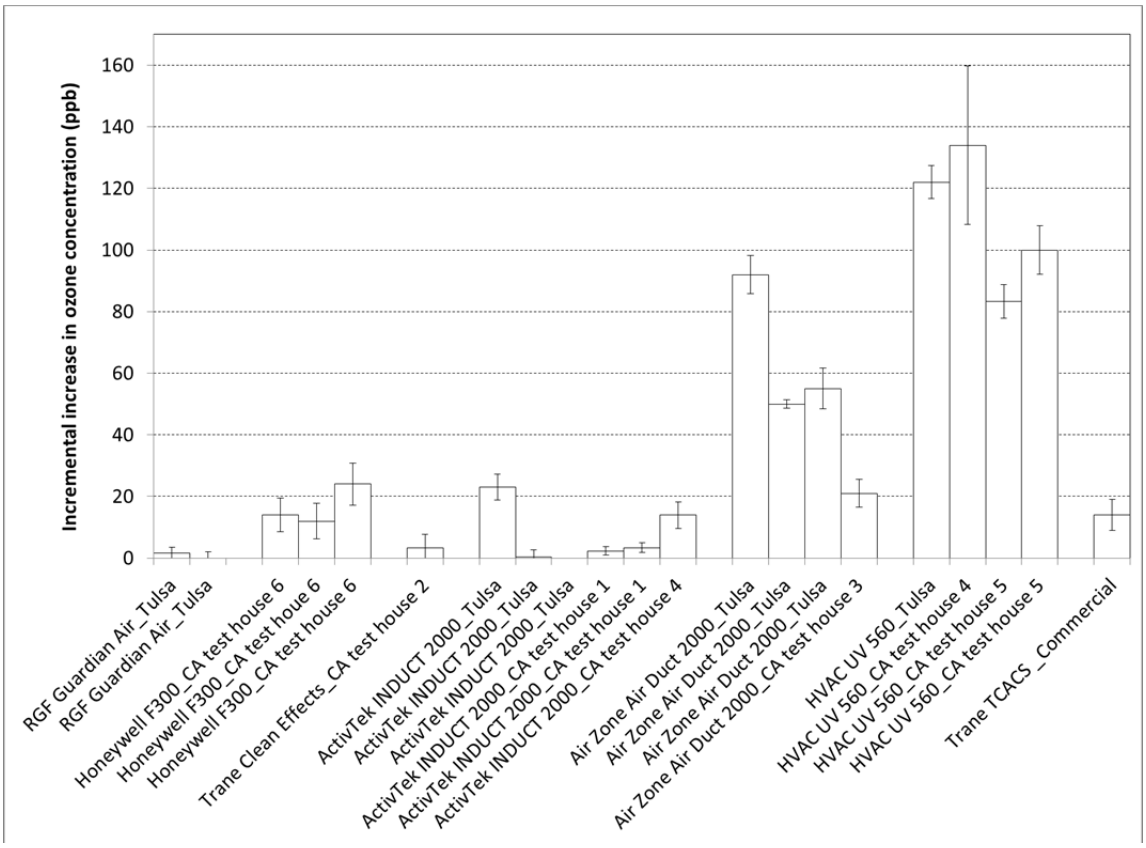


Figure 3.15. Average incremental increase in the indoor ozone concentration at all field sites at return.

Electrically connected in-duct air cleaners produced ozone to varying degrees, increasing the indoor concentration by as much as 130 ppb or more with emission rates as high as 400 mg h^{-1} while operating normally in residences. The Air Guardian had the lowest ozone emission rate, at or near the ability to quantify any increase in indoor ozone. Initially, the activTek INDUCT 2000 generated ozone with an OER of approximately 100 mg h^{-1}, but subsequent tests were less than 20 mg h^{-1}. The incremental increase in ozone in California field tests ranged from near detection limits to about 14 ppb. The Air Zone Air Duct 2000 emitted about 440 mg h^{-1} in its first run and generated an incremental increase in the ozone concentration of 92 ppb. At least one manufacturer (producer of the HVAC UV 560) notes that the ozone emission rate will decrease with continued use of the lamp. Every subsequent test had emission rates of about 150 mg h^{-1} or lower. The 2000 in the product name refers to the manufacturers claimed high ozone output of 2000 mg h^{-1} (achieved by turning a knob to maximum on face of device). In tests of two different units of this model in the field, turning the knob did not quantifiably change the ozone emission rate of the device. The devices appeared to be unreliable and, on at least one occasion in test house 1, an Air Duct 2000 device produced a short burst of ozone at

a high emission rate based on measurements at the supply. On May 29 this device was tested after installation to ensure correct operation. For 45 minutes (16:47 to approximately 17:33) the ozone concentration at the living room supply duct increased dramatically. The O3 concentration at the supply duct during this time average 439 ppb and peaked at 894 ppb. The HVAC UV 560 generally produced a higher emission rates (90-280 mg h^{-1}) and produced the highest observed incremental increase in the ozone concentration in field tests (134 ppb) with device operating normally. This device was also operated in "shock mode" (November 1,2 and 5) to determine its upper limits and encourage lamp break-in. These tests resulted in an emission rate of 357 mg h^{-1}. During these tests the return concentration rose to about 120 ppb. The supply reached about 500 ppb. Shock mode is intended, according to the manufacturer, to control strong odors or to decontaminate the indoor environment (e.g. such as the presence of extensive mold). The 560 in the product name refers to the manufacturers claimed ozone emission rate of 560 mg h^{-1}. The two electrostatic precipitator devices tested (Honeywell F300 and Trane Clean Effects) exhibited low to moderate emission rates. The increase in the ozone concentration, and the emission rate, were below the level of detection for the Trane Clean Effects device. The Honeywell F300 had relatively consistent emission rates in 3 tests ranging from 27 to 48 mg h^{-1}, raising the indoor concentration by 12 to 24 ppb.

In residential field tests, two devices increased the indoor ozone concentration by more than 50 ppb: the Air Zone Air Duct 2000 and the HVAC UV 560. The highest steady-state incremental increase in the ozone concentration was 92 and 134 respectively while both devices were operated normally.

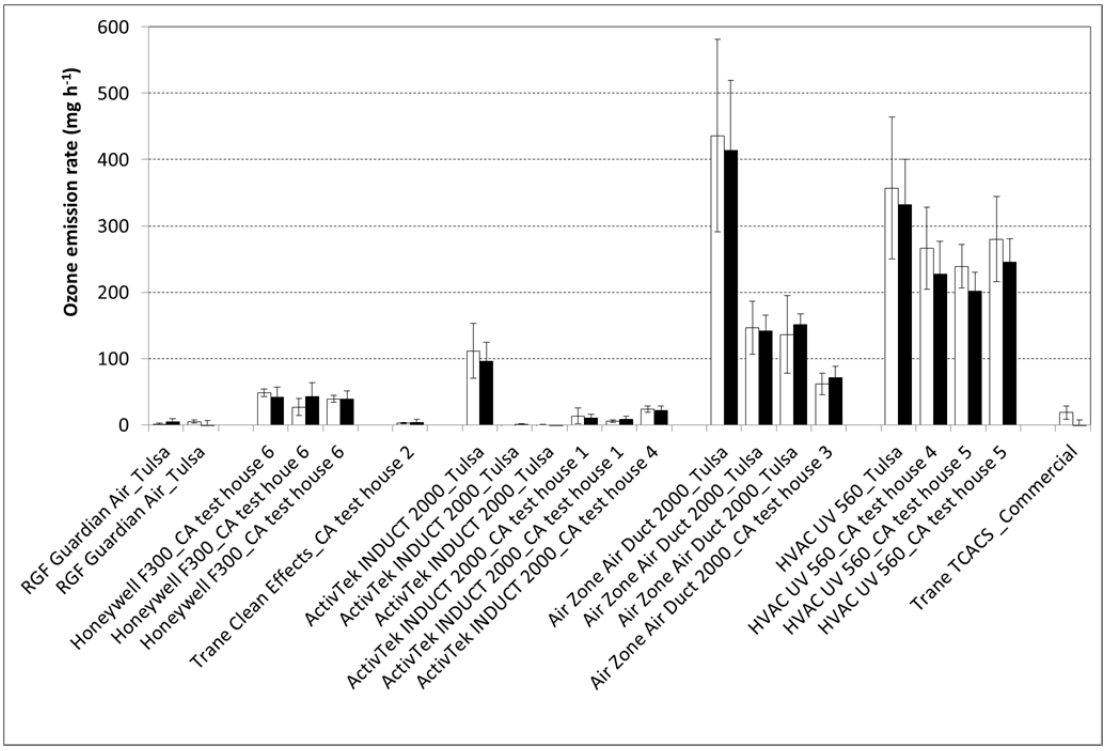


Figure 3.16. Ozone emission rates for field sites. White bar is OER1, black bar is OER2.

The Trane commercial air cleaning system (TCACS) produced an estimated OER of 2.7 mg O3/hour. Due to low emission rates and high outdoor ozone levels (average 20.4 ppb) relative to the indoor level (steady state equilibrium level of 14.4 ppb) the uncertainty estimates are high. Also, throughout the test period outdoor ozone levels increased steadily. Full application of the field test method was not possible in this setting because the test space was occupied periodically by students.

Some evidence of a temperature effect on ozone emission rates was observed for the HVAC UV 560. Under normal operation, the device consistently had OERs above 200 mg O3/hour and increased the indoor ozone concentration above 80 ppb in two California test houses. In both test houses, the device was installed downstream of the air handler. During the January 7-8 overnight test in Test House 4, the HVAC system was operating in the "on" position (fan on at all times) because overnight low temperatures may have created freezing indoor temperatures. The ozone concentration at three locations (return, bedroom and living room) appeared to cycle up and down. Direct observation confirmed that this cycling is related to the heater cycling on and off. Figure 3.17 shows this ozone concentration cycling. Starting around midnight extended periods of heating cycles began. At approximately 7:42 am on January 8 the device was turned off and the ozone concentration declined. Note that the concentration in the living room rose to over 200 ppb during the last 2 heating cycles.

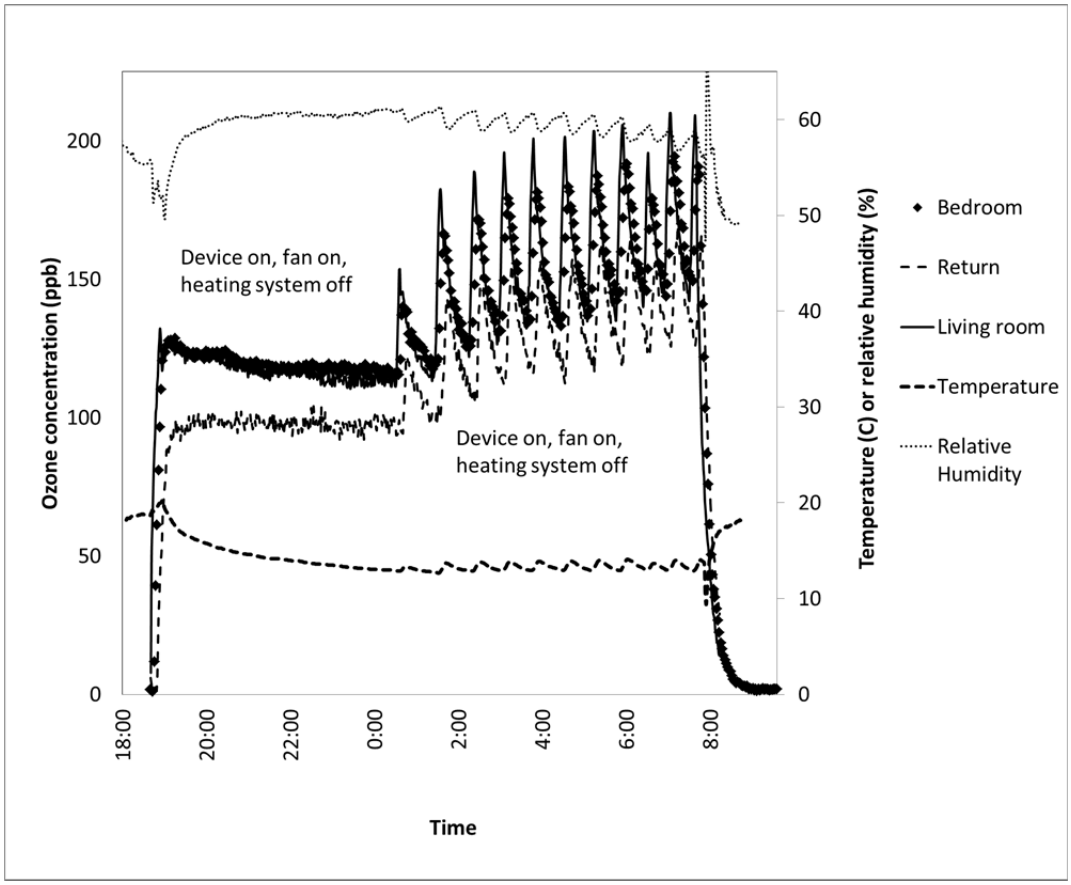


Figure 3.17. Evidence of the ozone emission rate being influenced by temperature in California test house 4. Indoor concentration increases when HVAC heater operating.

Ozone decay rates and air exchange rates are consistent with those measured in other residential field studies. Ozone decay rates (ODR) for field homes in this study varied from about 1.5 to 11 h^{-1}. The range of results in an individual house was as much as a factor of 2-3. For example, California test houses 1 and 3 had ODRs that ranged from 3.3 to 6.1 and 3.7 to 8.5. However, repeated tests of the ODR in test houses 2,3 and 5 were within 15% of one another. Repeated testing over short time periods in the Tulsa test house revealed a possible reduction in surface reactivity due to repeated ozone exposure during seeding and operation of in-duct devices. Ozone decay rates declined during three tests on February 22. At 10 am, the ODR was 8.8 h^{-1}, at 1 pm it was 2.8 h^{-1} and at 4pm it was 3.2 h^{-1}. It is hypothesized that the initial introduction of ozone removed (oxidized) readily available surface sites, reducing deposition velocities for subsequent tests. The Tulsa test house initially contained a large amount of scented candles, air fresheners and perfumes. In addition, a medium sized dog lived in the house; dog hair and dander where observed on surfaces throughout the house. Although obvious sources of reactive VOCs were removed prior to testing, residual reactive compounds could have increased surface reactivity. Later tests with higher ozone decay rates suggested

that these surfaces can increase in reactivity over time, perhaps due to cooking, cleaning, use of fragranced products and so forth.

Air exchange rates (AER) ranged from less than 0.2 h^{-1} to 1.5 h^{-1}. The latter value was early in the Tulsa test house work when the house was considered particularly "leaky". High air exchange rates make it more difficult to discern an incremental increase in the ozone concentration due to indoor ozone sources. To reduce the AER, it was necessary to seal the front and rear doors with tape and an air current barrier was installed on the front door. The pantry door was sealed with tape because of penetrations to the attic inside the pantry. The attic door was sealed during tests, and a suspended ceiling plenum in the bathroom was sealed. The HVAC technician had to reboot the ducts to the supply vents because they were not properly installed and caused conditioned air loss into the attic. After this, the Tulsa test house air exchange rate averaged approximately 0.5 air changes per hour. The highest measured AER was 0.8 (h^{-1}) and the lowest was 0.13 (h^{-1}) when the HVAC fan was off. The AER was higher when the HVAC fan is in the "on" position. The Tulsa experience with leakage prompted the field team to seal areas that might result in large AERs such as fireplaces, attic penetrations and loosely fitting windows and doors. Therefore, the air exchange rates measured in California field homes are likely to be somewhat lower than they would have been without active sealing of the houses.

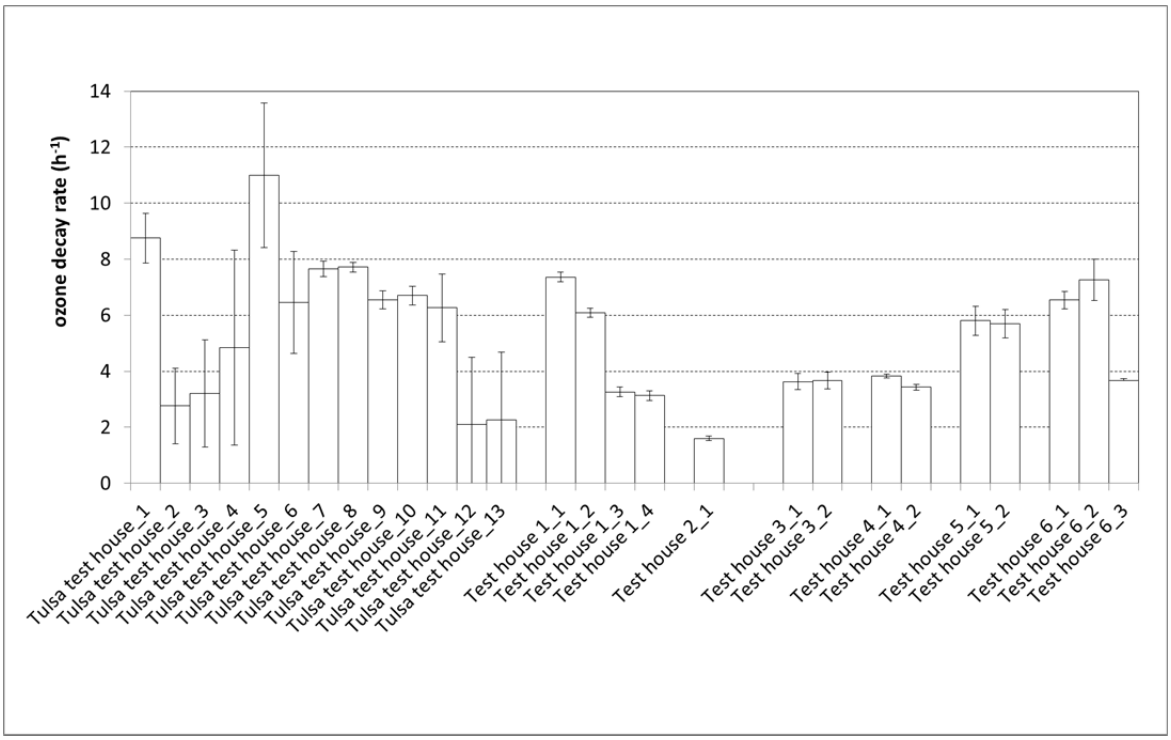


Figure 3.18. Ozone decay rates (ODR) at field sites. No ODR was obtained at the classroom site with the Trane TCACS system.

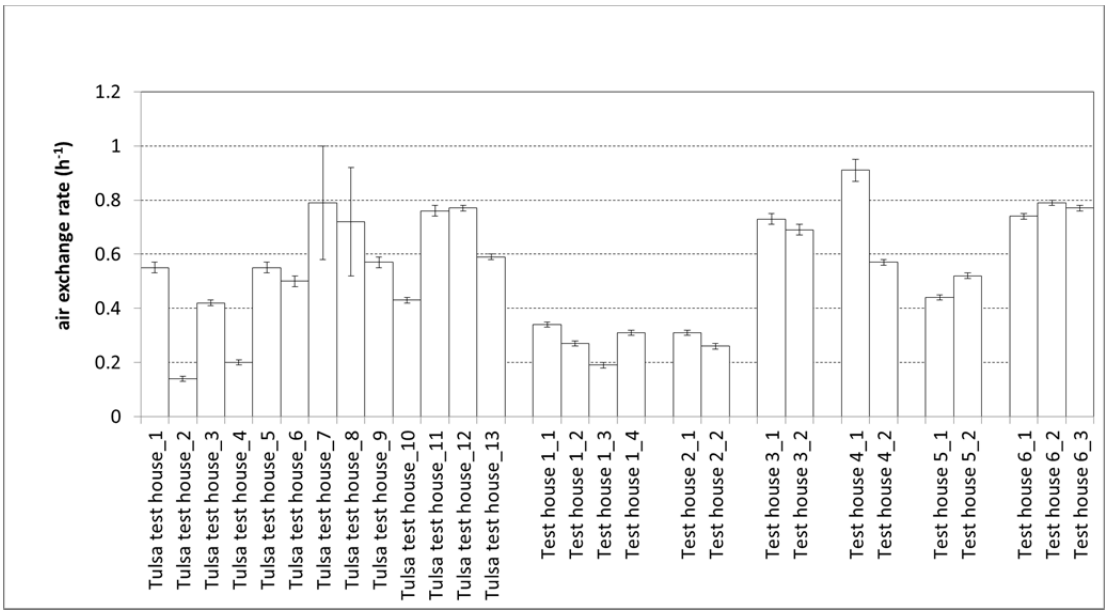


Figure 3.19. Air exchange rates measured at field sites. The AER was not measured using CO_2 decay in the classroom site with the Trane TCACS system.

3.4 Building ozone concentration simulations

The results for building simulations are separated into two sections: Single zone and Multizone simulations.

3.4.1 Single zone

3.4.1.1 Standard House and at Risk House

The Standard House results are based on using central values (Table 2.4) for parameters in equation (2). Applying these values, the indoor concentration of ozone in the Standard House is 27 ppb with a source emission rate of 100 mg h^{-1}. The At Risk House results are based on values chosen to amplify indoor ozone concentrations (e.g. low indoor reactivity or decay rates, low air exchange rates, small volume, etc.) but using a lower source emission rate. The resulting indoor concentration 100 ppb with a source emission rate of 50 mg h^{-1}. For a source emission rate of 100 mg h^{-1} (same as the Standard House), the indoor ozone concentration is 200 ppb, approximately 7 times greater than for the Standard House. Thus indoor ozone concentrations are very sensitive to building characteristics.

Shown in Figure 3.21 through Figure 3.24 are simulations that vary multiple parameters around a baseline of the Standard House parameter values. In Figure 3.20, ozone concentration is plotted as a function of source emission rate at a range of air exchange rates. Ozone rises linearly with source emission rate to a high value of 87 ppb for a source emission rate of 300 mg h^{-1} and an air exchange rate of 0.1 h^{-1}. To visualize this data in a slightly different way, Figure 3.21 shows the ozone

concentration plotted as a function of air exchange rate for different source emission rates.

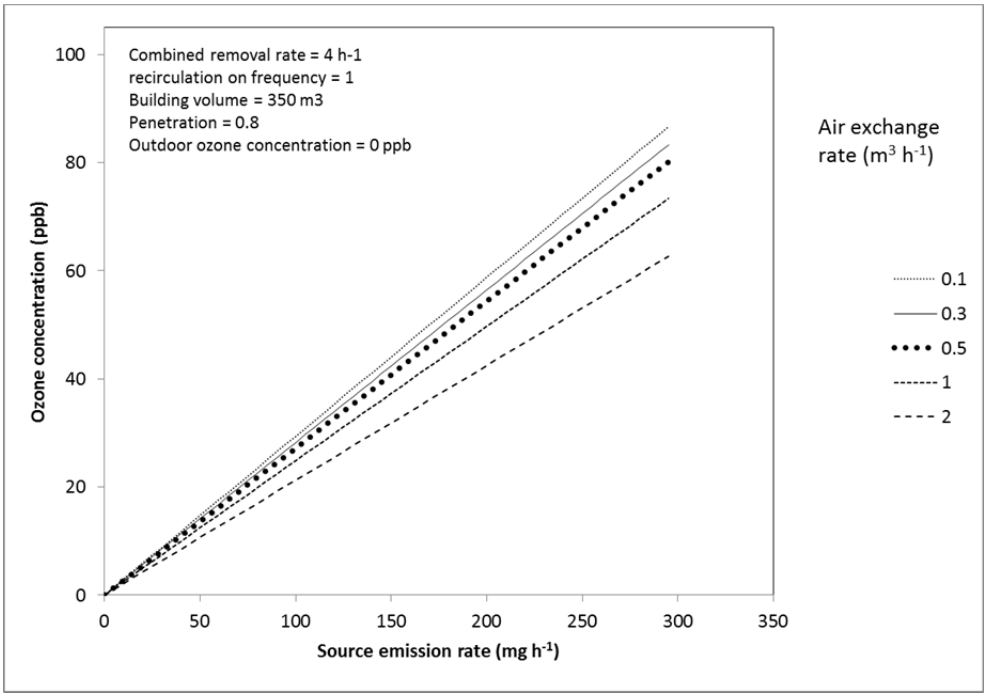


Figure 3.20. Ozone concentration as a function of source emission rate and air exchange rate for the Standard House.

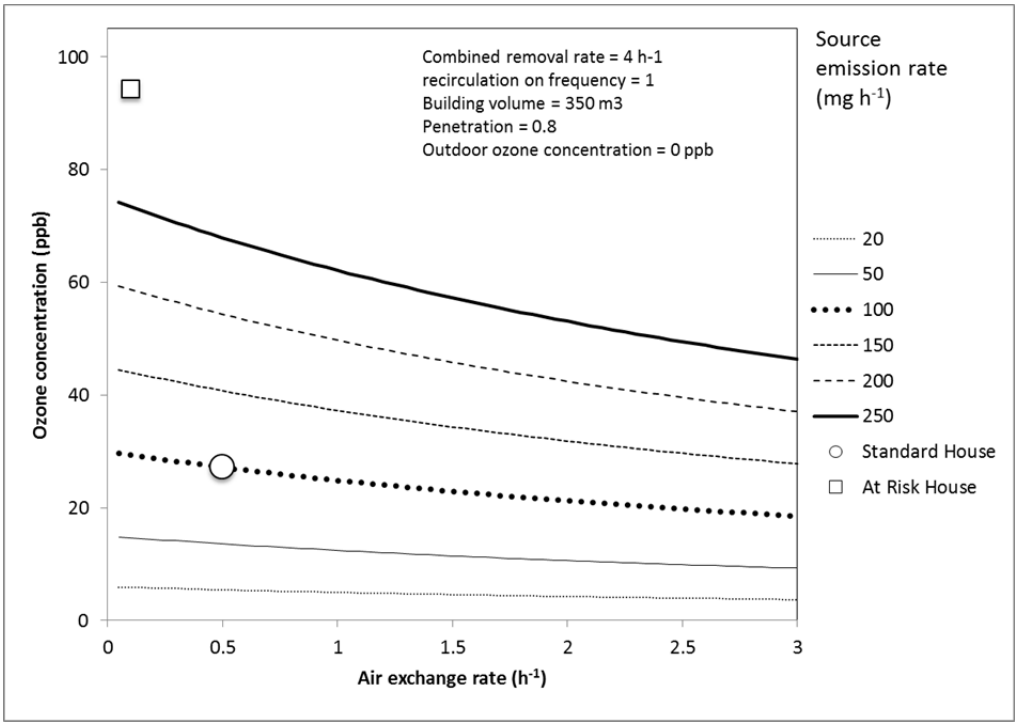


Figure 3.21. Ozone concentration as a function of air exchange rate and source emission rate for the Standard House.

In Figure 3.22 is shown the indoor ozone concentration as a function of air exchange rate for a range of building volumes, where all other parameters of the Standard House are as shown in Table 2.4. The results for the Standard House and At Risk House conditions are shown as points on the figure. As anticipated, smaller houses have higher indoor ozone concentrations. Increasing air exchange rates improves conditions, but not substantially so. For example, increasing air exchange rates from 0.1 to 1 h^{-1} (factor of 10) only reduces the indoor concentration by about 15% because a large amount of ozone removal is achieved through reactions with interior surfaces (decay rate is 4 h^{-1} for the standard house). This effect is shown more clearly in Figure 3.23 where the ozone concentration is plotted vs. air exchange rate for different ozone decay rates. For a decay rate of 1.5 h^{-1}, an increase in the air exchange rate from 0.1 to 10 reduces indoor ozone concentrations by 28%, but the indoor concentration starts much higher than for the 4 h^{-1} (Standard House) case. Ventilation rates have a much smaller effect on indoor ozone concentrations in buildings with high background decay rates (e.g. 10 h^{-1}), such as those measured by Stephens et al. (2012).

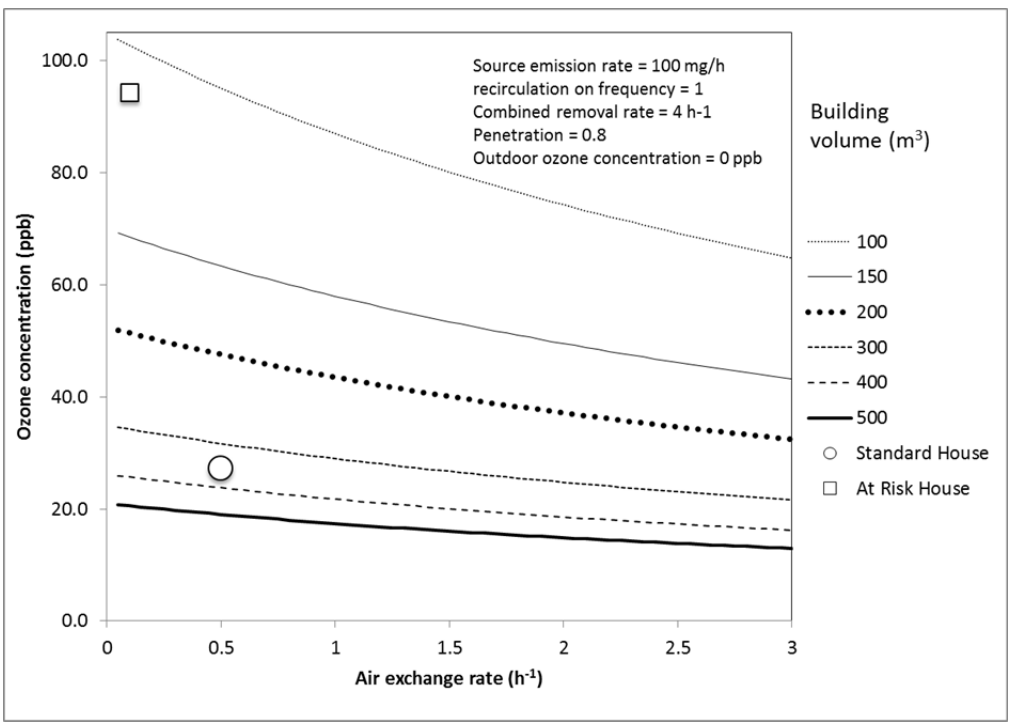


Figure 3.22. Ozone concentration as a function of air exchange rate and building volume for the Standard House.

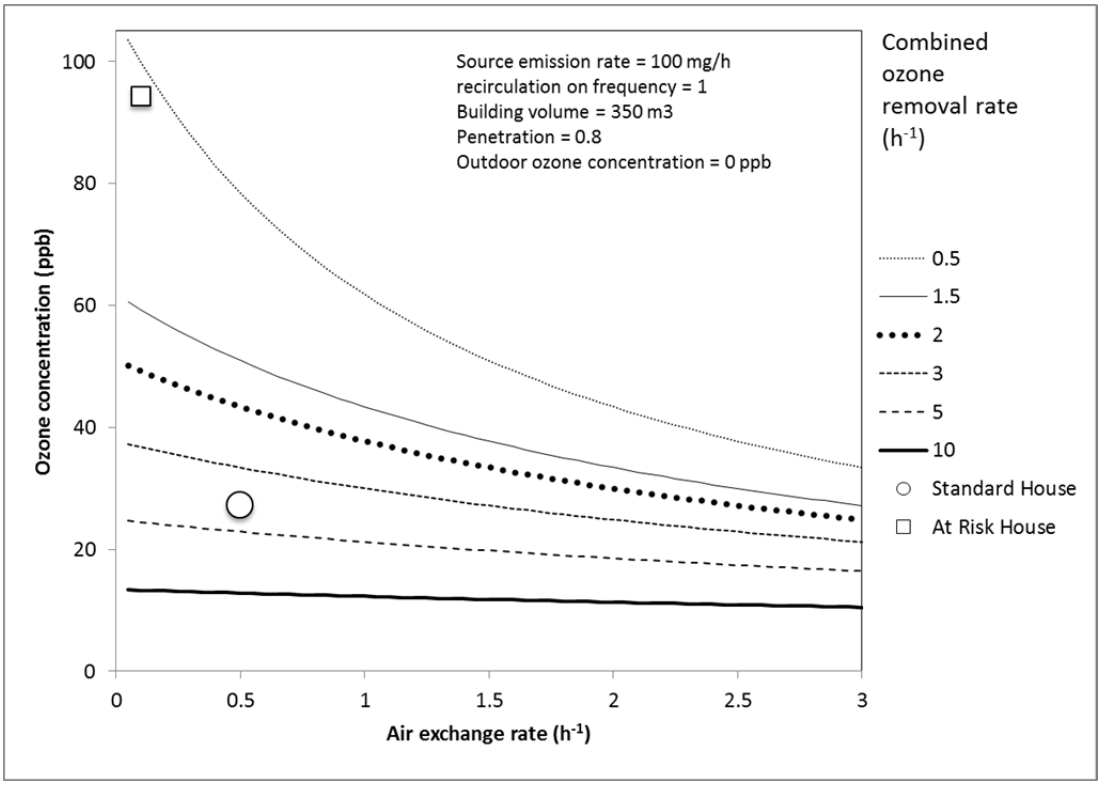


Figure 3.23. Ozone concentration as a function of air exchange rate and combined removal rate for the Standard House.

The influence of infiltrated outdoor ozone is shown in Figure 3.24. For low outdoor ozone concentrations, increased air exchange reduces indoor ozone concentrations. For high outdoor ozone concentrations, increased air exchange increases indoor ozone concentrations. For the Standard House, an outdoor concentration of approximately 38 ppb results in an indoor concentration (30 ppb) that is independent of the air exchange rate. For standard conditions (and a 100 mg h^{-1} source emission rate), the outdoor ozone concentration would have to rise above 300 ppb for the indoor concentration to reach 50 ppb. The fraction of indoor ozone due to an indoor source reduces as the air exchange rate increases. Assuming an outdoor concentration equal to the National Ambient Air Quality Standard (8-hour average) of 75 ppb, 83% of the indoor ozone concentration is due to the indoor source (standard conditions). For an air exchange rate of 2 h^{-1}, which is four times the standard value, only about 55% of the indoor ozone concentration is due to the indoor source.

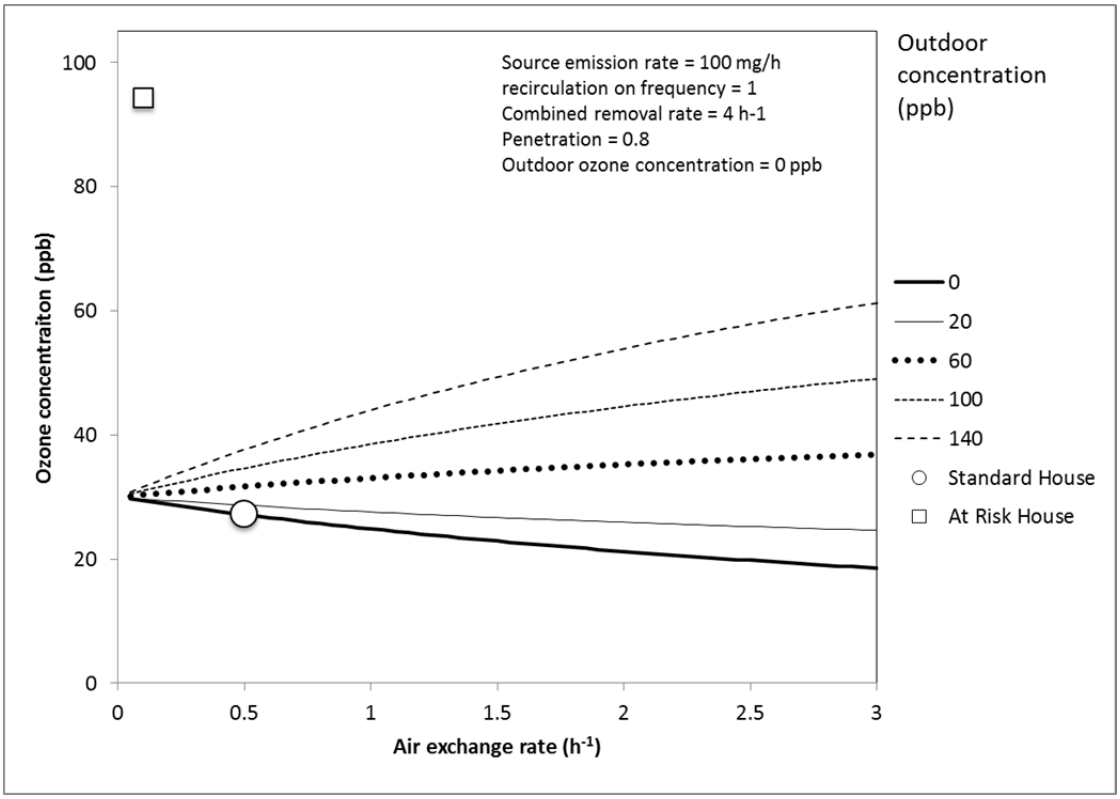


Figure 3.24. Ozone concentration as a function of air exchange rate and source emission rate for the Standard House with outdoor ozone infiltration.

At risk house

Shown in Figure 3.25 are the results for the at-risk home simulations, plotting the predicted indoor ozone concentration vs. source emission rate. Indoor ozone concentrations are much higher than for the Standard House (Figure 3.20) and rise above 50 ppb for source emission rate ranging from 27 mg h^{-1} to 55 mg h^{-1} for air exchange rates ranging from 0.1 to 2 h^{-1}. Indoor ozone concentrations are very sensitive to air exchange rates, when compared with the Standard House.

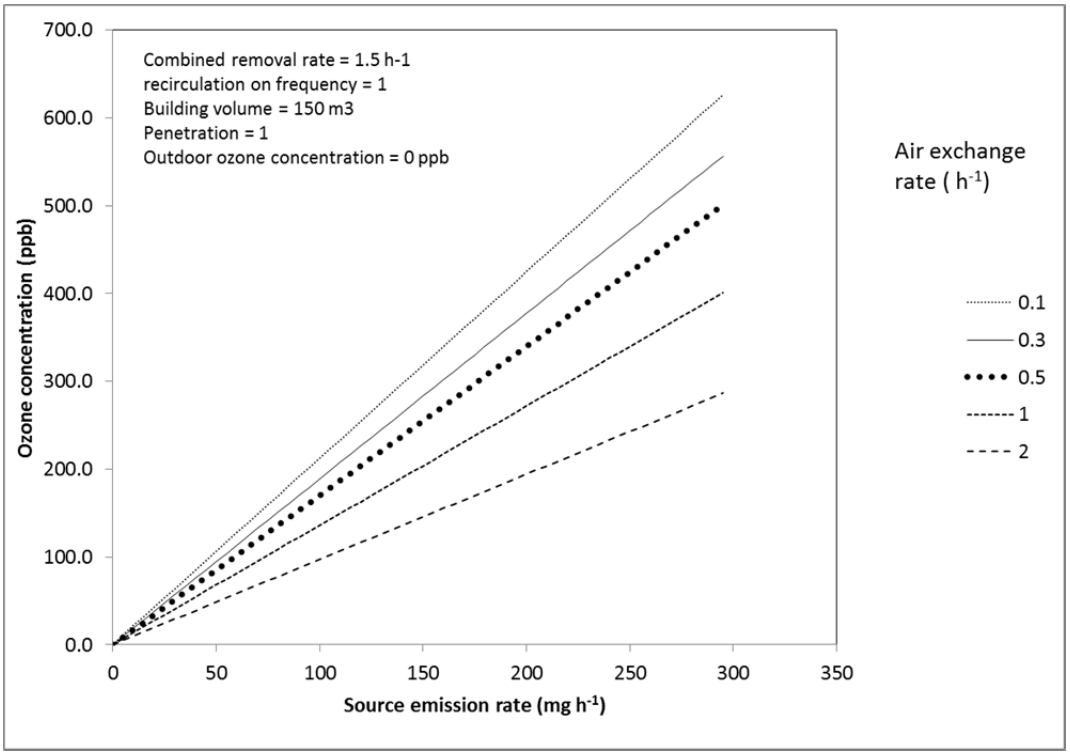


Figure 3.25. Ozone concentration as a function of source emission rate for the At Risk House.

3.4.2 Multiple zone

Selected results for multiple zone simulations are shown in Figure 3.26 through Figure 3.50, separated into Steady-state results and Dynamic results. Note that ozone concentration is reported in units of ppm instead of ppb in this section.

3.4.2.1 Steady-state results

Effect of wind direction: air handler off

Shown in Figure 3.26– Figure 3.35 are results for the situation in which an in-duct device emits ozone, independent of the on-off state of the air handler. In this case, ozone will build up within the duct system and can be delivered to rooms by small flows induced by pressure differences among compartments. For this simulation, pressure differences are induced by wind and the direction the wind impinges on the building changes the direction of flow among compartments. Under these conditions, the house average concentrations were less than 0.017 ppm. However, there is a stark distribution of room concentrations with some rooms at very low concentration and other rooms as high as 0.08 ppm. This is because a small amount of ozone is pushed through ducts (source zone concentration 1.4 to 1.8 ppm) by pressure differences into down-wind rooms. The air exchange rates ranged from 0.045 h^{-1} (wind direction 90°, wind speed 2 m h^{-1}) to 0.59 (wind direction 135°, wind speed 8 m h^{-1}).

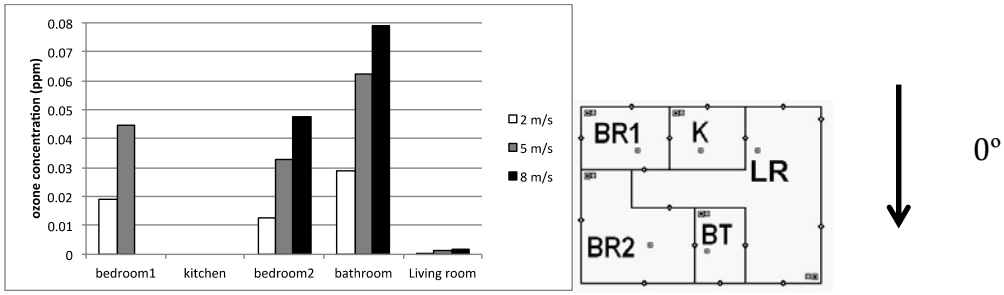


Figure 3.26. Steady-state ozone concentration simulation for multizone model. Air cleaner at 100% duty cycle, AHU off, wind from 0°.

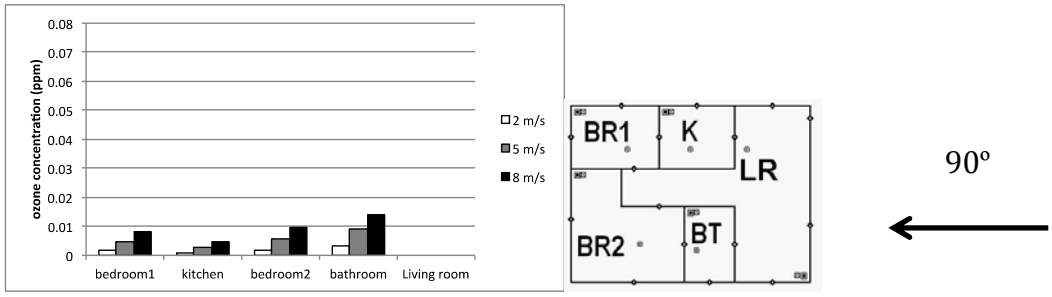


Figure 3.27. Steady-state ozone concentration simulation for multizone model. Air cleaner at 100% duty cycle, AHU off, wind from 90°

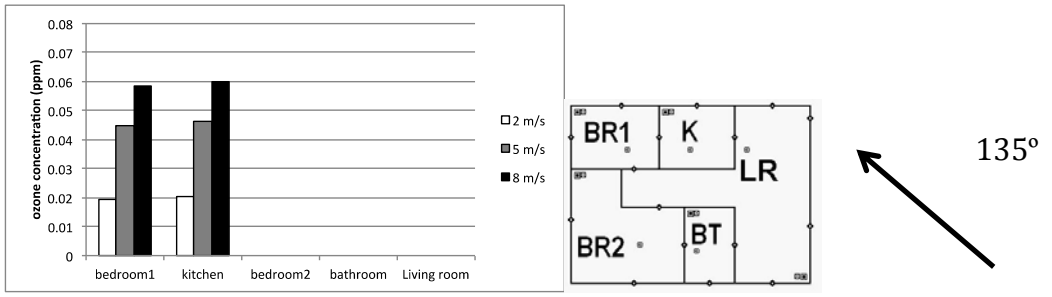


Figure 3.28. Steady-state ozone concentration simulation for multizone model. Air cleaner at 100% duty cycle, AHU off, wind from 135°.

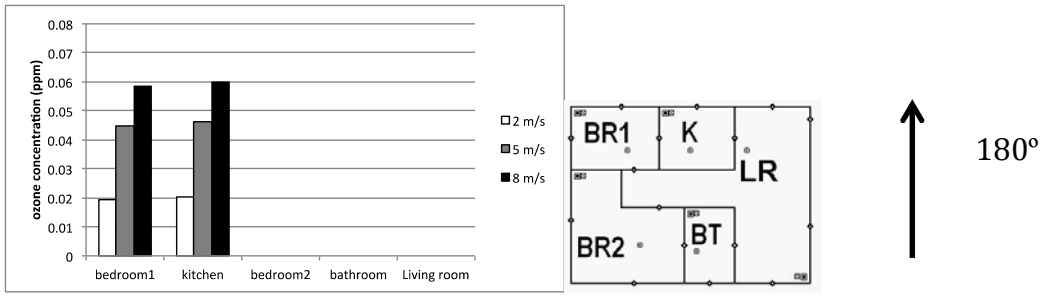


Figure 3.29. Steady-state ozone concentration simulation for multizone model. Air cleaner at 100% duty cycle, AHU off, wind from 180°

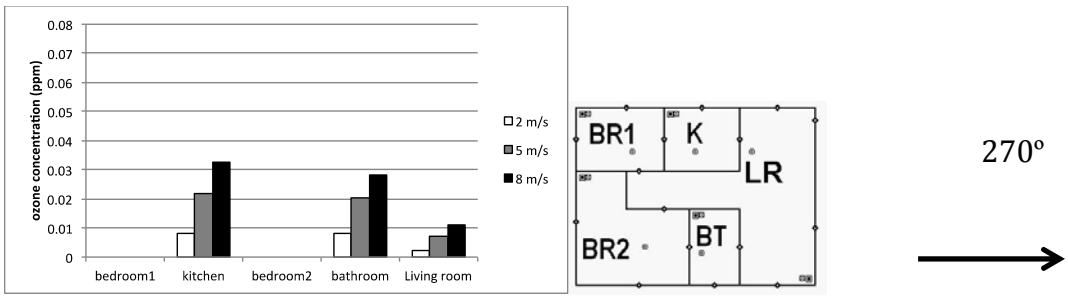


Figure 3.30. Steady-state ozone concentration simulation for multizone model. Air cleaner at 100% duty cycle, AHU off, wind from 270°

Effect of wind direction: air handler on (100%)

Shown in Figure 3.31to Figure 3.35 are the room-by-room steady-state concentrations resulting from operating the air handler at 100% duty cycle, for 3 wind speeds (2, 5 and 8 m/s). The results shown are for a lower-reactivity (a; low v_d) and higher-reactivity (b; high v_d) building surfaces with wind impinging on the building from different directions.

With the air handler operating, the ozone concentration throughout the house is much more uniform with only modest differences in the resulting concentration among rooms. Neither wind direction or wind speed has a strong influence on the spatial distribution of ozone. As anticipated, the indoor ozone concentration in the higher reactivity house is substantially lower (0.040± 0.007 ppm) than in the less reactive house (0.080± 0.013 ppm).

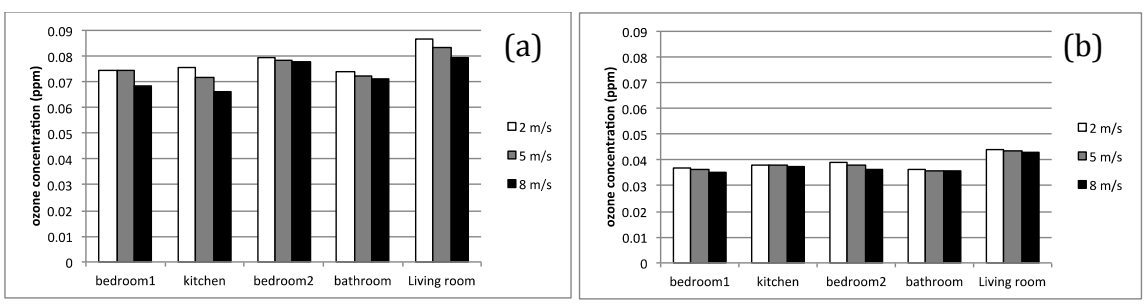


Figure 3.31. Steady-state concentration for each room in the multizone house. Air handler is on full time (100%), wind direction is 0°, deposition velocity is low (a) or high (b), ambient concentration is set to zero.

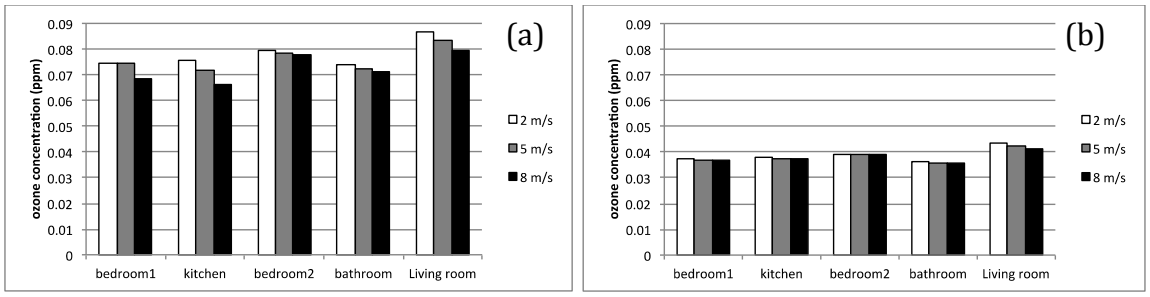


Figure 3.32. Steady-state concentration for each room in the multizone house. Air handler is on full time (100%), wind direction is 90°, deposition velocity is low (a) or high (b), ambient concentration is set to zero.

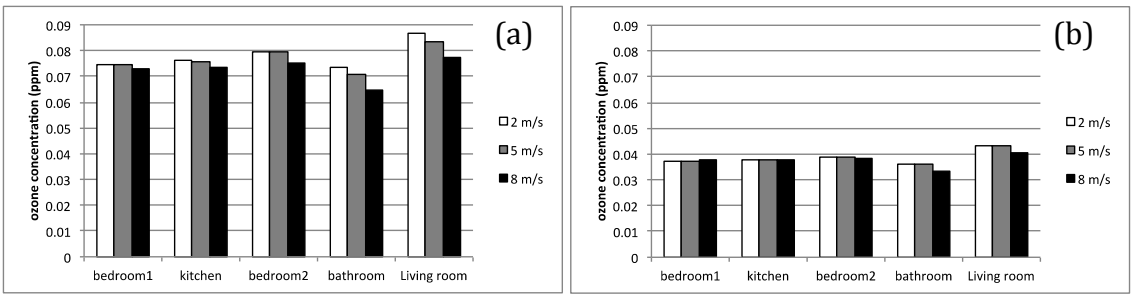


Figure 3.33. Steady-state concentration for each room in the multizone house. Air handler is on full time (100%), wind direction is 135°, deposition velocity is low (a) or high (b), ambient concentration is set to zero.

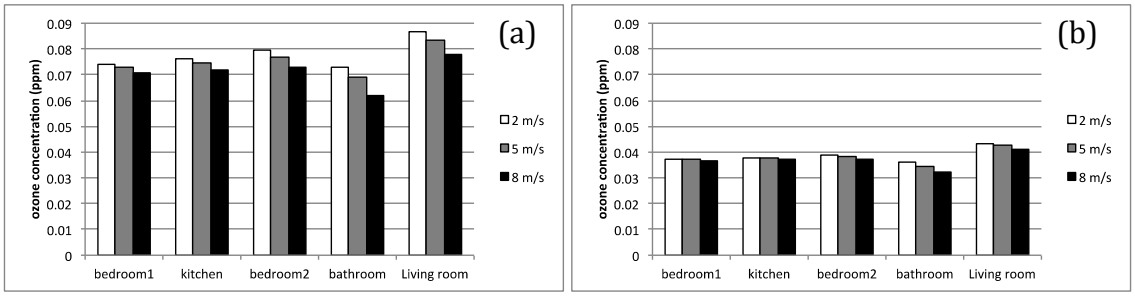


Figure 3.34. Steady-state concentration for each room in the multizone house. Air handler is on full time (100%), wind direction is 180°, deposition velocity is low (a) or high (b), ambient concentration is set to zero.

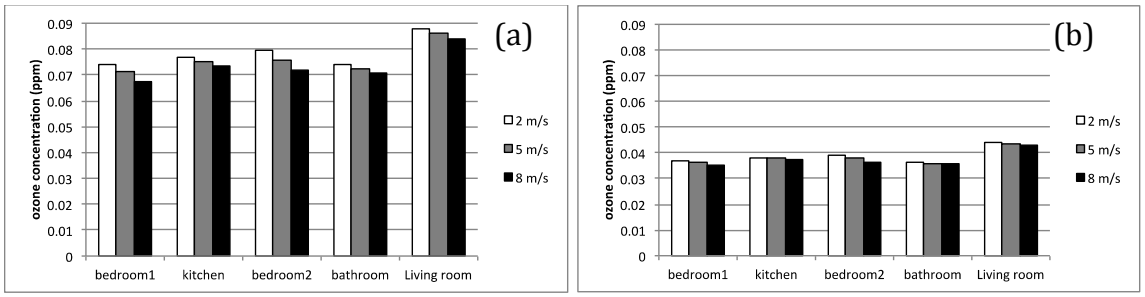


Figure 3.35. Steady-state concentration for each room in the multizone house. Air handler is on full time (100%), wind direction is 270°, deposition velocity is low (a) or high (b), ambient concentration is set to zero.

3.4.2.2 Dynamic results without ambient ozone

Shown in Figure 3.36 through Figure 3.39 are the results of the system operated with the air handler on a 50% duty cycle (1 hour on, 1 hour off), but setting the ambient (outdoor) ozone concentration to zero. For consistency, the entire 24 hour set of results is shown in these figures, although the ozone concentration reaches "steady-cycle" after about 6 to 8 hours. Wind is from 0 degrees at 5 m/s.

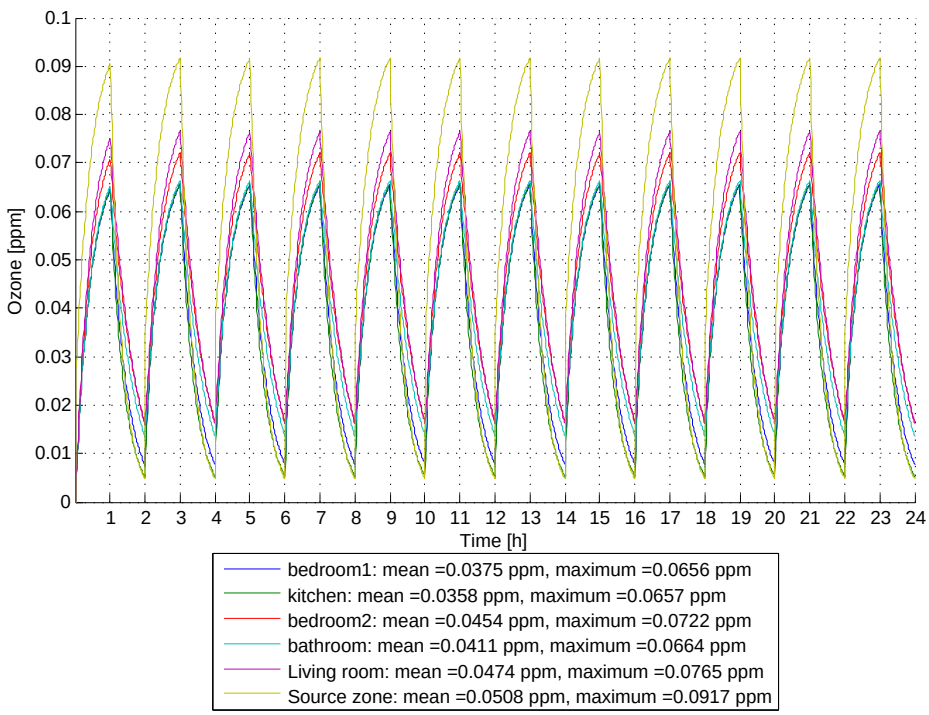


Figure 3.36. Dynamic indoor ozone concentration for: air handling system on 1-hour on/off cycle (AHU on 0-1 h, off 1-2 h, etc.), ambient ozone set to zero, ozone source on same 1-hour on/off cycle, low deposition velocity.

Figure 3.36(Low V_d) and Figure 3.37 (High V_d) are simulations in which the ozone source turns on and off with the air handler at a 1-hour interval (i.e. 1 hour on, 1 hour off). This is what would be expected from most in-duct devices (only on when

needed). In the low deposition velocity case, all rooms experience concentrations greater than 50 ppb for at least ½ hour of each cycle. For the high deposition velocity case no rooms ever experience greater than 50 ppb.

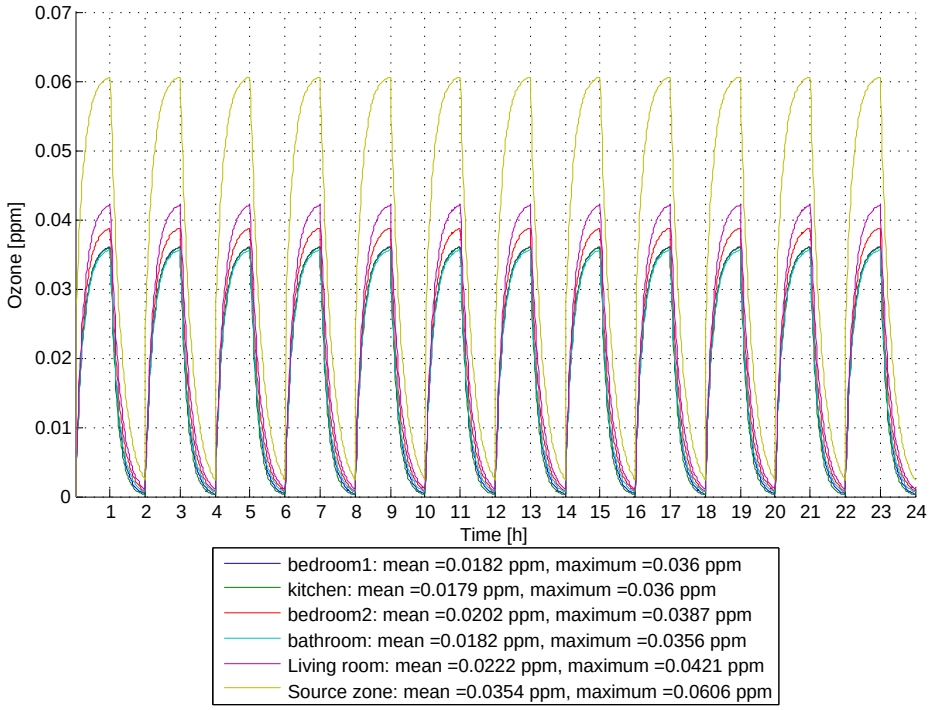


Figure 3.37. Dynamic indoor ozone concentration for: air handling system on 1-hour on/off cycle (AHU on 0-1 h, off 1-2 h, etc.), ambient ozone set to zero, ozone source on 1-hour on/off cycle, high deposition velocity.

Figure 3.38 (Low V_d) and Figure 3.39 (High V_d) are simulations in which the ozone source is on at all times, but the air handler remains at the 50% duty cycle at a 1-hour interval (i.e. 1 hour on, 1 hour off). Some devices plug into a regular outlet (or are directly connected to a circuit) that is not tied into the air handling unit. In these cases ozone will rise rapidly in the source zone when the AHU is off, and rise to 1.5 ppm or more in this zone. The room concentrations are higher, naturally, than in the case where the air cleaner is on a 50% duty cycle with the AHU In the low deposition velocity case, all rooms experience concentrations greater than 50 ppb for at least ½ hour of each cycle. For the high deposition velocity case rooms experience concentrations greater than 50 ppb for only very short time periods.

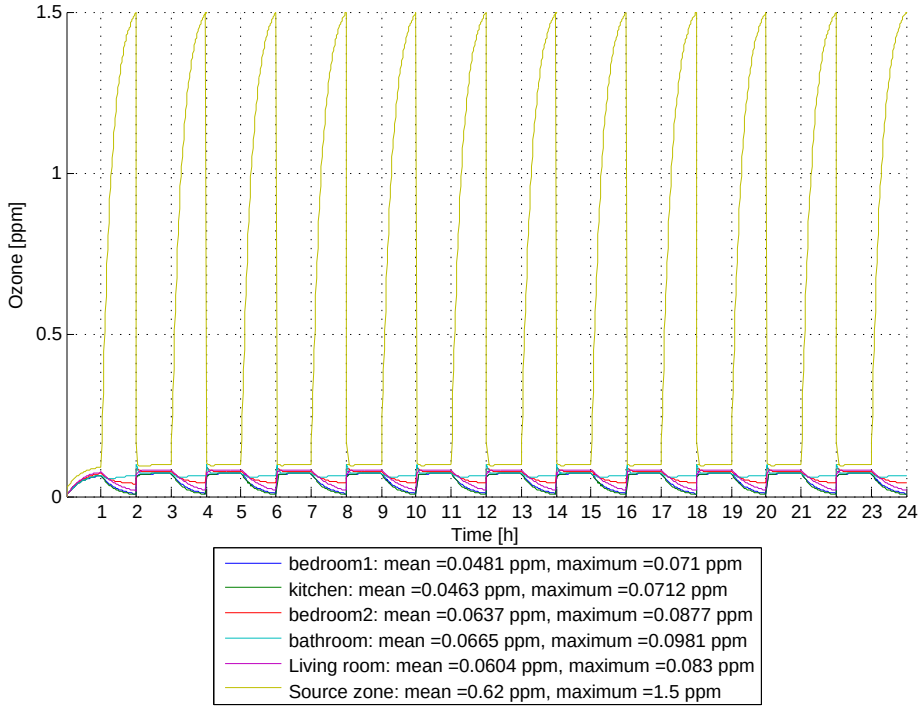


Figure 3.38. Dynamic indoor ozone concentration for: air handling system on 1-hour on/off cycle (AHU on 0-1 h, off 1-2 h, etc.), ambient ozone set to zero, ozone source on at all times, low deposition velocity.

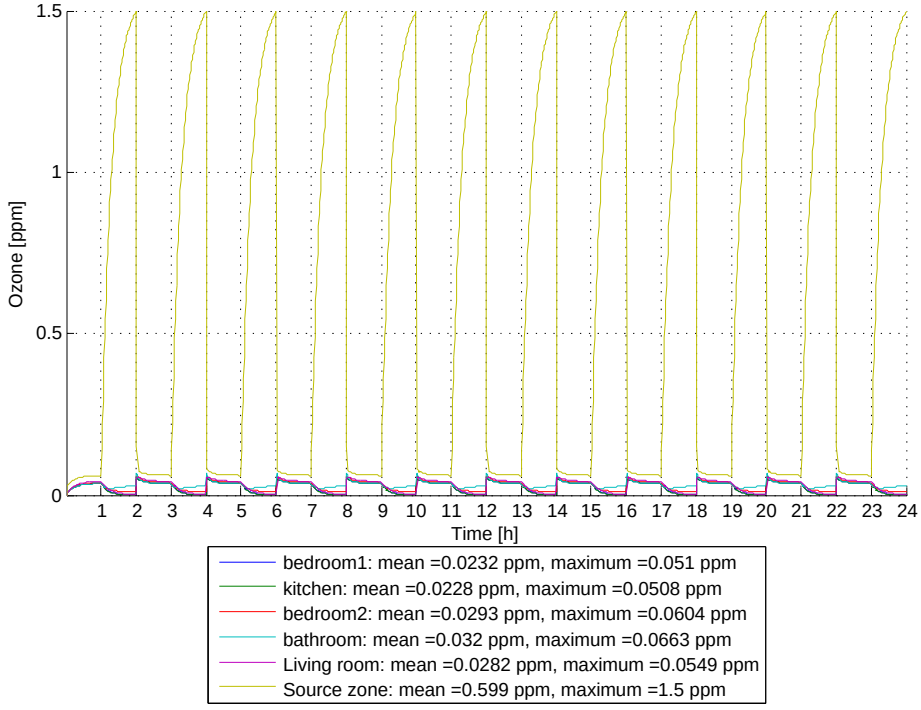


Figure 3.39. Dynamic indoor ozone concentration for: air handling system on 1-hour on/off cycle (AHU on 0-1 h, off 1-2 h, etc.), ambient ozone set to zero, ozone source on at all times, high deposition velocity.

3.4.2.3 Dynamic results with ambient ozone

Shown in Figure 3.40 through Figure 3.47 are the results for the system operated with the air handler on a 1 hour on/off cycle and the outdoor concentration varies as shown in Figure 2.8 (all other parameters are Base Case; see Table 2.6). The dynamic indoor ozone concentrations for the situation where the ozone source is OFF throughout the entire day are shown in Figure 3.40 for a low indoor deposition velocity (Low V_d) and Figure 3.41for a high indoor deposition velocity (High V_d). Outdoor ozone is drawn in by pressure gradients induced by wind and by the operation of the air handling system. However, much of the ozone is removed by surface reactions, resulting in indoor concentrations that are always lower than outdoor concentrations. These two figures represent the dynamic, incremental increase in indoor ozone that is due to infiltration. For example, at roughly 15:00 (Figure 3.41, bedroom 1), the indoor concentration will be 0.018 ppm (18 ppb) higher than that due to indoor sources.

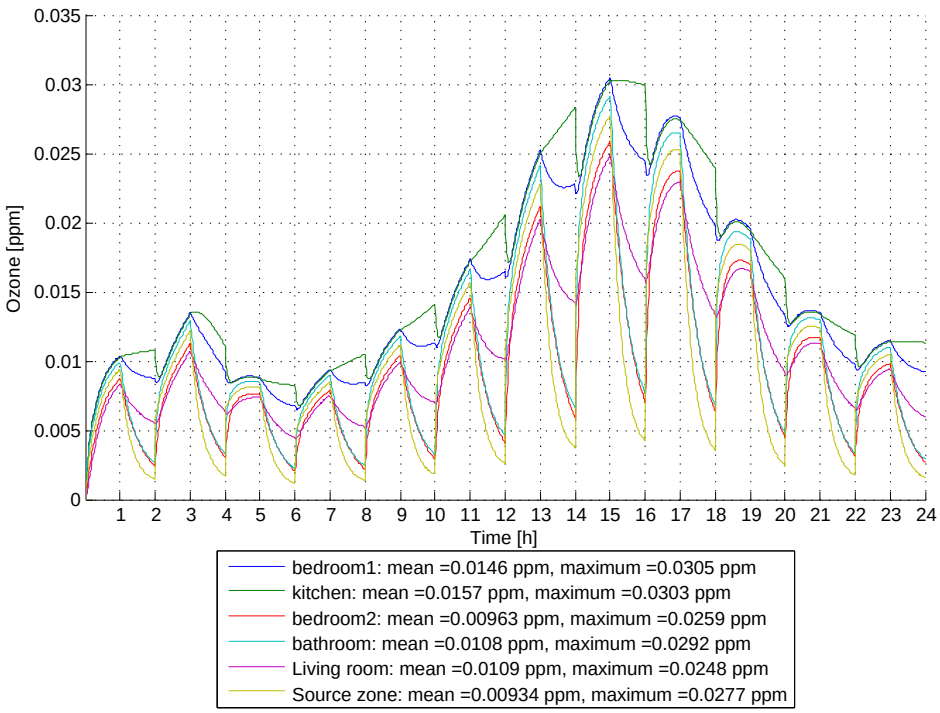


Figure 3.40. Dynamic indoor ozone concentration for: air handling system on 1-hour on/off cycle (AHU on 0-1 h, off 1-2 h, etc.), ambient ozone infiltration, ozone source OFF, low deposition velocity.

Note that some rooms are more heavily influenced by wind-induced infiltration of ozone than others. In this Base Case scenario, the wind (5 m/s from the North or 0°) impinges on the wall with the kitchen, bedroom 1 and the living room. In each of these, the ozone concentration tends to be higher than the other rooms, when the air handler is off. This is consistent with the steady-state results inFigure 3.26 The difference in room ozone concentrations is amplified by the choice to keep interior

doors closed (to identify spatial differences). Open doors would even out the ozone distribution throughout the house.

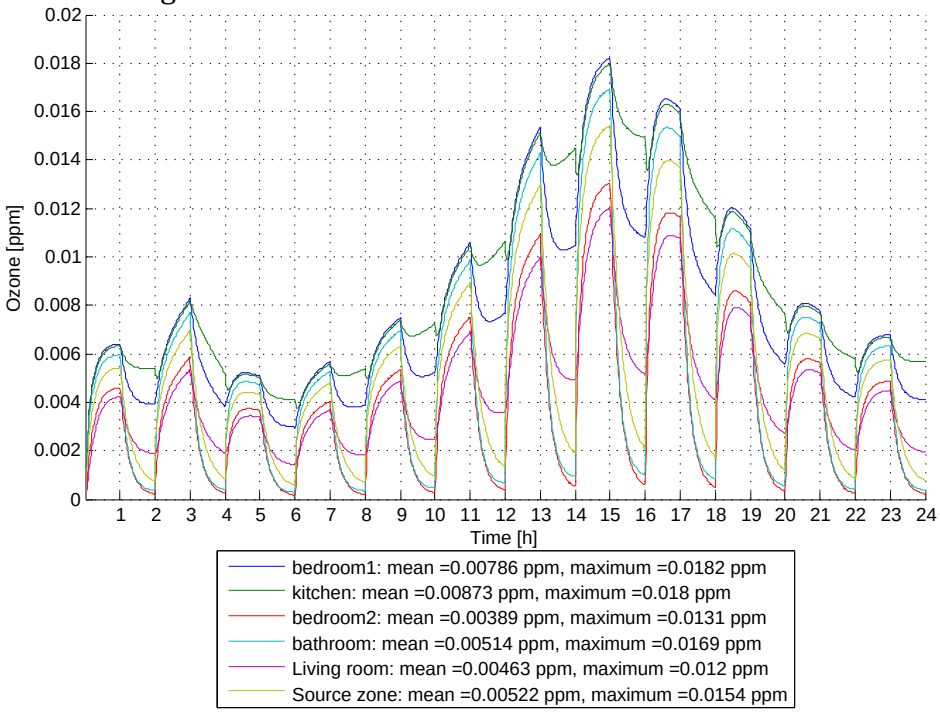


Figure 3.41. Dynamic indoor ozone concentration for: air handling system on 1-hour on/off cycle (AHU on 0-1 h, off 1-2 h, etc.), ambient ozone infiltration, ozone source OFF, high deposition velocity.

The effect of outdoor infiltration on indoor ozone with the ozone source ON (1-hour cycle) is shown in Figure 3.42(Low V_d) and Figure 3.43 (High V_d). Comparing Figure 3.42with Figure 3.40, it can be seen that the ozone concentration follows the dynamics of Figure 3.40 overlaid on the ozone concentration resulting from the in-duct source emissions of ozone. The ozone concentration in all zone decays rapidly when the ozone source is turned off. Even though the deposition velocity in the duct (source zone) is relatively low, the ozone decays more rapidly than in the rooms. This is because the surface-area to volume ratio is much larger in the source zone.

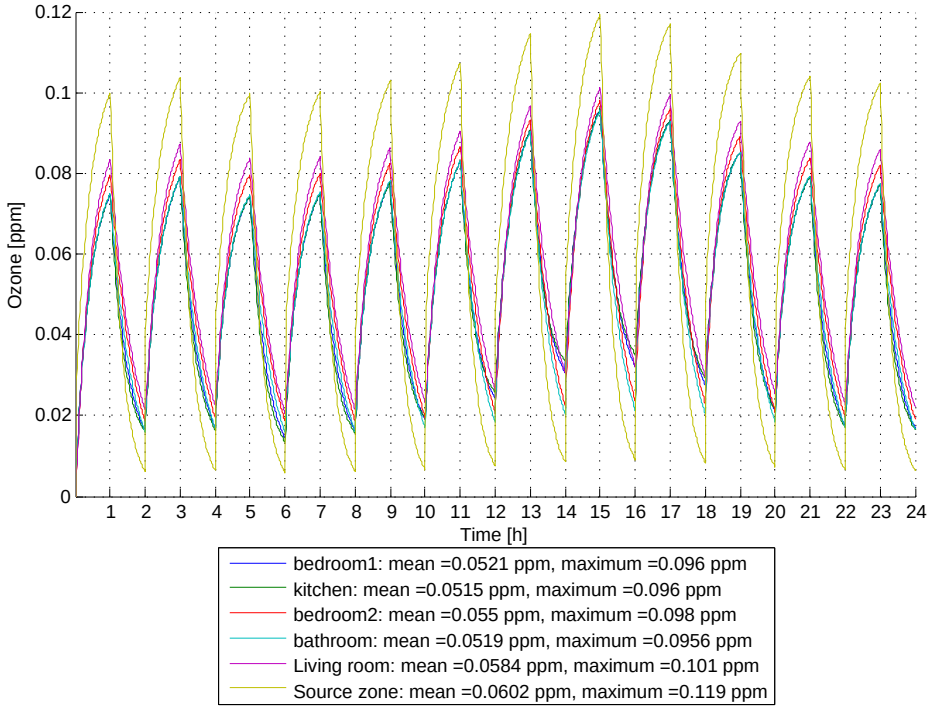


Figure 3.42. Dynamic indoor ozone concentration for: air handling system on 1-hour on/off cycle, ambient ozone infiltration, ozone source on 1-hour on/off cycle (AHU on 0-1 h, off 1-2 h, etc.), (50% duty cycle), low deposition velocity.

A similar effect is shown in Figure 3.44 (Low V_d) and Figure 3.45 (High V_d), with the source ON at all times (compare with Figure 3.42 and Figure 3.43). Note, however, that the source zone (duct) ozone concentration rises to a maximum of 1.5 ppm while the air handler is off.

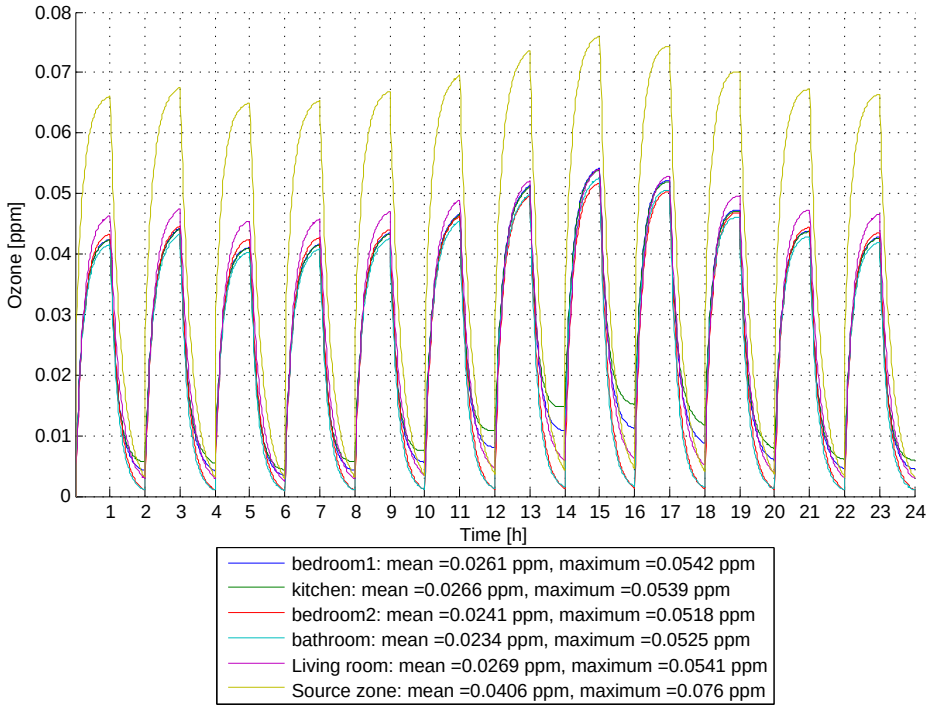


Figure 3.43. Dynamic indoor ozone concentration for: air handling system on 1-hour on/off cycle(AHU on 0-1 h, off 1-2 h, etc.), ambient ozone infiltration, ozone source on 1-hour on/off cycle, high deposition velocity.

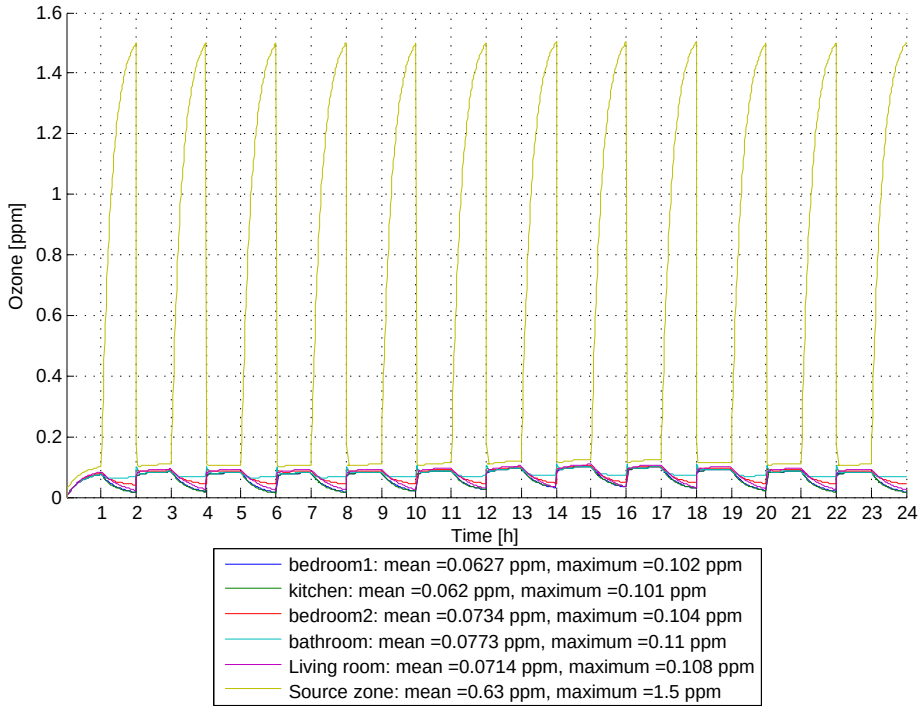


Figure 3.44. Dynamic indoor ozone concentration for: air handling system on 1-hour on/off cycle (AHU on 0-1 h, off 1-2 h, etc.), ambient ozone infiltration, ozone source on at all times, low deposition velocity.

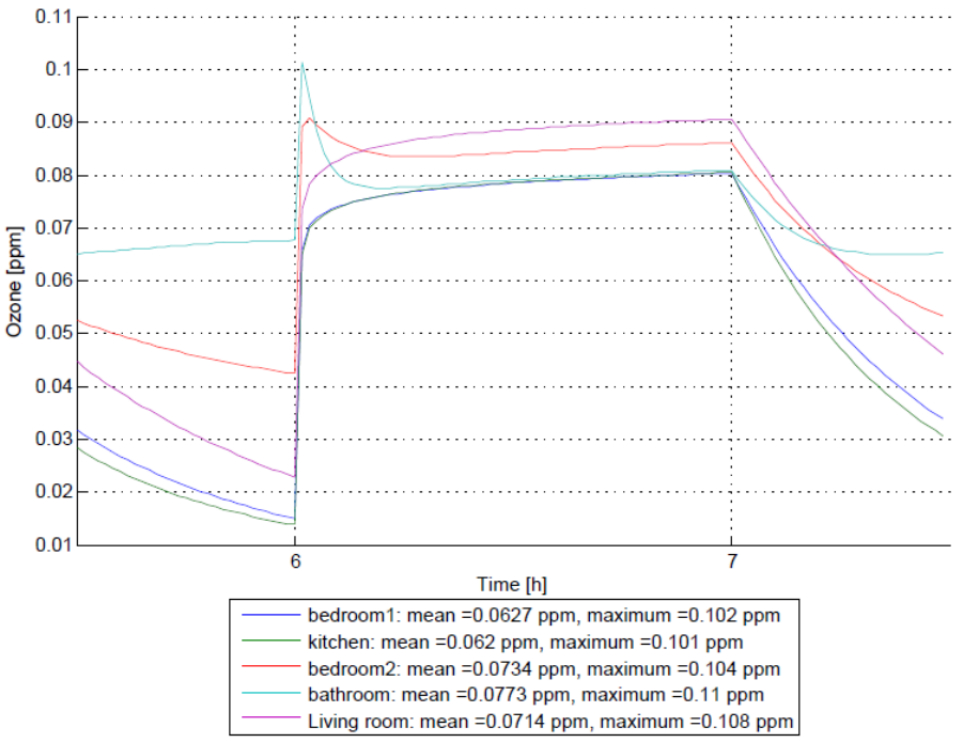


Figure 3.45. Dynamic indoor ozone concentration for: air handling system on 1-hour on/off cycle (AHU on 0-1 h, off 1-2 h, etc.), ambient ozone infiltration, ozone source on at all times, low deposition velocity. (2 hour selection from Figure 3.44 to better show room-specific ozone dynamics)

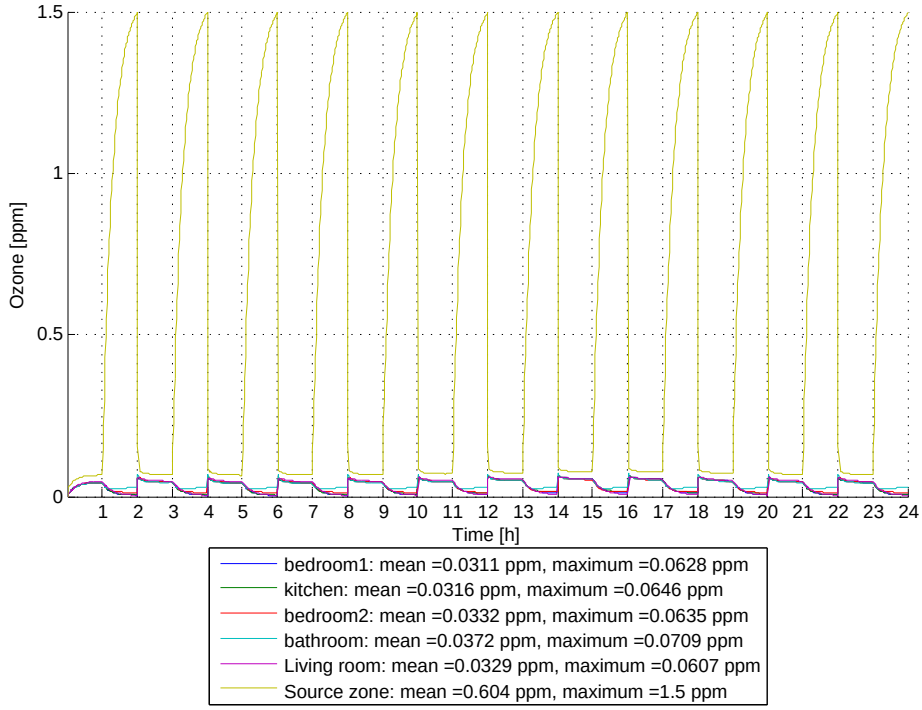


Figure 3.46. Dynamic indoor ozone concentration for: air handling system on 1-hour on/off cycle (AHU on 0-1 h, off 1-2 h, etc.), ambient ozone infiltration, ozone source on at all times, high deposition velocity.

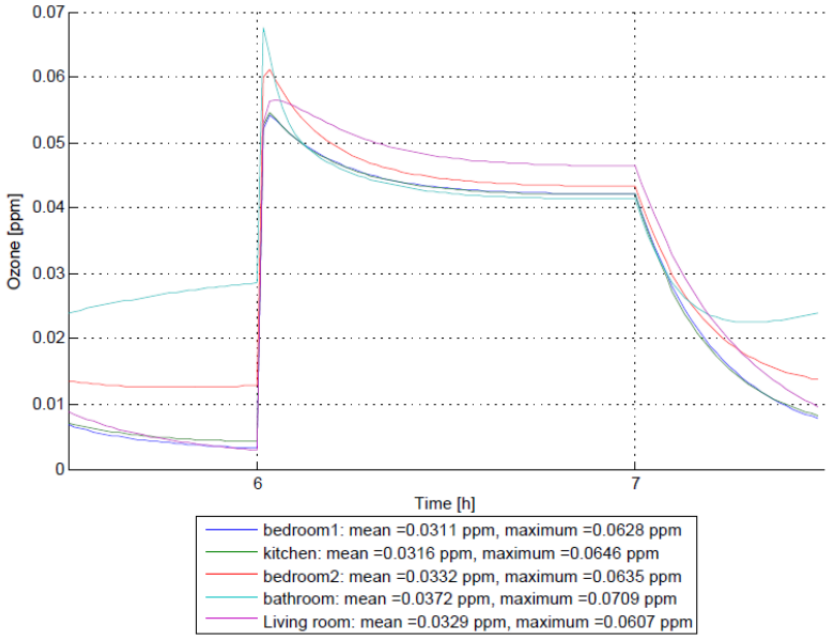


Figure 3.47. Dynamic indoor ozone concentration for: air handling system on 1-hour on/off cycle (AHU on 0-1 h, off 1-2 h, etc.), ambient ozone infiltration, ozone source on at all times, high deposition velocity. (2 hour selection from Figure 3.46 to show room-specific ozone dynamics)

The results for two 20% AHU and source duty-cycle simulations are shown in Figure 3.48 and Figure 3.49(low V_d, no ambient ozone) and Figure 3.50 (low V_d, with ambient ozone). The source zone is not shown for clarity. At 20% duty cycle, the indoor ozone concentration is, on average, considerably less than with 50% duty cycle. Comparing Figure 3.48(20%) to Figure 3.36(50%), the average ozone concentration is approximately 40% of the 50% duty cycle value. A close-up of Figure 3.48 is shown in Figure 3.49. At 20% duty-cycle, the indoor ozone concentration ranges from about 0.010 to 0.026 ppm over a 25 minute period. The dynamics of ambient ozone infiltration are more apparent in Figure 3.50 than Figure 3.42 (50% duty cycle) since the source-induced indoor ozone concentration is much lower. In this case, the maximum indoor ozone concentration rises to 0.047 ppm nearly double that of the case without ambient ozone. Thus, infiltration and the in-duct ozone source are contributing roughly equal amounts of ozone to the building.

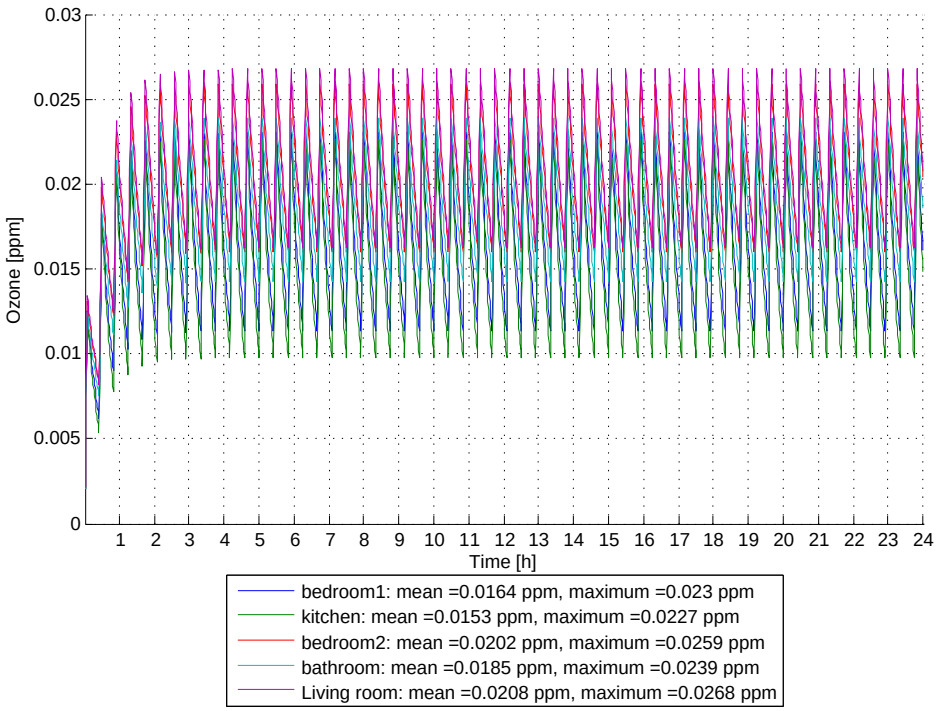


Figure 3.48. Dynamic indoor ozone concentration for: air handling system and source on a 20% duty cycle (5 min on, 20 min off), ambient ozone set to zero, low deposition velocity.

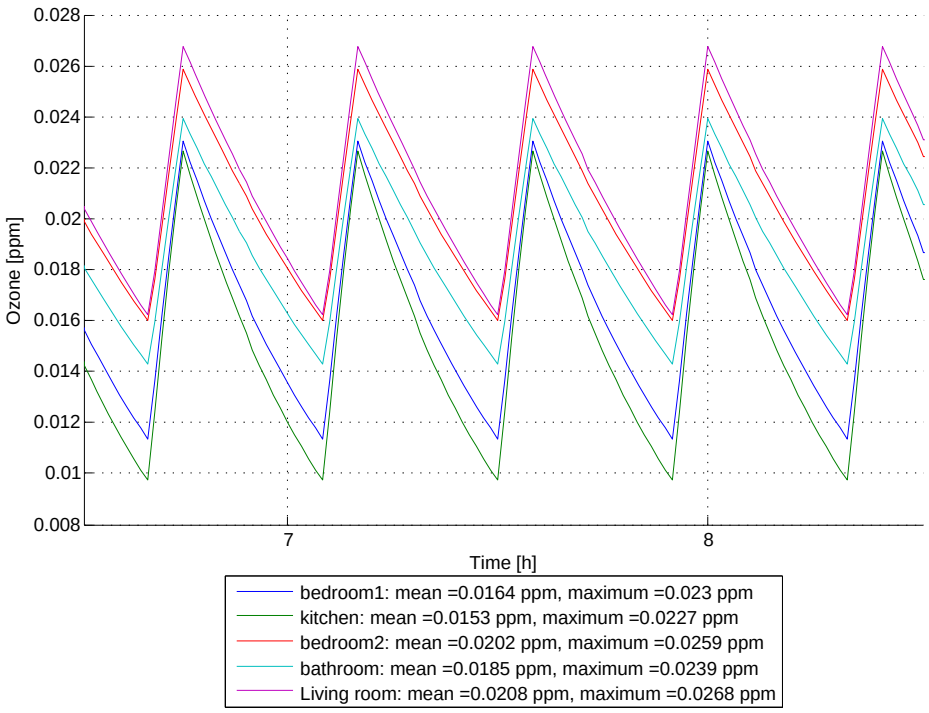


Figure 3.49. Dynamic indoor ozone concentration for: air handling system and source on a 20% duty cycle (5 min on, 20 min off), ambient ozone set to zero, low deposition velocity. (2 hour selection)

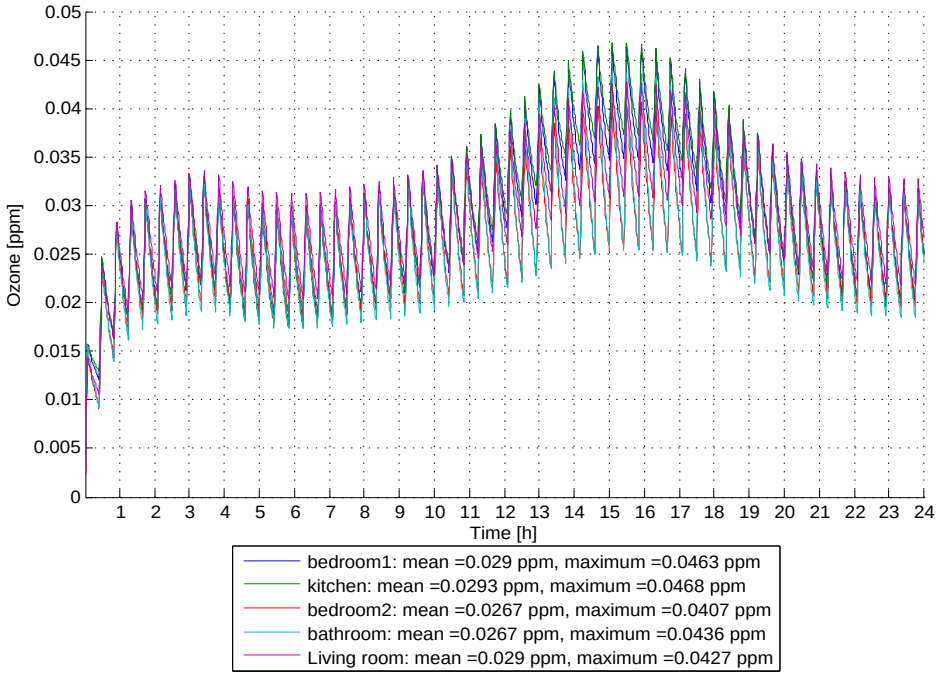


Figure 3.50. Dynamic indoor ozone concentration for: air handling system and source on a 20% duty cycle (5 min on, 20 min off), ambient ozone infiltration, low deposition velocity.

4 Discussion

4.1 Application of Standard Test Method

Although there have not been extensive measurements of ozone emission rates from comparable air cleaners, emission rates of devices tested in this research are generally consistent with those reported in prior literature. Viner et al. (1992) tested two in-duct units that were most similar to Air Cleaner 3 in this work and found emission rates of approximately 18 mg h-1 for one unit and 18 – 29 mg h-1 for the other unit. The apparatus used to test these operated at a much lower flow rate than in the present work, the units were not identified (although there is anecdotal evidence that AC3 and the higher emission unit in Viner et al. (1992) were very similar), and uncertainty was not explicitly quantified so a direct comparison is not possible. Viner et al. (1992) also showed a decline in emission rate with increasing relative humidity, but this trend was not evident in our testing. Bowser et al. (1999) conducted field testing of ozone emission on 15 residential EPs (again generally similar to Air Cleaner 3), and found emission rates that ranged from 13-62 mg h-1. Given the generally larger uncertainties associated with field testing, as well as the range of devices (including many that were well-used at the time of testing), only the general finding of reasonable agreement with the results herein is practical. Given the focus in earlier work on corona-based systems, there are no known comparable emission rates for UV-based systems. This should be interpreted as a major contribution of this effort.

This work also represented one of the few efforts to assess uncertainty in emission rate from in-duct devices. Ozone monitor uncertainty was the largest contributor to uncertainty for almost all of the reported tests, even without the use of a flow nozzle or other similar higher accuracy flow measurement approach. This is a fundamental limitation of trying to test at realistic air flow rates and the consequent small rises in ozone concentration.

An open question is whether the standard should require reporting of the emission rate at a certain flow rate (or at certain flow rates). The benefit of consistency in reporting is that it simplifies comparing different air cleaners as well as allows for a relatively simple regulatory framework if desired. However, different air cleaners are designed for different systems. There is also a wide range of air flow rates in residential HVAC systems depending on the design, operation, and size of the system. One approach would be to report ozone emission rate at a variety of air flow rates (for example, 100 $m^3 h^{-1}$ to represent a system in a very low flow/ventilation only mode, 1000 $m^3 h^{-1}$ to represent a small residential system, 2000 $m^3 h^{-1}$ to represent a medium-sized system, and 3000 $m^3 h^{-1}$ to represent a large system). Such an approach would generally require interpolation/extrapolation from laboratory test results which may lead to uncertainties and it may not be reasonable to report all flows for all air cleaners

because of flow switches or other reasonable sizing guidelines (for example, information provided by manufacturers to HVAC installers). Another approach is to report the ozone emission rate at a single typical air flow rate for the device. As long as the typical reporting flow rate is well defined, this approach may provide for actionable information on likely resulting indoor ozone concentrations, but it becomes difficult to compare different air cleaners.

Another potential regulatory issue involving flow rates is the role of flow switches as they introduce added complexity in assessing ozone emission rates. Some air cleaners had a flow switch that did not permit air cleaner operation unless a certain flow rate was flowing over the device, others did not. On some air cleaners, this switch could only be bypassed by soldering a connection on a circuit board or applying an artificial pressure signal to the switch (e.g., AC 3). Other devices (e.g., AC 6a-b) simply required that the switch be bypassed with a jumper plug included with the device. Still others had no flow switch at all (e.g., AC 2a-c) and operated whether there was flow or not. Thus, any regulatory framework needs to consider the role of such switches in ozone emission. This in turn will require a decision about the state of any flow-switch during testing. The most conservative approach would be to require that any flow switch be bypassed during testing as this will produce a worse-case emission rate. This is not entirely reasonable for an air cleaner such as AC 3, which is really designed to not energize unless there is sufficient air flow. There are also a variety of quality and types of flow switches that complicate such testing. Some devices may be very precise and cut-off at a precisely-determined air flow rate. Other devices, may utilize switches that are strongly affected by temperature, air turbulence or other parameters.

Another issue that may affect regulation of devices is the fact that we observed substantial variation in emission rates between different units of the same manufacturer and model. Some air cleaner tests, such as ASHRAE Standard 52.2, allow a manufacturer to choose what results to provide. This approach would lead to emission rates that varied by as much as a factor of two for some of the tested air cleaners (e.g., AC 2a and 2c). This sample variation is generally an issue in the testing of any device, and the results presented in this report suggest that tests on multiple models and a framework for integrating the results into testing data be considered.

4.2 Comparison of field results with prior literature

Although not much literature exists on ozone emissions and resulting field concentrations from in-duct air cleaners, some comparisons can be made. In this research, use of devices resulted in incremental increases in ozone concentrations ranging from below detection to nearly 170 ppb. The current study was dominated by devices that included ultraviolet lights, with only two plate-and-wire style electrostatic precipitators. Bowser (1999) studied 15 homes with in-duct "electronic air cleaners" (type not specified, but probably plate-and-wire electrostatic precipitators) and reported ozone emission rates ranging from 13 to 62 mg h^{-1}. They observed indoor concentrations of ozone, but were not able to

ascribe what fractional increase was due to device emissions. The highest indoor ozone concentration during testing of electrostatic precipitators was 25 ppb with an outdoor concentration of 35 ppb. It is not possible to make a prediction of the incremental increase from the information available. However, it is likely that ozone increased to some degree because the typical indoor to outdoor ratio (~0.2) is much lower than that observed by Bowser (1999). The in-field emission rates for the two EP devices tested in the current study ranged from 3 to 48 mg h^{-1}, intersecting with those in the study by Bowser. In contrast, Emmerich and Nabinger (2000) tested two electrostatic precipitators in a full-scale test house. One device increased the indoor ozone concentration to 200 ppb with an outdoor concentration of 22 ppb. This house was small and had a fairly low air exchange rate of 0.22 h^{-1}. To determine the emission rate, they used an ozone decay rate typical of a furnished office (3.7 h^{-1}), although it is possible to roughly estimate the actual decay rate from the decay of ozone shown in Figure 10 of that report (we estimate 1.3 h^{-1}). They report an emission rate of 5.4×10^{-4} m^3 h^{-1} or about 1100 mg h^{-1}. This is much greater than observed for similar devices in the current study. Emmerich and Nabinger observed no ozone production from a second unit. Overall, this demonstrates that devices, even of the same style, can produce ozone over a wide range of emission rates.

The bulk of the devices tested in the current research produced ozone via ultraviolet light irradiation of the air stream. It is well understood that mercury-vapor lamps operating in the UV-C range, with some fraction of the photon energy emitted at 185 nm, will produce ozone through oxygen photolysis and recombination of oxygen radicals with oxygen molecules. These lamps can be used to irradiate the air with the intent of generating ozone, killing microorganisms (germicidal) or activating titanium dioxide for photocatalytic oxidation. Although some studies have measured the output of in-duct systems that incorporate UV lamps in laboratory settings (Chen et al. ,2005; Jeong et al., 2005; Kadribegovic et al., 2011), we were not able to identify any that measured ozone emission rates or resulting indoor ozone concentrations in field homes or commercial settings.

4.3 House conditions, reactivity and impact on resulting ozone concentrations

The Tulsa and California field tests indicate that in-duct ozone air cleaners can produce widely varying O_3 concentrations in homes. The variation is likely driven by a combination of environmental and device factors. The environmental factors include temperature, O_3 reactivity of specific indoor spaces, condition of the HVAC system and its operation, and housing characteristics that affect air and O_3 exchange. Experience in the Tulsa test house indicated that surface reactivity can diminish rapidly when exposed to higher concentrations of ozone. This is consistent with laboratory research showing that surfaces "age" with continued ozone exposure (e.g. Morrison and Nazaroff, 2002). Device factors may be related to the design and quality of construction of the devices. At least one device did not work properly or consistently. The Air Zone Air Duct 2000 exhibited erratic output and the California Test House 3 experience suggests the device is prone to failure. Ultraviolet light lamps have limited life spans and light intensity may diminish over the time.

Likewise, the performance of catalytic materials that are intended to generate various oxidizing species may change with time as the device is exposed to dust and other contaminants.

4.4 Comparison of laboratory and field emission rate results

Broadly, field and laboratory ozone emission rate results correlate for models tested in both settings. Those with higher emission rates in the lab were observed to have estimated emission rates that were higher. However, the estimates from the field were, on average, higher than those in the lab. This could be due to operating at different conditions than in the lab and/or the highly uncertain nature of estimated emission rates in the field. Several models were tested using the standard laboratory emission rate test and in field tests including the RGF Guardian Air, the Honeywell F300 electronic air cleaner, the activTek INDUCT 2000, the AirZone Air Duct 2000 and the HVAC UV 560. Results comparisons are shown in Figure 4.1.

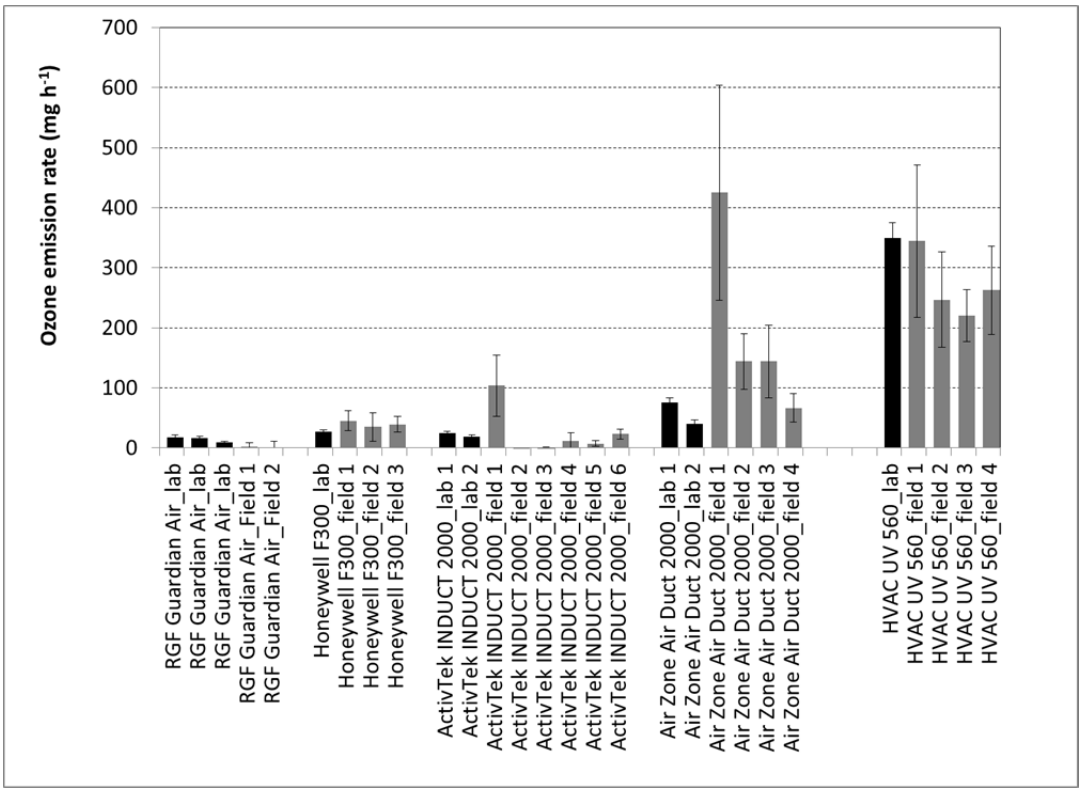


Figure 4.1. Comparison of ozone emission rates measured using the Standard Test Method (lab) and estimated from field data (Field).

4.5 Comparison of incremental increase in ozone concentration vs predicted

Using the same equation, it is possible to estimate the incremental increase in ozone that we would anticipate based on the laboratory emission rates and the field measured air exchange rates and ozone decay rates. While this is simply a rearrangement of the equation used to compare emission rates, it tells a slightly different story. Shown in Figure 4.2 is a comparison of 1) the average estimated indoor concentration, using lab emission rates and field ORR measurements with 2)

the measured incremental increase in the indoor ozone concentration. The ozone concentration that results in indoor air while using these devices increases with increasing emission rate, as anticipated and is generally consistent with the predicted value. Use of the Air Zone device appears to result in the largest discrepancy between predicted and measured, but this device also was observed to exhibit a great deal of variable ozone output and was thought to "fail" several times in lab and field tests. The RGF unit has such a low emission rate that increases in the ozone concentration in the field was difficult to discern.

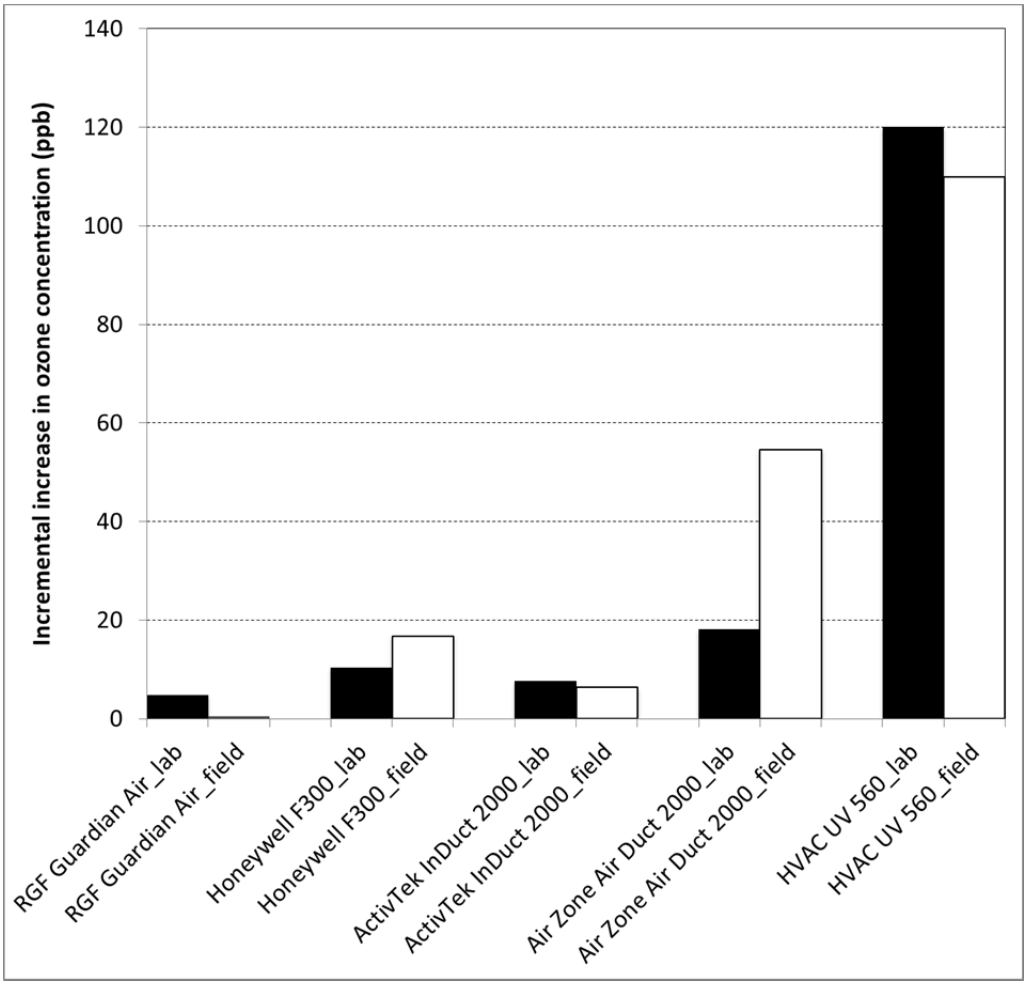


Figure 4.2. Comparison of 1) predicted ozone concentration based on laboratory measured emission rate and 2) average incremental increase measured in field sites.

4.6 Use of theoretical models to predict indoor air concentrations

The well-established mass-balance model of indoor air quality, for both steady-state and dynamic multi-compartment systems, showed that building characteristics will significantly influence the impact of these devices on indoor ozone concentrations. A small, low-reactivity, low-air exchange rate building can an experience incremental increase in the indoor concentration ten or more times greater, for the same emission rate, than what would be predicted to develop in a large, reactive, well ventilated building. Emission rates will not scale directly with the resulting

incremental increase in the ozone concentration for all homes. Therefore, any attempt to establish a regulatory limit on the emission rate, based on the indoor ozone concentration, must consider the heterogeneity of building characteristics and will likely need to focus on the more "at risk" buildings that are smaller and have lower ventilation rates.

The comparisons shown in the prior two sections are a direct use of the indoor air quality (mass balance) model. What was established was broad consistency between laboratory, field and model predictions. However, given the realities of field research, a great deal more uncertainty would be expected (and is observed) and deviations from predicted emission rates or incremental increases in ozone concentration are to be expected. Despite these uncertainties, Indoor concentration predictions using such a model resulted in predicted values within a factor of 3. Thus regulatory use of these kinds of models is appropriate, where care is taken to note the heterogeneity of building types, installation variability, occupant activities and other things that will reduce the precision of direct prediction of outcomes for individual buildings.

4.7 Applying building simulation models to measured ozone emission rates

Laboratory and field measurements resulted in emission rates ranging from undetectable (or below method quantification limits) to greater than 400 mg h^{-1}. Building simulations suggest that the a typical California home (termed the Standard House) would require an emission rate of greater than 150 mg h^{-1} to experience an indoor incremental increase in the ozone concentration of 50 ppb or more. However, a much lower emission rate is required to increase the ozone concentration by 50 ppb in the At Risk House (27 to 55 mg h^{-1} for an air exchange rate of 0.1 to 2 h^{-1} respectively). Only two devices were observed to have emission rates greater than 150 mg h^{-1} and both were intentional ozone generators. In laboratory tests, three devices had emission rates greater than 27 mg h^{-1} for at least one set of conditions. In field tests, estimated emission rates for four devices rose above 27 mg h^{-1} for at least one set of conditions. Note that only 2 of these devices were intentional ozone generators. Therefore, devices not intended to generate ozone emit ozone at rates (based on field results) that could increase indoor ozone concentrations by 50 ppb in homes that are small, well-sealed and are relatively unreactive with ozone.

4.8 Other impacts of the use of ozone-emitting in-duct air cleaners

It is anticipated that the use of ozone emitting in-duct devices would result in adverse outcomes above and beyond the direct increase in indoor ozone concentrations. Many laboratory, field and theoretical studies show that ozone reactions in indoor environments produce irritants and odorous aldehydes and carboxylic acids (Weschler et al., 1992; Morrison et al., 1998; Wolkoff et al., 1999; Reiss et al 1995; Morrison and Nazaroff, 2002; Wang and Morrison 2006; Wolkoff et al., 2006; Coleman et al., 2008; Weschler et al., 2007; Anderson et al., 2007), aerosols

(Weschler and Shields, 1999; Hubbard et al., 2005; Waring et al., 2008), short-lived highly-reactive free radicals (Vibenholt et al., 2009).

Highly reactive indoor environments reduce ozone concentrations but will tend to have higher reaction product concentrations. The reduction in indoor ozone as characterized by the decay rate (k_d or *ODR*) is due entirely to reactions taking place on surfaces (mainly) and in the gas phase. The higher the observed decay rate, the more ozone will be removed by reaction and the lower the resulting indoor air concentration (all else being equal). These reactions result in products, many of which are problematic as noted above. Therefore, the advantage of reduced ozone in a highly reactive environment is offset by increased air concentrations of unwanted chemical byproducts. It is unclear whether this replacement is advantageous or more dangerous (Weschler, 2004; Weschler, 2006`)

Given the heterogeneity of indoor environments, it is not possible to predict the impact an in-duct ozone emitting device on a specific indoor environment without complete information about surface types, reactive chemicals in air, building related parameters, infiltrated reactants and aerosols, emissions from combustions sources and so forth. However, some broad generalizations can be made. For most indoor environments, ozone is removed primarily by heterogeneous (surface) reactions (Weschler, 1989). Laboratory and field studies of typical indoor surface materials show, broadly, that these reactions generate gas-phase aldehydes, ketones and carboxylic acids at molar yields typically ranging from about 0.2 to 0.8 (molar yield is defined as the moles of product generated per mole of ozone consumed by reaction). One way of looking at this is that, for every 10 ppb reduction in ozone due to surface reactions, we should observe an increase of 2 to 8 ppb of products. Note that concentration units of ppb are based on molar ratios.

To illustrate the impact of this chemistry, the single-compartment model (section 2.4) can be applied. For example, using the building parameters associated with the Standard House, with an air exchange rate of 0.5 h^{-1}, the ozone concentration as a function of source emission rate is as shown in Figure 4.3. The Standard House combined removal rate (decay rate, k_d) is 4 h^{-1}. By running the model with a decay rate equal to 0 h^{-1}, the indoor ozone concentration can be simulated for the theoretical situation in which there is no chemical conversion of ozone to products. By subtracting the results with k_d=4 h^{-1} from the results where $\underline{k_d}$ = 0 h^{-1}, and multiplying by a middle value of molar yield (0.5), an estimate of the incremental increase in the concentration of ozone reaction products can be calculated. This is also shown in Figure 4.3. For this situation, the incremental increase in the indoor concentration of ozone reaction products (in ppb units) is anticipated to be greater than that for ozone itself, because much more ozone has been reacted away to generate the reaction product than remains in the room.

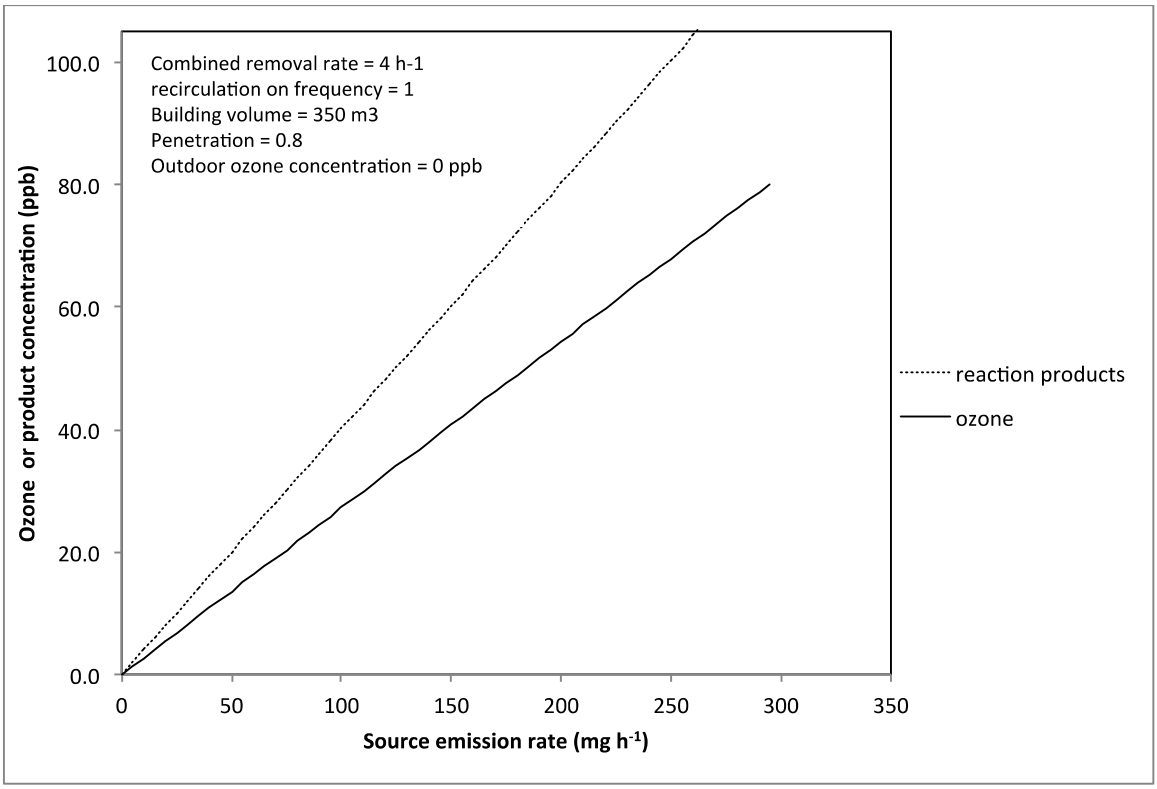


Figure 4.3 Ozone and reaction product concentrations resulting from the use of an ozone emitting device in the Standard Home.

5 Summary and Conclusions

The ozone emission rate and the increase in indoor ozone concentrations from the use of electrically connected in-duct air cleaners were studied in this research. A combination of laboratory studies, test standard development, field studies and theoretical analyses were applied.

5.1 Laboratory test method and device testing

5.1.1 Test method

A detailed Standard Test Method was developed in parallel with the construction and development of a laboratory test apparatus. This test method and apparatus allow for the measurement of the ozone emission rate from electrically connected in-duct devices. The emission rate is derived from the product of the flowrate and the increase in the ozone concentration across the device while operating under a typical range of flow conditions in residential HVAC systems. The method allows for open loop and closed loop operation and requires measurement of flowrate, ozone concentrations at two points, temperature, humidity and device electrical power draw. Thorough testing of the laboratory test apparatus found a method quantification limit (MQL) for the ozone emission rate to be 2.3 mg h^{-1}.

5.1.2 Device testing

Eleven electrically connected in-duct air cleaners (seven models) were tested on the laboratory test apparatus using the Standard Test Method. Emission rates ranged from less than the MQL to greater than 100 mg h^{-1}. Most devices tested incorporated ultraviolet light lamps which likely accounts for the ozone production. One electrostatic precipitator style air cleaner (Honeywell F300) emitted ozone at a rate of 8 to 18 mg h^{-1}. The highest emitter was the Air Duct 2000 with the highest emission rate measured at 110 mg h^{-1}. The ozone emission rate was not sensitive to flowrate for most devices. Two models (Air Zone Air Duct 2000 and the activTek INDUCT 2000) exhibited some flow sensitivity. The emission rate from the Air Zone device more than doubled (44 to 110 mg h^{-1}) over the range of flows used (750 to 2300 m^3 h^{-1}). The activTek device exhibited the opposite relationship: lower emission rate at higher flowrate. Some temperature dependence of the emission rate was observed for the Honeywell F300 electrostatic precipitator.

5.2 Field tests

Field tests of electrically connected devices were completed in 7 residential buildings (1 in Tulsa, OK, 6 in the Davis/Sacramento area of California). One commercial unit was tested in a classroom. The incremental increase in the ozone

concentration due to the operation of these devices ranged from undetectable to as high as 170 ppb operated normally and tested with the standard method. Similarly, estimated emission rates ranged from undetectable to greater than 400 mg $h^{-=1}$. Two models (Air Zone Air Duct 2000 and HVAC UV 560) increased the ozone concentration in field residences by greater than 50 ppb. Both devices are intentional ozone generators based on product literature. The HVAC UV 560 appears to increase ozone output at higher temperatures and the peak ozone concentration in a California test house was greater than 200 ppb when the HVAC heater was on. Air exchange rates and ozone decay rates measured in test houses were within the reported range for measurements in other field studies.

5.3 Building ozone concentration simulations

The application of a standard "mass-balance" model of indoor air concentrations of ozone demonstrated that use of ozone-emitting, electrically connected in-duct air cleaners can raise ozone concentrations in buildings typical of residences in California. General trends predicted were that the incremental increase in the average indoor ozone concentration would increase with 1) higher emission rates, 2) smaller buildings, 3) lower air exchange rates and 4) the presence of lower-reactivity surfaces. For a typical (Standard) house, the model predicts that an emission rate of approximately 190 mg h^{-1} would raise the indoor concentration by about 50 ppb. For an "at risk" house, or one that has characteristics that enhance indoor ozone concentrations, 50 ppb could be achieved with emission rates as low as 27 mg h^{-1}. Outdoor ozone infiltration contributes approximately 17% of indoor ozone for the Standard House, and under reasonable conditions it is possible for changes in the air exchange rate to have no effect on indoor concentrations of ozone.

A dynamic (time-dependent) multi-zone model was also applied to probe the effect of spatially segregated compartments (rooms), on-off operation of the air handling unit and the infiltration of outdoor ozone. For devices that can remain on when the air handler fan is not operating, this model showed that separate rooms can have very different indoor air concentrations due to differential pressure inducing low flow through the ozone source zone out of some rooms and into others. The source zone (duct and air handler volume) is predicted to rise to over 1.5 ppm in these simulations. For lower-reactivity buildings, indoor concentrations over 50 ppb are achieved in all rooms with the air handler in operation. Operation of the air handler results in very dynamic indoor ozone concentrations that can rise from near zero to greater than 100 ppb in just a few minutes. For 100 mg h^{-1} devices tied to the operation of the air handling system, the model predicts typical indoor concentrations ranging from 15-20 ppb for a 20% duty cycle and 35-50 ppb for a 50% duty cycle.

5.4 **Conclusions**

The use of electrically connected in-duct air cleaners of the types studied in this research can increase indoor concentrations of ozone. Some devices had lab-measured ozone emission rates that were predicted to increase indoor ozone concentrations by 50 ppb or more. In field studies, two devices increased ozone concentrations by more than 50 ppb. Even allowing for the uncertainty inherent in measurement methods to make these determinations, laboratory, field and theoretical analyses were broadly consistent in showing that in-duct devices can significantly increase indoor room air ozone concentrations. If a regulatory goal is to reduce the potential for occupants to be exposed to excessive indoor ozone concentrations, then a theoretical approach can be reasonably applied to determine a laboratory-measured emission rate limit for these devices. Small houses were chosen for field studies because it is in these houses that ozone emission will result in the highest indoor ozone concentrations. Therefore, lower incremental increases in the ozone concentrations would be anticipated in larger, modern homes.

Overall, this research tells a consistent story: devices that emit ozone in buildings have the potential to raise indoor ozone concentrations above current California limits. A laboratory test method generates ozone emission rates that can, reasonably, be incorporated into mass balance models to predict the potential increase in indoor ozone concentrations. Therefore it is possible to establish a limit on the emission rate of in-duct air cleaners if the State of California sets a concentration limit and establishes what type of building they believe would provide an emission rate that is sufficiently protective of Californians.

While it is possible to set a standard, it is still unclear just how many highly emitting devices are installed or have the potential to be installed. An effort was made to determine which devices were popular among installers. However, this research did not generate a comprehensive list of devices that are, or have the potential to be, installed in California homes. Representatives from most HVAC companies (sales, installation, service) indicated that they would not install devices that purport to generate ozone or radicals. In this research, the ozone generators were the highest emitters. Further, some companies will not sell their devices in California, even though there is no current regulation covering in-duct air cleaners. These facts, however, do not necessarily mean that Californians are not exposed to excessive ozone concentrations from highly emitting in-duct air cleaners. Some devices can be ordered directly from manufacturers and installed by homeowners. From our testing, we observed erratic behavior of some devices, resulting a very wide range of ozone emission rates. Even devices not claiming to emit ozone could, unintentionally emit too much. Finally, this research did not comprehensively test all possible in-duct devices, and new devices have and will come on the market.

We do not recommend that further research take place on the impact of the devices on California homes. We believe it is clearly established that increasing ozone

emissions increases ozone concentrations and that the resulting indoor concentrations can be predicted, within reason, for California building types. However, we do recommend the State of California make an effort to better understand the market of these devices and determine the potential for their installation, especially in smaller homes that have low air exchange rates. This will be key to establishing risk to California residents. We further recommend that more testing be done on multiple devices of the same model (consistency in manufacture), they be tested under adverse conditions (e.g. very high temperatures in attic spaces), they be tested for erratic behavior and establish how this impacts the Standard Test Method, and that they be tested over long periods in field sites to establish how age and real-world soiling affects performance.

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7 List of inventions and publications

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8 Glossary of Terms, Abbreviations, and Symbols

AER	Air exchange rate	h^{-1}
AHU	Air handling unit	
A_i	Area of surface *i*	m^2
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers	
C	Indoor ozone concentration	ppb, ppm or $\mu g\ m^{-3}$
CFM	Cubic feet per minute	$ft^3\ min^{-1}$
C_i	Concentration of reactive species i	ppb, ppm or $\mu g\ m^{-3}$
CFL	Compact fluorescent light	
C_o	Outdoor ozone concentration	ppb, ppm or $\mu g\ m^{-3}$
CO_2	Carbon dioxide	
COV	Coefficient of variation	
CRTM	California residential test methd	
EEF	Electrically enhanced filter	
EP	Electrostatic Precipitator	
HEPA	High efficiency particle arresting (or High efficiency particulate air)	
HVAC	Heating, ventilation and air conditioning system	
IEST	Institute of Environmental Sciences and Technology	
k_d	Ozone decay rate	h^{-1}
k_i	Kinetic rate constant for species i	$h^{-1}\ \mu g^{-1}\ m^3$
MQL	Method quantification limit	Parameter specific
ORR	Ozone removal rate	h^{-1}
ODR	Ozone decay rate	h^{-1}
OER	Ozone emission rate (effective for installed device)	$mg\ h^{-1}$
O_3	Ozone	
P	Penetration factor, building shell	--
P_x	Penetration factor, x= recirculation system, r; return grill, RG; return duct, RD; air handler, AH; filter, F; supply duct, SD; supply grill, SG	--
		--
PCO	Photocatalytic oxidation	
ppb	Parts per billion	
ppm	Parts per million	

PTFE	Polytetrafluoroethylene	
S	Source emission rate	mg h^{-1}
STM	Standard test method	
UL	Underwriters Laboratory	
UV	Ultraviolet	
V	Volume	m^3
η	Overall removal efficiency of duct/filter/HVAC	--
λ	Building air exchange rate	h^{-1}
λ_r	Recirculation air exchange rate	h^{-1}

9 Appendices

9.1 Device descriptions

Table 9.1. Devices tested in laboratory and/or field

Air Cleaner	Product	Technology
1	Dust Free Bio Fighter Lightstick	Ultraviolet light
2a	Guardian Air by RGF #1	Photohydroionization
2b	Guardian Air by RGF #2	Photohydroionization
2c	Guardian Air by RGF #3	Photohydroionization
3	Honeywell F300 Electronic Air Cleaner	Electrostatic Precipitation
4	Lennox PureAir Air Purification System	Photocatalytic Oxidation
5a	activTek INDUCT 2000 #1	Ultraviolet light
5b	activTek INDUCT 2000 #2	Ultraviolet light
6a	Air-Zone Air Duct 2000 #1	Ozone generator
6b	Air-Zone Air Duct 2000 #2	Ozone generator
7	APCO Fresh-aire	UV / PCO / Carbon
8	HVAC UV 560	Ultraviolet light
9	Trane Clean Effects	Electrostatic Precipitation
10	Trane Catalytic Air Cleaning system	UV/PCO/ MERV 13

Dust Free Bio Fighter Lightstick
Description: Germicidal ultraviolet light bulb inserted perpendicular to flow direction of duct.
Specifications from manufacturer:

Dimensions: 24V: 4.75"L x 2.25"W x 2"H.
Bracket: 1.75"L x 2.25"W x 3.5"H.
Power: 24V, 50/60Hz.
Amps: 14" lamp - 1.1A. 16" lamp - 1.5A.
Weight: Less than 2 lbs.
Lamp Life: 9000 hours continuous operation.
Ozone Generation: Optional.
Warranty: 5-year ballast. 1-year lamp.
Model number: Bio-Fighter Lightstick

Product claims, in brief: From product literature, "UV-C light emitted by the Bio-Fighter® penetrates the cell walls of the microbe, damaging its genetic structure by severing the bonds in the DNA strand. The affected microbe is neutralized."
Product/manufacturer website: http://www.dustfree.com/products/uv-purification/bio-fighter-lightstick

Figure 9.1. Bio-Fighter Lightstick image from product literature.

RGF Environmental Group, Guardian Air
Description: Ultraviolet light bulb surrounded by a perforated sheath of unknown material. Sheath and bulb are inserted perpendicular to the flow direction of duct, typically downstream of air handler and filters.
Model number(s):
Product claims, in brief: device is described as applying advanced oxidation technologies by producing hydroperoxides that deactivate microorganisms. From product literature, "The Guardian Air by RGF® is designed to eliminate sick building syndrome risks by reducing odors, air pollutants, VOCs (chemical odors), smoke, mold bacteria and viruses*. The HVAC-PHI Cells are easily mounted into air conditioning and heating systems air ducts where most sick building problems start. When the HVAC system is in operation the HVAC-PHI Cell creates an Advanced Oxidation Process consisting of: Hydro-peroxides, super oxide ions and hydroxide ions. All are friendly oxidizers. By friendly oxidizers we mean oxidizers that revert back to oxygen and hydrogen after the oxidation of the pollutant."
Product/manufacturer website: http://www.rgf.com/index.cfm

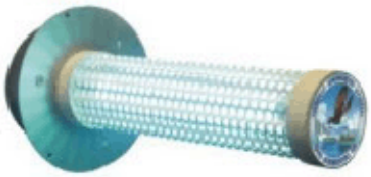

Figure 9.2. RGF Guardian Air image from product literature.

Honeywell F300 Electronic Air Cleaner
Description: Electronic air cleaner (electrostatic precipitator with charge wire and particle collection surfaces).
Product claims, in brief: Captures up to 99% of airborne particles.
Specifications (selected):
Fractional Efficiency
Efficiency Ratings: Efficiency ratings are based on American Society of Heating, Refrigerating and Air
Conditioning Engineers Standard 52.2-1999. Efficiency ranges are defined for small particles, E1 =.3 to 1.0
micron; medium particles, E2 = 1.0 to 3.0 microns; and large particles, E3 = 3.0 to 10.0 microns.

Fractional Efficiency With and Without Postfilter.
With Postfilter Without Postfilter
E1 = Up to 81% at 492 fpm. E1 = Up to 73% at 492 fpm.
E2 = Up to 93% at 492 fpm. E2 = Up to 88% at 492 fpm.
E3 = Up to 99% at 492 fpm. E3 = Up to 95% at 492 fpm.

Temperature Rating
Operating Ambient:
40° to 125°F (4° to 52°C).
Temperature of Airflow Through Cells:
40° to 125°F (4° to 52°C).
Maximum Cell Washing Temperature:
220°F (140°C).
Storage and Shipping Ambient:
-40°F to +140°F (-40°C to +60°C).

Electrical Ratings
Voltage and Frequency:
Models available for 120V, 60 Hz., 240V, 60Hz.
120V models can be converted in the field to
240V, 60 Hz or 220/240V, 50 Hz with the 203365A
Conversion Kit.
Power Consumption:
One cell models: 22 W maximum
Two cell models: 36 W maximum.
Current Draw: See Table 2.
Ionizer Voltage: 8150 Vdc.
Collector Voltage: 4075 Vdc.

Manufacturer/product website:
http://yourhome.honeywell.com/home/Products/Air+Cleaning/Whole-House+Electronic/F300.htm

Figure 9.3. Honeywell F300 Electronic Air Cleaner image from product literature.

Lennox PureAir Air purification system
Description: Combination system that includes Merv 9 pleated filter and a photocatalytic surface activated by ultraviolet lamps (UV-A).

Specifications:
DIMENSIONS:
Model PCO-12C: 29" L x 11 5/8" W x 19 1/2" H
(737mm x 295mm x 495mm)
Model PCO-20C: 29" L x 11 5/8" W x 23 7/8" H
(737mm x 295mm x 606mm)
WEIGHT:
Model PCO-12C: 54 lbs.(24 kg.) Installed
67 lbs.(30 kg.) Shipping
Model PCO-20C: 62 lbs.(28 kg.) Installed
76 lbs.(34 kg.) Shipping
ELECTRICAL:
Model PCO-12C: 120V, 1.6 Amps, 60Hz
Model PCO-20C: 120V, 2.4 Amps, 60Hz
Line Voltage: 108V-132V (If unit operates above
128V, a reduction in lamp life on the order of 10 -
15 may occur.)
POWER CONSUMPTION:
Model PCO-12C: 192 Watts
Model PCO-20C: 288 Watts
OPERATING ENVIRONMENT:
0°F - 140°F (-18°C - 60°C) Outside of duct.
10 -60 relative humidity. (PCO has optimal performance
at 50 relative humidity.)
PLEATED FILTER EFFICIENCY:
Minimum Efficiency Rating Value - MERV 9. Tested
to ASHRAE Standard 52.2.

Product claims, in brief: "The PureAir™ air purification system helps to significantly reduce levels of airborne volatile organic compounds, cooking odors, common household odors, airborne dust particles and mold spores, and pollen in residential spaces. The PureAir™ air purification system includes a MERV 9 Pleated Filter, UVA lamps, and a Metal Insert that is coated with a titanium dioxide catalyst. As air enters the system, a percentage of airborne particles and bioaerosols, such as mold and bacteria, larger than .3 microns are captured by the pleated filter. The smaller airborne particles, odors, and chemicals continue through the system. The UVA lamp activates the catalyst on the Metal Insert. The catalyst combines with water vapor in the air to form hydroxyl radicals that destroy a percentage of the remaining odors and chemicals."

Manufacturer/product website: http://www.lennox.com/products/indoor-air-quality-systems/PureAir/

Figure 9.4. Lennox PureAir image from product literature.

activTek INDUCT 2000

Description: Ultraviolet light with possible photocatalytic surface. Probe inserts perpendicular to direction of air flow.

Specifications:

electrical	100/277 VAC, 50/60 Hz | .17A 19 watts
mechanical	UV bulb monitoring system installed | Safety interlock switch installed
dimensions	9.62"H x 9.62"W X 11.25" D | 24cm L x 24.5cm W x 28.5cm D
weight	3 pound | 1.2 kilograms
coverage	up to 2000 square feet
max temp	<200°F

Product claims, in brief: "The activTek INDUCT 2000 utilizes tested ActivePure® technology to substantially reduce odors, visible smoke in the air, and treat contamination on surfaces."

Manufacturer/product website:
https://www.activtek.net/CatalogProduct.aspx?ProductId=US40663B

Figure 9.5**. activTek INDUCT 2000 image from product literature.**

Air-Zone Air Duct 2000

Description: Ultraviolet light that acts as an ozone generator.
Product claims, in brief: Purifies air and removes odor using ozone. Features a variable ozone output from 80 to 2000 mg/h using dial on front of device.
Specifications: none identified in product literature.
Manufacture/product website: http://www.air-zone.com/airduct2000.html

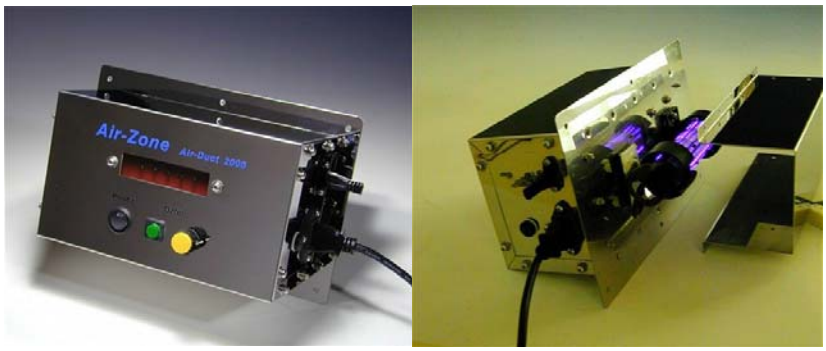

Figure 9.6. Air-Zone Air-Duct 2000 images from product literature.

APCO Fresh-aire
Description: Photocatalytic surface (TiO_2) activated by ultraviolet light bulb. Bulb and catalyst surface inserted perpendicular to direction of flow.
Product claims, in brief: "The Fresh-Aire UV APCO is installed in the ductwork of your central air system and is designed to help reduce airborne odors, toxic chemical vapors, germs and mold in your home. The APCO system (Advanced Photocatalytic Oxidation) represents an entirely new type of air purifier. The combination of germicidal UV light and activated carbon cells inside APCO make it uniquely effective at reducing volatile organic compounds in the air without producing any harmful ozone. VOCs cause odors and include toxic chemical vapors like formaldehyde and toluene."

Specifications:
UV Lamp Standard 100% 254 NM
Germicidal UV-C Spectrum Quartz Hot Filament
PCO Cell Advanced Monolithic Absorptive PCO cell with proprietary absorption media and proven TiO2 photo-catalyst,
Pressure Drop <0.01" w.c. @ 400 FPM
Dimensions Cell & Lamp: 5.25"W x 3"H x 9.25"D
SI-DI, DER Enclosure: 10"L x 10"W x 2"D
ER Enclosure: 8"L x 8"W x 2"D

Electrical
ER Series
18-32 VAC, 60 Hz, 0.68 Amps, 16 VA
Low-voltage power-supply
Electrical
SI / DI Series
120-277 VAC, 50/60 Hz,
0.51 Amps/120V Thru 0.22 Amps/277V
High-voltage power-supply

Warranty Lifetime on all parts except lamp
Manufacturer/product website: http://www.freshaireuv.com/apco.html

Figure 9.7. APCO Fresh-aire image from product literature.

HVAC UV 560 (manufacturer unclear)

Description: Ultraviolet light intentional ozone production.

Product claims, in brief: Claimed to reduce/remove odors, remediate mold, fire and smoke remediation, kill allergens, germs and viruses, control dust mites, decompose proteins.

Specifications:
Generation method: Variable output UV ozone generation
Supply Gas: Ambient Air
Ozone output: 560 mg/hr (will produce 615mg/hr for first week)
Controls: On off rocker switch. Fully variable control for ozone output. Optional shock treatment timer with 9 time settings, (10, 30, 60min, 2, 4, 8, 12, 18, 36hr).
Dimensions: Control box: 5" W X 22" H X 3"D
Tube mount W/tube installed: 5.5" x 5.5" x 15.75 long
Electrical: 120 Volt, .4 Amp, 40 Watt, 50/60Hz
240 Volt, .4 Amp, 40 Watt, 50/60Hz (please note that 240VAC models come with an IEC power cord connector. You will need to supply your own cord, the cord is the same one used on every desktop computer in the world)
Construction: Stainless steel
UV tube life expectancy: 12-24 months plus, depending on output setting. (the higher the setting the shorter the life)
Warranty: The HVAC 560 electronics are warranted against defects in materials and workmanship for a period of six years from date of purchase. The UV tubes are warranted for 6 months. Liability is limited to parts and labor only. Shipping is the sole responsibility of the customer. Crystal Air is not liable for damage caused by shipping, misuse, neglect or lack of regular maintenance.
Uses: The HVAC 560 is a small low cost ozone generator designed for use in a Building up to approx. 5000+ sq/ft. This unit does have a variable control for adjusting the output. The output starts at approx. 20 mg/hr and goes up to 560 mg/hr.
Options: Standard unit comes with 2 ft cable between control box and UV tube. Optional is a 10 ft cable or on special order up to 100 ft.

Manufacturer/product websites:
http://www.odordr.com/id9.html

Figure 9.8. HVAC UV 560 image from product literature.

Trane Clean Effects

Description: Electrostatic precipitator.
Product claims, in brief: "Trane CleanEffects™, can reduce the presence of potential asthma and allergy attack triggers in your home, like dust, pollen, pet hair and dander, dust mites, mildew, lint, fungus, most tobacco smoke, cooking grease, and even bacteria… remove up to an astounding 99.98% of airborne allergens from the air that passes through the filter. It catches particles as small as .1 micron, making it 8 times more effective than even the best HEPA room filters and up to 100 times more effective than a standard 1" filter."
Manufacturer/product website: http://www.trane.com/residential/products/air-cleaners/cleaneffects%E2%84%A2-air-cleaners

Figure 9.9. Trane Clean Effects image from product literature.

Trane Catalytic Air Cleaning System (TCACS)

Description: Combination system including photocatalytic oxidation, ultraviolet germicidal irradiation and MERV 13 particle capture for commercial systems. Product claims, in brief: Reduces concentrations of VOCs, including odors, particles and kills microorganisms.

Design specfications:
1. The Trane Catalytic Air Cleaner System shall be a three part integral assembly for treatment of air by: (1) High Efficiency Particle Filtration (2) Ultraviolet Germicidal Irradiation (UVGI) using UV-C lamps and fixtures; and (3) Photocatalytic Oxidation (PCO) catalyst media using titanium dioxide (TiO2).
2. High Efficiency Particle Filters shall be rated MERV 13 or higher. Filters are positioned upstream of the PCO media.
3. UV-C lamps and ballasts designed specifically to provide type-C ultraviolet light with a wavelength at or near 253.7 Angstroms and shall not produce any ozone. Lamps shall be imbedded in the center of the catalyst media bank, spaced no further than 6" apart, and shall achieve a minimum coverage of 5 milliwatts per square inch of UVC light across all exposed surfaces of the PCO media.
4. The catalyst media shall consist of six-inch deep (direction of airflow) grid with face area to match casing opening, one pleat per inch (nominal), and coated with 40-200 nanometer TiO2. The complete PCO media bank assembly shall be housed in a galvanized or stainless steel casing and placed in the air handler perpendicular to the airflow.
5. All UV lamps and PCO media shall be removable from outside the AHU casing through a side access door for maintenance purposes.
6. An air flow switch shall be wired into the control circuit to disable the UV lights when the AHU fan is not running.
7. The Trane Catalytic Air Cleaner System can be configured to operate with 120V/1 phase/60 hz, 200-208V/3ph/60hz, 230V/3ph/60hz, 460V/3ph/60hz, or 575V/3ph/60hz electrical power. All 120V/1ph./60hz systems shall have an independent single point external power connection. Three phase systems shall be either independent single point power or integral with the AHU main power as shown on the drawings. All necessary main fusing shall be included.
8. Electrical fixtures shall meet the UL drip proof design criteria. Component enclosures shall be constructed of galvanized steel or stainless steel to resist corrosion. Fixtures shall have been tested and recognized by UL/C-UL under Category Code ABQK (Accessories, Air Duct Mounted), UL Standards 1995.
9. For Line Voltage options, the TCACS shall be provided with a UL 508 listed panel for power distribution and over-current protection.
10. TCACS assemble shall be capable of withstanding 750 fpm face velocity with no structural damage
11. All polymeric materials that come into direct or indirect (reflected) contact with UV-C light shall be tested and certified as UV-C tolerant. Any non-conforming construction materials or components within the exposure zone shall be completely shielded from the UV-C light using a certified UV-C tolerant material.. UV-C tolerance

is defined as being capable of performing its intended duty for a minimum of 20 years.

Manufacturer/product website:
http://www.trane.com/COMMERCIAL/DNA/View.aspx?i=2591

Figure 9.10. TCACS image from product literature.

9.2 Detailed results of laboratory testing of electrically connected in-duct devices using the Standard Test Method

Table 9.2. Detailed results from laboratory testing of device 1

Parameter	Units	Tests												
date		7/13/12	7/13/12	7/13/12	7/18/12	7/18/12	7/18/12	7/18/12	7/18/12	7/18/12	7/18/12	7/18/12	7/18/12	7/18/12
Test #		1	1	1	2	2	2	2	2	2	2	2	2	2
Test description		STM	STM	STM	MQL	MQL	MQL	MQL	MQL	MQL	MQL	MQL	MQL	MQL
Air cleaner power	W	21	21	21	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
Air cleaner current	A	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
Air cleaner voltage	V	120.8	120.8	120.8	120.6	120.6	120.6	120.6	120.6	120.6	120.6	120.6	120.6	120.6
Flow #		1	2	3	1	2	3	4	5	6	7	8	9	10
Flow rate	$m^3 h^{-1}$	574.0	451.4	506.9	539.4	538.8	539.3	531.1	531.0	528.9	533.2	528.0	530.4	529.0
SD, flow rate	$m^3 h^{-1}$	17.0	14.3	18.8	14.3	14.2	19.4	14.9	13.9	14.4	14.5	13.8	13.2	15.0
Mean, upstream O3	$\mu g\ m^{-3}$	3.8	3.5	4.1	2.9	3.7	2.7	3.0	3.2	3.3	2.5	2.6	3.0	3.9
SD, upstream O3	$\mu g\ m^{-3}$	1.9	0.3	1.0	0.5	1.5	0.6	0.8	1.3	1.0	0.4	0.6	0.6	1.5
Mean, downstream O3	$\mu g\ m^{-3}$	8.2	7.8	8.7	7.7	6.4	6.9	7.5	6.7	8.1	6.7	5.9	7.4	7.0
SD, downstream O3	$\mu g\ m^{-3}$	1.7	1.7	2.0	1.3	1.6	1.3	1.6	2.6	2.2	1.5	1.9	1.1	1.8
Delta O3	$\mu g\ m^{-3}$	4.4	4.3	4.6	4.8	2.8	4.2	4.5	3.5	4.8	4.2	3.3	4.4	3.2
Abs. error, delta O3	$\mu g\ m^{-3}$	0.9	0.9	1.1	0.8	0.7	0.8	1.0	1.4	1.3	1.0	1.1	0.7	0.8
Emission rate	$mg\ m^{-3}$	2.6	1.9	2.3	2.6	1.5	2.3	2.4	1.9	2.5	2.2	1.8	2.4	1.7
Abs. error, emission rate	$mg\ m^{-3}$	0.6	0.4	0.6	0.5	0.4	0.5	0.5	0.7	0.7	0.5	0.6	0.4	0.4
Mean, T	◦C	24.0	24.0	24.0	23.6	23.6	23.7	23.7	23.7	23.7	23.7	23.7	23.8	23.8
SD, T	◦C	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mean, RH	%	57.0	57.0	57.1	61.1	61.2	61.3	61.3	61.4	61.4	61.5	61.5	61.5	61.6
SD, RH	%	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values(DS-US)
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.3. Detailed results of laboratory testing Air cleaner 2a.

Parameter	Units	Tests				
date		7/12/12	7/12/12	7/12/12	7/12/12	7/12/12
Test #		1	1	1	1	1
Test description		STM	STM	STM	STM	STM
Air cleaner power	W	13	13	13	13	13
Air cleaner current	A	0.19	0.19	0.19	0.19	0.19
Air cleaner voltage	V	120.2	120.2	120.2	120.2	120.2
Flow #		1	2	3	4	5
Flow rate	$m^3 h^{-1}$	2246.1	1703.4	1319.0	1016.1	595.3
SD, flow rate	$m^3 h^{-1}$	24.6	25.2	27.3	25.3	16.2
Mean, upstream O3	$\mu g\ m^{-3}$	2.9	3.2	3.7	2.9	5.2
SD, upstream O3	$\mu g\ m^{-3}$	1.0	1.3	1.2	0.9	4.5
Mean, downstream O3	$\mu g\ m^{-3}$	9.2	13.8	17.1	20.0	36.1
SD, downstream O3	$\mu g\ m^{-3}$	1.8	3.5	1.8	1.6	1.6
Delta O3	$\mu g\ m^{-3}$	6.3	10.6	13.4	17.1	30.9
Abs. error, delta O3	$\mu g\ m^{-3}$	1.2	2.7	1.4	1.4	1.4
Emission rate	$mg\ m^{-3}$	14.2	18.1	17.6	17.4	18.4
Abs. error, emission rate	$mg\ m^{-3}$	3.0	4.7	2.2	1.9	1.5
Mean, T	◦C	34.4	32.6	31.0	29.3	27.2
SD, T	◦C	0.0	0.4	0.3	0.4	0.5
Mean, RH	%	35.7	36.5	38.5	40.9	43.4
SD, RH	%	0.2	0.5	0.6	0.7	0.7

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.4. Detailed results of laboratory testing Air cleaner 2b.

Note: Air cleaner 2b was tested in a preliminary mode that did not strictly adhere to the standard test method. Only emission rates are reported here.

Parameter	Units	Tests				
date		10/13/11	10/13/11	10/13/11	10/13/11	10/13/11
Flow #						
Flow rate	$m^3\ h^{-1}$	512	598	821	1084	1218
Emission rate	$mg\ m^{-3}$	13.1	12.9	13.1	12.6	12.8
Abs. error, emission rate	$mg\ m^{-3}$	1.7	1.9	2.5	3.2	3.6

Table 9.5. Detailed results of laboratory testing Air cleaner 2c.

Parameter	Units	Tests			
date		7/13/12	7/13/12	7/13/12	7/13/12
Test #		1	1	1	1
Test description		STM	STM	STM	STM
Air cleaner power	W	14.5	14.5	14.5	14.5
Air cleaner current	A	0.21	0.21	0.21	0.21
Air cleaner voltage	V	120.6	120.6	120.6	120.6
Flow #		1	2	3	4
Flow rate	$m^3 h^{-1}$	618.3	625.8	643.9	663.6
SD, flow rate	$m^3 h^{-1}$	17.9	17.1	15.9	15.7
Mean, upstream O3	$\mu g\ m^{-3}$	4.2	4.3	4.4	4.6
SD, upstream O3	$\mu g\ m^{-3}$	0.9	0.8	0.7	1.0
Mean, downstream O3	$\mu g\ m^{-3}$	17.2	16.2	17.9	18.6
SD, downstream O3	$\mu g\ m^{-3}$	2.3	1.7	2.4	2.2
Delta O3	$\mu g\ m^{-3}$	13.0	11.9	13.5	14.0
Abs. error, delta O3	$\mu g\ m^{-3}$	1.8	1.3	1.8	1.6
Emission rate	$mg\ m^{-3}$	8.0	7.5	8.7	9.3
Abs. error, emission rate	$mg\ m^{-3}$	1.2	0.9	1.3	1.3
Mean, T	◦C	23.5	24.0	24.2	24.4
SD, T	◦C	0.2	0.1	0.0	0.0
Mean, RH	%	51.9	53.5	54.9	55.9
SD, RH	%	0.5	0.3	0.3	0.2

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.6. Detailed results of laboratory testing Air cleaner 3, part 1.

Parameter	Units	Tests										
date		6/26/12	6/26/12	6/26/12	6/26/12	6/26/12	6/26/12	6/27/12	6/27/12	6/27/12	6/27/12	6/27/12
Test #		1	1	1	1	2	2	3	3	3	3	3
Test description		high T, high RH	high T, high RH	high T, high RH	high T, high RH	high RH, STM T	high RH, STM T	STM	STM	STM	STM	STM
Air cleaner power	W	24	24	24	24	24.5	24.5	NC	NC	NC	NC	NC
Air cleaner current	A	0.31	0.31	0.31	0.31	0.31	0.31	NC	NC	NC	NC	NC
Air cleaner voltage	V	120.1	120.1	120.1	120.1	120.4	120.4	NC	NC	NC	NC	NC
Flow #		1	2	3	4	1	2	1	2	3	4	5
Flow rate	$m^3 h^{-1}$	2151.7	1797.0	1450.5	981.2	2244.7	1732.3	2260.4	1690.0	1316.7	1005.9	555.2
SD, flow rate	$m^3 h^{-1}$	31.4	28.2	24.2	30.7	24.9	25.8	17.8	27.3	24.5	30.4	18.0
Mean, upstream O3	$\mu g\ m^{-3}$	2.4	3.4	3.1	2.0	4.9	3.6	7.1	10.1	6.5	10.9	10.9
SD, upstream O3	$\mu g\ m^{-3}$	0.7	1.1	1.3	0.7	1.5	1.0	4.5	3.1	4.7	5.2	6.6
Mean, downstream O3	$\mu g\ m^{-3}$	8.2	11.6	14.9	19.4	12.9	15.7	13.3	13.7	19.8	27.7	39.3
SD, downstream O3	$\mu g\ m^{-3}$	1.8	1.6	2.2	1.8	1.6	1.1	3.3	5.0	5.0	4.9	5.8
Delta O3	$\mu g\ m^{-3}$	5.8	8.2	11.7	17.3	8.0	12.1	6.3	3.5	13.3	16.7	28.5
Abs. error, delta O3	$\mu g\ m^{-3}$	1.3	1.2	1.7	1.6	1.0	0.8	1.5	1.3	3.4	3.0	4.2
Emission rate	$mg\ m^{-3}$	12.6	14.8	17.0	17.0	18.0	20.9	14.1	6.0	17.5	16.8	15.8
Abs. error, emission rate	$mg\ m^{-3}$	2.9	2.3	2.8	2.0	2.5	2.1	3.6	2.3	4.6	3.2	2.6
Mean, T	◦C	39.8	38.6	36.8	36.0	31.4	30.4	33.5	32.0	30.6	29.1	27.6
SD, T	◦C	0.3	0.4	0.3	0.4	0.3	0.4	0.1	0.3	0.2	0.3	0.5
Mean, RH	%	58.2	59.3	59.9	59.1	70.7	71.0	42.2	40.1	39.8	40.5	41.5
SD, RH	%	2.1	0.9	1.4	1.6	1.2	1.1	0.5	0.2	0.1	0.4	0.4

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.7. Detailed results of laboratory testing Air cleaner 3, part 2.

Parameter	Units	Tests							
date		6/27/12	6/27/12	6/27/12	6/27/12	6/28/12	6/28/12	6/28/12	6/28/12
Test #		4	4	4	4	5	5	5	5
Test description		High T: STM RH	High T: STM RH	High T: STM RH	High T: STM RH	High RH: single beam	High RH: single beam	High RH: single beam	High RH: single beam
Air cleaner power	W	NC	NC	NC	NC	NC	NC	NC	NC
Air cleaner current	A	NC	NC	NC	NC	NC	NC	NC	NC
Air cleaner voltage	V	NC	NC	NC	NC	NC	NC	NC	NC
Flow #		1	2	3	4	1	2	3	4
Flow rate	$m^3 h^{-1}$	2223.3	1735.8	1318.2	993.6	2267.0	1698.8	1339.1	1000.1
SD, flow rate	$m^3 h^{-1}$	25.8	25.6	24.6	24.9	12.9	27.2	22.9	25.3
Mean, upstream O3	$\mu g\ m^{-3}$	5.5	7.8	5.6	5.6	11.1	11.5	10.5	10.8
SD, upstream O3	$\mu g\ m^{-3}$	3.4	4.8	3.1	4.9	5.6	6.4	4.2	5.7
Mean, downstream O3	$\mu g\ m^{-3}$	11.7	13.3	18.4	23.4	18.2	21.6	27.2	31.9
SD, downstream O3	$\mu g\ m^{-3}$	7.5	4.1	3.5	4.5	5.7	3.9	5.3	6.0
Delta O3	$\mu g\ m^{-3}$	6.2	5.4	12.8	17.8	7.2	10.1	16.7	21.1
Abs. error, delta O3	$\mu g\ m^{-3}$	4.0	1.7	2.4	3.4	2.2	1.8	3.3	4.0
Emission rate	$mg\ m^{-3}$	13.7	9.4	16.8	17.7	16.2	17.2	22.4	21.1
Abs. error, emission rate	$mg\ m^{-3}$	8.9	3.0	3.4	3.6	5.2	3.3	4.7	4.3
Mean, T	◦C	44.4	43.4	41.5	40.5	31.4	30.6	29.1	27.8
SD, T	◦C	0.1	0.3	0.2	0.2	0.3	0.5	0.4	0.4
Mean, RH	%	20.8	20.1	21.1	21.9	52.5	51.9	54.4	55.0
SD, RH	%	0.4	0.1	0.2	0.2	1.1	1.1	1.1	1.6

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.8. Detailed results of laboratory testing Air cleaner 3, part 3.

Parameter	Units	Tests							
date		6/28/12	6/28/12	6/28/12	7/11/12	7/11/12	7/11/12	7/11/12	7/11/12
Test #		6	6	6	7	7	7	7	7
Test description		High T: Single beam	High T: Single beam	High T: single beam	STM (low to high flow)	STM (low to high flow)	STM (low to high flow)	STM (low to high flow)	STM (low to high flow)
Air cleaner power	W	24	24	24	24.5	24.5	24.5	24.5	24.5
Air cleaner current	A	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Air cleaner voltage	V	119.5	119.5	119.5	159.9	159.9	159.9	159.9	159.9
Flow #		1	2	3	1	2	3	4	5
Flow rate	$m^3 h^{-1}$	2240.3	1699.0	1316.6	2271.2	1703.8	1328.1	1018.2	566.0
SD, flow rate	$m^3 h^{-1}$	27.8	24.8	22.8	7.2	25.5	23.4	32.9	20.0
Mean, upstream O3	$\mu g\ m^{-3}$	9.0	9.1	10.7	7.2	6.8	8.8	8.4	14.4
SD, upstream O3	$\mu g\ m^{-3}$	5.4	5.1	2.6	1.7	2.0	2.5	2.1	2.4
Mean, downstream O3	$\mu g\ m^{-3}$	12.6	15.3	15.2	18.8	23.0	28.2	33.7	57.8
SD, downstream O3	$\mu g\ m^{-3}$	6.5	3.8	8.1	1.4	1.7	1.3	1.8	2.1
Delta O3	$\mu g\ m^{-3}$	3.6	6.1	4.5	11.5	16.3	19.5	25.3	43.4
Abs. error, delta O3	$\mu g\ m^{-3}$	1.9	1.5	2.4	0.8	1.2	0.9	1.4	1.7
Emission rate	$mg\ m^{-3}$	8.2	10.4	6.0	26.2	27.7	25.9	25.7	24.6
Abs. error, emission rate	$mg\ m^{-3}$	4.2	2.7	3.2	2.6	2.9	2.2	2.3	2.0
Mean, T	◦C	42.2	41.2	40.0	28.5	29.7	29.0	28.0	26.4
SD, T	◦C	0.3	0.3	0.1	1.1	0.0	0.1	0.2	0.4
Mean, RH	%	32.0	30.2	29.0	56.0	49.8	48.2	48.4	49.8
SD, RH	%	1.2	0.9	1.5	2.2	0.6	0.1	0.4	0.7

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.9. Detailed results of laboratory testing Air cleaner 4.

Parameter	Units		Tests
date		7/24/12	7/24/12
Test #		1	2
Test description		STM	STM
Air cleaner power	W	102.5	102.5
Air cleaner current	A	0.86	0.86
Air cleaner voltage	V	120.6	120.7
Flow #		1	1
Flow rate	$m^3 h^{-1}$	524.4	519.7
SD, flow rate	$m^3 h^{-1}$	14.1	14.0
Mean, upstream O3	$\mu g\ m^{-3}$	2.8	3.3
SD, upstream O3	$\mu g\ m^{-3}$	0.9	1.2
Mean, downstream O3	$\mu g\ m^{-3}$	2.5	2.4
SD, downstream O3	$\mu g\ m^{-3}$	0.6	0.6
Delta O3	$\mu g\ m^{-3}$	-0.3	-0.9
Abs. error, delta O3	$\mu g\ m^{-3}$	-0.1	-0.2
Emission rate	$mg\ m^{-3}$	-0.1	-0.5
Abs. error, emission rate	$mg\ m^{-3}$	0.0	-0.1
Mean, T	◦C	23.5	23.9
SD, T	◦C	0.2	0.1
Mean, RH	%	62.8	62.1
SD, RH	%	0.1	0.1

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.10. Detailed results of laboratory testing Air cleaner 5a, part 1.

Parameter	Units	Tests									
date		2/8/12	2/8/12	2/8/12	2/8/12	2/8/12	NC	NC	NC	NC	NC
Test #		1	1	1	1	1	2	2	2	2	2
Test description		STM	STM	STM	STM	STM	STM	STM	STM	STM	STM
Air cleaner power	W	11	11	11	11	11	11	11	11	11	11
Air cleaner current	A	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Air cleaner voltage	V	121.2	121.2	121.2	121.2	121.2	122.8	122.8	122.8	122.8	122.8
Flow #		1	2	3	4	5	1	2	3	4	5
Flow rate	$m^3 h^{-1}$	516.7	995.6	1360.7	1832.3	2284.4	511.4	1010.7	1358.8	1896.8	2276.5
SD, flow rate	$m^3 h^{-1}$	9.2	9.0	11.9	10.4	13.6	7.6	11.1	9.8	14.5	10.7
Mean, upstream O3	$\mu g\ m^{-3}$	28.0	25.0	12.9	11.5	7.0	3.3	3.6	2.9	3.0	2.2
SD, upstream O3	$\mu g\ m^{-3}$	0.7	12.1	0.2	2.1	0.2	1.3	1.1	1.0	1.1	0.7
Mean, downstream O3	$\mu g\ m^{-3}$	28.6	25.0	13.2	11.4	7.1	74.4	24.7	18.4	14.8	13.3
SD, downstream O3	$\mu g\ m^{-3}$	0.2	12.0	0.4	2.0	0.1	2.8	1.6	1.2	1.5	1.1
Delta O3	$\mu g\ m^{-3}$	0.6	0.0	0.2	-0.1	0.1	71.1	21.1	15.6	11.8	11.1
Abs. error, delta O3	$\mu g\ m^{-3}$	0.0	0.0	0.0	0.0	0.0	2.8	1.4	1.0	1.2	1.0
Emission rate	$mg\ m^{-3}$	0.3	0.0	0.3	-0.2	0.1	36.4	21.3	21.2	22.4	25.3
Abs. error, emission rate	$mg\ m^{-3}$	0.0	0.0	0.0	0.0	0.0	2.9	2.1	2.0	2.8	2.8
Mean, T	◦C	23.1	23.7	25.1	26.8	29.0	22.6	23.2	24.7	26.7	28.8
SD, T	◦C	0.2	0.4	0.5	0.6	0.6	0.2	0.4	0.5	0.6	0.6
Mean, RH	%	25.8	25.8	24.9	23.5	21.9	22.7	23.2	22.8	21.6	20.0
SD, RH	%	0.0	0.1	0.4	0.4	0.5	0.1	0.1	0.3	0.4	0.5

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.11. Detailed results of laboratory testing Air cleaner 5a, part 2.

Parameter	Units	Tests									
date		NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Test #		3	3	3	3	3	4	4	4	4	4
Test description		STM	STM	STM	STM	STM	STM	STM	STM	STM	STM
Air cleaner power	W	10.5	10.5	10.5	10.5	10.5	11	11	11	11	11
Air cleaner current	A	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Air cleaner voltage	V	120.3	120.3	120.3	120.3	120.3	121.0	121.0	121.0	121.0	121.0
Flow #		1	2	3	4	5	1	2	3	4	5
Flow rate	$m^3 h^{-1}$	513.1	981.1	1350.0	1888.4	2286.3	523.3	1019.6	1355.8	1934.1	2299.5
SD, flow rate	$m^3 h^{-1}$	5.9	25.4	8.5	27.2	15.1	8.2	11.0	9.2	17.2	12.0
Mean, upstream O3	$\mu g\ m^{-3}$	2.9	3.1	2.7	2.1	3.3	5.2	4.4	2.7	2.7	3.7
SD, upstream O3	$\mu g\ m^{-3}$	1.3	1.3	1.1	0.7	1.7	0.5	2.4	1.1	0.9	1.1
Mean, downstream O3	$\mu g\ m^{-3}$	64.6	29.8	22.0	15.2	14.2	69.5	27.2	18.8	13.7	13.8
SD, downstream O3	$\mu g\ m^{-3}$	2.0	1.1	1.1	1.5	1.8	1.5	1.1	1.6	1.8	1.1
Delta O3	$\mu g\ m^{-3}$	61.8	26.7	19.4	13.1	10.9	64.3	22.9	16.1	11.0	10.1
Abs. error, delta O3	$\mu g\ m^{-3}$	2.0	1.0	1.0	1.3	1.4	1.5	0.9	1.4	1.5	0.8
Emission rate	$mg\ m^{-3}$	31.7	26.2	26.1	24.8	24.8	33.7	23.3	21.8	21.3	23.2
Abs. error, emission rate	$mg\ m^{-3}$	2.5	2.1	2.3	3.0	3.6	2.5	1.9	2.4	3.2	2.4
Mean, T	◦C	30.7	29.3	29.0	29.8	31.3	22.3	23.4	25.0	27.3	29.4
SD, T	◦C	0.7	0.4	0.2	0.4	0.4	0.2	0.4	0.4	0.5	0.6
Mean, RH	%	15.4	17.0	18.0	18.0	17.3	29.0	30.4	30.4	28.8	27.2
SD, RH	%	0.4	0.4	0.1	0.1	0.3	0.2	0.1	0.2	0.4	0.5

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.12. Detailed results of laboratory testing Air cleaner 5b, part 1.

Parameter	Units	Tests									
date		6/11/12	6/11/12	6/11/12	6/11/12	6/11/12	6/12/12	6/12/12	6/12/12	6/12/12	6/12/12
Test #		1	1	1	1	1	2	2	2	2	2
Test description		STM, low-high flow	STM, low-high flow	STM, low-high flow	STM, low-high flow	STM, low-high flow	STM, high-low flow	STM, high-low flow	STM, high-low flow	STM, high-low flow	STM, high-low flow
Air cleaner power	W	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
Air cleaner current	A	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Air cleaner voltage	V	120.6	120.6	120.6	120.6	120.6	121.2	121.2	121.2	121.2	121.2
Flow #		1	2	3	4	5	1	2	3	4	5
Flow rate	$m^3 h^{-1}$	576.4	1097.5	1318.4	1728.9	2223.5	2217.9	1720.9	1326.2	989.2	559.3
SD, flow rate	$m^3 h^{-1}$	17.9	146.8	24.5	25.6	29.1	30.8	26.0	32.7	32.9	14.9
Mean, upstream O3	$\mu g\ m^{-3}$	3.0	1.9	1.5	1.7	1.7	3.2	3.8	4.3	3.7	4.2
SD, upstream O3	$\mu g\ m^{-3}$	1.0	0.9	0.7	1.2	0.9	0.7	1.2	1.7	1.1	1.6
Mean, downstream O3	$\mu g\ m^{-3}$	46.9	12.0	16.9	11.7	9.2	12.3	13.8	17.0	24.7	49.8
SD, downstream O3	$\mu g\ m^{-3}$	2.4	8.1	1.5	1.7	1.2	1.1	1.8	2.3	1.3	2.5
Delta O3	$\mu g\ m^{-3}$	43.9	10.1	15.4	10.0	7.5	9.1	10.0	12.7	21.0	45.6
Abs. error, delta O3	$\mu g\ m^{-3}$	2.3	6.8	1.4	1.5	0.9	0.8	1.3	1.8	1.1	2.3
Emission rate	$mg\ m^{-3}$	25.3	11.0	20.3	17.2	16.7	20.2	17.2	16.9	20.8	25.5
Abs. error, emission rate	$mg\ m^{-3}$	2.2	7.5	2.3	2.8	2.4	2.2	2.6	2.6	1.8	2.2
Mean, T	◦C	23.7	25.3	27.1	29.3	31.7	33.2	32.1	30.4	28.8	26.6
SD, T	◦C	0.0	0.5	0.3	0.3	0.4	0.1	0.3	0.3	0.3	0.4
Mean, RH	%	60.2	58.7	54.4	49.7	46.6	43.8	42.4	42.6	44.0	46.3
SD, RH	%	0.0	1.0	1.1	0.7	0.8	0.5	0.1	0.2	0.6	0.7

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.13. Detailed results of laboratory testing Air cleaner 5b, part 2.

Parameter	Units	Tests									
date		6/13/12	6/13/12	6/13/12	6/13/12	6/13/12	6/14/12	6/14/12	6/14/12	6/14/12	6/14/12
Test #		3	3	3	3	3	4	4	4	4	4
Test description		STM, low-high flow	STM, low-high flow	STM, low-high flow	STM, low-high flow	STM, low-high flow	STM, low-high flow	STM, low-high flow	STM, low-high flow	STM, low-high flow	STM, low-high flow
Air cleaner power	W	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
Air cleaner current	A	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Air cleaner voltage	V	120.7	120.7	120.7	120.7	120.7	120.3	120.3	120.3	120.3	120.3
Flow #		1	2	3	4	5	1	2	3	4	5
Flow rate	$m^3 h^{-1}$	555.8	990.6	1324.2	1742.1	2217.4	546.5	995.3	1317.8	1734.1	2228.7
SD, flow rate	$m^3 h^{-1}$	16.2	24.8	24.6	27.0	30.9	19.2	28.4	24.7	26.7	28.9
Mean, upstream O3	$\mu g\ m^{-3}$	4.8	5.6	4.0	3.6	4.3	5.2	3.0	3.6	5.0	3.9
SD, upstream O3	$\mu g\ m^{-3}$	1.0	1.7	1.0	0.6	1.1	1.4	1.4	0.7	1.2	0.8
Mean, downstream O3	$\mu g\ m^{-3}$	48.4	24.5	17.5	14.8	10.9	49.3	20.6	18.4	13.5	12.9
SD, downstream O3	$\mu g\ m^{-3}$	2.2	1.5	2.0	2.0	2.5	2.5	3.1	2.5	1.9	0.8
Delta O3	$\mu g\ m^{-3}$	43.5	18.8	13.5	11.3	6.6	44.0	17.6	14.8	8.4	9.0
Abs. error, delta O3	$\mu g\ m^{-3}$	2.0	1.2	1.5	1.5	1.5	2.3	2.7	2.0	1.2	0.6
Emission rate	$mg\ m^{-3}$	24.2	18.7	17.8	19.6	14.7	24.1	17.5	19.5	14.6	20.0
Abs. error, emission rate	$mg\ m^{-3}$	2.0	1.7	2.4	3.0	3.6	2.1	2.9	3.0	2.3	1.9
Mean, T	◦C	23.9	25.8	28.0	29.9	32.7	23.6	24.7	26.3	28.0	30.2
SD, T	◦C	0.0	0.5	0.4	0.4	0.5	0.0	0.3	0.3	0.3	0.5
Mean, RH	%	54.4	53.4	49.4	46.0	42.4	50.2	51.9	51.5	49.5	47.3
SD, RH	%	0.2	1.1	1.1	0.8	1.1	0.3	0.1	0.3	0.4	0.6

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.14. Detailed results of laboratory testing Air cleaner 5b, part 3.

Parameter	Units	Tests				
date		6/18/12	6/18/12	6/18/12	6/18/12	6/18/12
Test #		6	6	6	6	6
Test description		RH high: T low: High to low flow	RH high: T low: High to low flow	RH high: T low: High to low flow	RH high: T low: High to low flow	RH high: T low: High to low flow
Air cleaner power	W	11	11	11	11	11
Air cleaner current	A	0.10	0.10	0.10	0.10	0.10
Air cleaner voltage	V	120.6	120.6	120.6	120.6	120.6
Flow #		1	2	3	4	5
Flow rate	$m^3 h^{-1}$	2200.9	1728.0	1296.3	982.4	534.9
SD, flow rate	$m^3 h^{-1}$	31.8	27.1	26.1	32.8	17.3
Mean, upstream O3	$\mu g\ m^{-3}$	5.0	4.4	4.8	5.1	2.5
SD, upstream O3	$\mu g\ m^{-3}$	1.4	1.0	1.2	0.6	1.6
Mean, downstream O3	$\mu g\ m^{-3}$	9.7	12.5	14.7	19.5	38.8
SD, downstream O3	$\mu g\ m^{-3}$	1.3	1.6	2.1	2.4	1.6
Delta O3	$\mu g\ m^{-3}$	4.7	8.1	9.8	14.3	36.3
Abs. error, delta O3	$\mu g\ m^{-3}$	0.6	1.0	1.4	1.7	1.5
Emission rate	$mg\ m^{-3}$	10.4	14.0	12.8	14.1	19.4
Abs. error, emission rate	$mg\ m^{-3}$	1.6	2.0	2.0	2.0	1.6
Mean, T	◦C	31.5	30.8	28.6	27.1	25.6
SD, T	◦C	0.4	0.7	0.3	0.5	0.7
Mean, RH	%	64.3	63.7	67.7	69.4	69.7
SD, RH	%	2.4	3.0	1.7	1.4	1.2

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.15. Detailed results of laboratory testing Air cleaner 5b, part 4.

Parameter	Units	Tests				
date		6/20/12	6/20/12	6/20/12	6/20/12	6/20/12
Test #		7	7	7	7	7
Test description		RH low: T high: High to low flow (reverse)	RH low: T high: High to low flow (reverse)	RH low: T high: High to low flow (reverse)	RH low: T high: High to low flow (reverse)	RH low: T high: High to low flow (reverse)
Air cleaner power	W	11	11	11	11	11
Air cleaner current	A	0.10	0.10	0.10	0.10	0.10
Air cleaner voltage	V	120.6	120.6	120.6	120.6	120.6
Flow #		1	2	3	4	5
Flow rate	$m^3 h^{-1}$	2146.6	1797.8	1526.8	984.4	548.4
SD, flow rate	$m^3 h^{-1}$	30.2	26.4	26.4	26.6	17.9
Mean, upstream O3	$\mu g\ m^{-3}$	2.7	3.4	2.8	3.1	4.1
SD, upstream O3	$\mu g\ m^{-3}$	0.7	0.7	0.6	0.6	1.0
Mean, downstream O3	$\mu g\ m^{-3}$	8.6	11.1	13.0	18.9	36.6
SD, downstream O3	$\mu g\ m^{-3}$	1.2	2.5	1.5	2.0	1.8
Delta O3	$\mu g\ m^{-3}$	5.9	7.7	10.2	15.7	32.4
Abs. error, delta O3	$\mu g\ m^{-3}$	0.8	1.7	1.2	1.7	1.6
Emission rate	$mg\ m^{-3}$	12.7	13.8	15.6	15.5	17.8
Abs. error, emission rate	$mg\ m^{-3}$	2.0	3.3	2.1	2.0	1.5
Mean, T	◦C	43.4	42.5	41.3	39.8	38.5
SD, T	◦C	0.2	0.3	0.3	0.3	0.2
Mean, RH	%	34.9	34.9	35.2	35.1	35.4
SD, RH	%	0.6	0.8	0.5	0.5	0.3

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.16. Detailed results of laboratory testing Air cleaner 5b, part 5.

Parameter	Units	Tests			
date		6/21/12	6/21/12	6/21/12	6/21/12
Test #		8	8	8	8
Test description		RH high: T high: High to low flow (reverse)	RH high: T high: High to low flow (reverse)	RH high: T high: High to low flow (reverse)	RH high: T high: High to low flow (reverse)
Air cleaner power	W	11	11	11	11
Air cleaner current	A	0.10	0.10	0.10	0.10
Air cleaner voltage	V	121.1	121.1	121.1	121.1
Flow #		1	2	3	4
Flow rate	$m^3 h^{-1}$	2153.2	1817.1	1300.1	1003.2
SD, flow rate	$m^3 h^{-1}$	31.9	29.2	36.1	28.7
Mean, upstream O3	$\mu g\ m^{-3}$	11.3	3.6	4.1	3.7
SD, upstream O3	$\mu g\ m^{-3}$	27.6	0.9	0.8	0.9
Mean, downstream O3	$\mu g\ m^{-3}$	10.9	14.2	16.2	19.0
SD, downstream O3	$\mu g\ m^{-3}$	2.5	12.4	2.1	2.4
Delta O3	$\mu g\ m^{-3}$	-0.3	10.6	12.1	15.3
Abs. error, delta O3	$\mu g\ m^{-3}$	-0.1	9.2	1.6	1.9
Emission rate	$mg\ m^{-3}$	-0.8	19.2	15.8	15.4
Abs. error, emission rate	$mg\ m^{-3}$	-0.2	16.8	2.4	2.2
Mean, T	◦C	40.8	40.0	38.4	37.3
SD, T	◦C	0.2	0.3	0.3	0.3
Mean, RH	%	60.7	60.5	60.9	60.6
SD, RH	%	1.0	1.3	0.9	1.0

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.17. Detailed results of laboratory testing Air cleaner 6a.

Parameter	Units	Tests				
date		NC	NC	NC	NC	NC
Test #		1	1	1	1	1
Test description		STM	STM	STM	STM	STM
Air cleaner power	W	28.5	28.5	28.5	28.5	28.5
Air cleaner current	A	0.39	0.39	0.39	0.39	0.39
Air cleaner voltage	V	120.1	120.1	120.1	120.1	120.1
Flow #		1	2	3	4	5
Flow rate	$m^3 h^{-1}$	748.6	1134.8	1932.7	1377.9	2288.6
SD, flow rate	$m^3 h^{-1}$	25.2	17.8	17.5	9.6	12.5
Mean, upstream O3	$\mu g\ m^{-3}$	4.2	4.3	4.4	3.9	5.9
SD, upstream O3	$\mu g\ m^{-3}$	1.2	0.8	1.1	1.6	1.3
Mean, downstream O3	$\mu g\ m^{-3}$	62.5	54.4	53.2	56.2	54.1
SD, downstream O3	$\mu g\ m^{-3}$	2.7	2.0	2.5	1.8	1.1
Delta O3	$\mu g\ m^{-3}$	58.3	50.1	48.8	52.3	48.2
Abs. error, delta O3	$\mu g\ m^{-3}$	2.6	1.9	2.3	1.8	1.1
Emission rate	$mg\ m^{-3}$	43.7	56.8	94.3	72.0	110.2
Abs. error, emission rate	$mg\ m^{-3}$	3.6	4.5	8.0	5.6	8.1
Mean, T	◦C	24.5	25.3	26.9	28.1	29.6
SD, T	◦C	0.2	0.4	0.6	0.2	0.5
Mean, RH	%	20.6	20.8	19.9	18.3	17.5
SD, RH	%	0.1	0.1	0.4	0.2	0.4

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.18. Detailed results of laboratory testing Air cleaner 6b.

Parameter	Units	Tests				
date		5/23/12	5/23/12	5/23/12	5/23/12	5/23/12
Test #		1	1	1	1	1
Test description		STM	STM	STM	STM	STM
Air cleaner power	W	NC	NC	NC	NC	NC
Air cleaner current	A	NC	NC	NC	NC	NC
Air cleaner voltage	V	NC	NC	NC	NC	NC
Flow #		1	2	3	4	5
Flow rate	$m^3 h^{-1}$	679.3	1041.0	1134.6	1842.3	2197.2
SD, flow rate	$m^3 h^{-1}$	20.9	28.8	40.7	27.7	31.4
Mean, upstream O3	$\mu g\ m^{-3}$	5.0	4.6	5.1	6.5	5.3
SD, upstream O3	$\mu g\ m^{-3}$	1.6	1.5	1.7	2.1	1.8
Mean, downstream O3	$\mu g\ m^{-3}$	62.5	48.5	45.6	43.1	40.1
SD, downstream O3	$\mu g\ m^{-3}$	2.3	1.4	3.0	1.6	1.9
Delta O3	$\mu g\ m^{-3}$	57.6	43.9	40.6	36.6	34.8
Abs. error, delta O3	$\mu g\ m^{-3}$	2.2	1.3	2.7	1.4	1.7
Emission rate	$mg\ m^{-3}$	39.1	45.7	46.0	67.4	76.5
Abs. error, emission rate	$mg\ m^{-3}$	3.1	3.5	4.5	5.4	6.6
Mean, T	◦C	24.4	25.9	27.3	29.5	32.4
SD, T	◦C	0.0	0.3	0.2	0.4	0.3
Mean, RH	%	53.1	52.1	49.0	46.1	42.2
SD, RH	%	0.1	0.8	0.6	0.7	0.6

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.19. Detailed results of laboratory testing Air cleaner 7.

Parameter	Units	Tests		
date		5/28/12	5/28/12	7/17/12
Test #		1	2	3
Test description		activated carbon downstream	activated carbon upstream	STM
Air cleaner power	W	0	0	13
Air cleaner current	A	0.00	0.00	0.12
Air cleaner voltage	V	0.0	0.0	120.8
Flow #		1	1	1
Flow rate	$m^3 h^{-1}$	791.2	799.8	532.0
SD, flow rate	$m^3 h^{-1}$	22.9	20.3	14.3
Mean, upstream O3	$\mu g\ m^{-3}$	1.3	1.6	1.0
SD, upstream O3	$\mu g\ m^{-3}$	0.4	0.6	1.1
Mean, downstream O3	$\mu g\ m^{-3}$	1.7	1.3	2.6
SD, downstream O3	$\mu g\ m^{-3}$	1.3	0.3	0.7
Delta O3	$\mu g\ m^{-3}$	0.4	-0.3	1.7
Abs. error, delta O3	$\mu g\ m^{-3}$	0.3	-0.1	0.4
Emission rate	$mg\ m^{-3}$	0.3	-0.2	0.9
Abs. error, emission rate	$mg\ m^{-3}$	0.2	-0.1	0.2
Mean, T	◦C	25.1	25.3	23.5
SD, T	◦C	0.0	0.0	0.0
Mean, RH	%	55.0	53.4	59.7
SD, RH	%	0.2	0.1	0.0

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

Table 9.20. Detailed results of laboratory testing Air cleaner 8.

Parameter	Units	Tests				
date		9/04/13	9/04/13	9/04/13	9/04/13	9/04/13
Test #		1	1	1	1	1
Test description		STM	STM	STM	STM	STM
Air cleaner power	W	26	26	26	26	26
Air cleaner current	A	0.22	0.22	0.22	0.22	0.22
Air cleaner voltage	V	121.5	121.5	121.5	121.5	121.5
Flow #		1	2	3	4	5
Flow rate	$m^3 h^{-1}$	467.9	2071.3	744.3	1319.4	1602.7
SD, flow rate	$m^3 h^{-1}$	13.8	29.4	20.0	33.3	36.8
Mean, upstream O3	$\mu g\ m^{-3}$	27.7	15.9	24.5	20.9	20.5
SD, upstream O3	$\mu g\ m^{-3}$	2.5	1.4	1.7	1.8	1.7
Mean, downstream O3	$\mu g\ m^{-3}$	755.1	181.8	479.3	291.7	246.9
SD, downstream O3	$\mu g\ m^{-3}$	21.3	5.5	18.7	4.6	3.8
Delta O3	$\mu g\ m^{-3}$	727.4	165.9	454.8	270.8	226.4
Abs. error, delta O3	$\mu g\ m^{-3}$	21.8	5.3	18.3	5.0	4.1
Emission rate	$mg\ m^{-3}$	340.4	343.7	338.5	357.3	362.8
Abs. error, emission rate	$mg\ m^{-3}$	25.9	26.5	27.3	25.9	26.2
Mean, T	◦C	24.3	33.6	27.6	25.9	26.5
SD, T	◦C	0.0	0.0	0.3	0.0	0.0
Mean, RH	%	51.6	39.0	39.1	43.5	44.5
SD, RH	%	0.1	0.5	0.5	0.2	0.1

Notes:
SD = standard deviation
Delta= difference between upstream and downstream values
RH = relative humidity
T = temperature
STM = Standard test method
MQL = Method Quantification Limit test
NC = not collected

9.3 **Survey of homes for Tulsa Testing in November 2011**

House selection is described in Section 2 and is based on size, availability, recent activities in the candidate homes, and upcoming plans within each of the homes. Specifics on reasoning as to selection, or lack thereof, are included related to each home.

TU Test 001 – Home is located (40 minutes NE of TU), in Claremore, Oklahoma. The home owners will have family in for both the Thanksgiving and Christmas Holiday. Testing will need to be limited to 8am to 5pm Monday-Friday. Supply air duct system is flexible ducting, installed in 2002 and may be nearing the end of the expected lifespan for this type of installation. Filtration is reported to have been rated at MERV 0-4 since the installation of the Heating and Cooling system. Due to travel time from TU, limited home access and the age of the flex-duct supply system this home would not be a primary candidate.

TU Test 002 – Home is located in the south mid-town area of Tulsa (15 minutes south of Tulsa University (TU)). The homeowners are relocating to Arkansas during the Thanksgiving Holiday. The home interior was updated in 2008-2010 by the previous owner. The windows are still single pane and in fact some may date back to the late sixties or early seventies. Carpet has been installed in each of the bedrooms. Access to the home would be coordinated with the listing agent and it is possible that some testing interruptions may occur during December 2011. Hard surface floors are going to be re-coated and buffed prior to showing the home in January 2012. Due to the size of the home (1569 sq. ft.) and the short test period available (2 – 3 weeks) prior to interior refinishing of the floors, this home would not be a primary candidate.

TU Test 003 – Interior painting of the home is scheduled to begin in mid December 2011. Due to the availability of the home prior to painting activity, this home would not be a primary candidate.

TU Test 004 – These units are side by side duplex units. Due to the structures being duplexes this home would not be a primary candidate as a "representative" home.

TU Test 005 – Home interior was painted and flooring re-finished in May – September 2011. Home had been a model home and is now a rental property ($1375.00 per month). Due to the recent painting, floor resurfacing and rental cost this home would not be a primary candidate.

TU Test 006 – Forced air unit is located in the garage. Residents of the home work part-time in construction. Garage has many types of paints, varnishes, floor finishes, and adhesives stored. Due to the occupant activity related to storage in the garage of construction products and the location of the forced air unit in the same space this home would not be a primary candidate.

TU Test 007 – This is a model home for the development and would be available for access after 5 PM and on Sunday only. Due to the limited access for the field technical staff to the structure this home would not be a primary candidate.

TU Test 008 – Home is a rental property. Currently no long term lease has been offered and the home owner would discuss month to month rental with the understanding that a long-term lease would require we vacate. Rental is $750 per month. Interior was freshly painted in October 2011. Due to the recent painting activity and potential for interruption of testing (if the home is leased) this home would not be a primary candidate.

TU Test 009 – Model home and empty for sale home have carpet in the Hallways and Bedrooms (west portion of the house) and hard surface floors in the east half of the home. Both homes have 2 return air ducts, one close to the Forced air unit and one at the opposite end of the home. Due to the location of the return air grilles and the flooring surface differences this home would not be a primary candidate.

TU Test 010 – Home interior was freshly painted in the fall of 2011. The Forced air unit is located in a central interior closet and has little or no access for modification work. Home also has 3 return air grilles of different sizes and may impact air flow within the home. Due to the number and location of the return air grilles, limited access to the forced air system and possible uneven air flow patterns within the structure this home would not be a primary candidate.

TU Test 011 –This home was selected as the primary test home. Egress to and from the home can be accomplished thru the mud room off of the kitchen (no direct door opening to the outside). The Forced air unit and all return and supply air ducts are in the attic (new in the summer of 2011) and provide full access for installation of test equipment. Home has one central return air duct. New double pane windows were installed in the home in the summer of 2011. Home has hard surface floors in all rooms. One occupant is living in the home and so minimal furniture is present. Occupant has agreed to remove all cleaning products, candles, air fresheners, etc. from the home. Occupant is also willing to relocate to her parents home during testing periods to allow testing crew unlimited access. Rental is $400.00 for each 30 day test period. Homeowner has also approved system modifications required to install and uninstall test equipment. Due to the expected cooperation of the homeowner and occupant, rental cost, location and access of the forced air system, consistent flooring type, central location of the return air grille, egress into and out of the structure this home *is* recommended.

9.4 California induct device testing checklist for homes

Test Name	
Date	
Address	
Test Device	

California Field Test Checklist	
If necessary, install In-Duct Ozone Generating Device—1-2 ;if new in-duct is device being installed, allow run-in time of 4 hours minimum if possible w/in test home location)	
A licensed HVAC technician must install the in-duct ozone generating device.	
HVAC technician tests device for specified operation.	
Monitoring Site Selection and Preparation—15 minutes	
Locate monitoring sites so that sampling tubes are 2 m or less in length.	
For AER & ODR tests, locate 2 representative indoor static monitoring locations e.g. bedroom and living room. Static monitoring sites are in center of room, free of obstructions, and 1 to 1.5 meters high. Sites should be away from VOC sources, air vents, partitions including large furniture pieces, and direct sunlight by at least 1 meter.	
Locate 1 outdoor monitoring location. Outdoor monitoring site is 1 to 2 meters from house and 1 to 1.5 meters high, and away from potential ozone sources or sinks sources.	
For OER test, locate an air supply (downstream) monitoring site that has the shortest duct run from the test device, and locate a return (upstream) monitoring site that has the shortest duct run to the test device. If the supply and returns with the shortest duct runs from the device are within 2 meters, select an alternate supply or return with the next shortest duct run from the test device.	
Place ozone monitors at OER supply and return monitoring locations and turn on to warm-up.	
Set-up 5 ozone sampling tubes, 2 in static monitoring sites, 1 outdoors, 1 at air supply vent, and 1 at air return vent. Supply vent sampling tubes are in center of vent or inserted into center of duct air stream. Return vent sampling tube is attached just below return vent grill (10 to 20 cm) near center of grill.	
Turn on ozone monitoring devices to warm-up for 30 minutes, until test cell temperature is 37.5 degrees C.	
Set-up logging computers for ozone monitors and establish data connection.	
Set-up carbon dioxide monitors within 1 meter of ozone sampling tubes.	
Set-up ozone generators near monitoring sites, and carbon dioxide cylinder for seeding process. Choose pathway for moving cylinder through house. Ozone generators should be located in primary ozone monitoring location rooms (e.g. living room, bedroom)	
Set-up mixing fans near monitoring sites. Use at least 2 box fans with long extension cords so fans can be moved about house.	
Building Inspection Preparation—30-60 minutes	
Inspect home interior to determine general air tightness. Close and lock all windows and doors, except egress door used in test. .	
Select egress door (use attached garage door if possible).	
Affix notification sign on entry doors.	
Measure humidity and temperature at indoor static monitoring sites and if possible, adjust to within 20% to 75% RH and 74° F +/-.	
Use air flow smoke tube to detect significant air leaks.	
Improve house air tightness, if large air leaks are detected. Seal with quick release painters tape and/or polyethylene sheeting (4 mil >) thickness.	
Open connecting doors within home.	
Close closet doors.	
Turn off all exhaust fans and cover fan switches with tape.	
Remove HVAC air filters.	
Seal suspected reactive emission sources like candles, personal care products and cleaners in air tight bags or containers.	
Turn off electrical or combustion emission sources, such as stand-alone heaters and air cleaners.	
Home O3 Concentration Rise due to In-Duct Device Operation (OER)—Device On—4 ½ hours	
HVAC settings; Fan On and System Off.	
Attach the 2 supply and return vent sampling tubes. Move monitors as necessary.	
Review ozone monitor conditions and resolve fault errors.	

Log baseline ozone concentration for 30 minutes prior to test release of O3. Need to establish background ozone readings.	
Start ozone and carbon dioxide data logging.	
Check cable connections and confirm data logging. Confirm correct test cell temperature.	
Record starting time, ozone, carbon dioxide, temperature, and relative humidity readings at each monitoring location (2 indoor, 1 outdoor).	

Test Start Time:		Notes	
	Outdoor:	Supply Vent	Return Vent
CO_2 (ppm)			
Temp (F)			
RH (%)			
O_3 (ppb)			

	TIME
Turn on ozone in-duct device, set to high setting if applicable.	
Turn on mixing fans.	
Seed carbon dioxide to > 4,000 ppm and monitor carbon dioxide concentration	
Move mixing fans about house to increase air mixing.	
When carbon dioxide concentrations differ by less than 10% at each monitoring site, turn off mixing fans.	
Close and lock egress door.	
After 4.5 hours, enter house.	
Record ending time, ozone, carbon dioxide, temperature, and relative humidity readings at each monitoring location (2 indoor, 1 outdoor).	

Test End Time:		Notes	
	Outdoor:	Supply Vent	Return Vent
CO_2 (ppm)			
Temp (F)			
RH (%)			
O_3 (ppb)			

Confirm successful data logging and that data appears valid and reasonable. If unsuccessful, repeat test.	
Download logged monitor data onto computer hard drives and flash drives. Use at least 2 storage media to ensure data is captured.	
Calculate AER & OER(estimates only) using "early" and "later" concentration values that are more representative of the actual test data (neglecting noise at start and end of test).	
AER (est):	OER (est):

AER & ODR Monitor Operation—Stage 1 Fan On—90 minutes	
Carbon dioxide meter calibration equipment should be brought onsite to use as needed. Normally the CO2 monitors should be calibrated the day before testing occurs if possible.	
Set ozone logging on 60 second averaging.	
Set carbon dioxide, temperature, and relative humidity logging on 60 second averaging.	
Review ozone monitor conditions and resolve fault errors.	
Log baseline ozone concentration for 30 minutes prior to test release of O3. Need to establish background ozone readings.	
Let home return to approximate (within 30%) O3 background and CO2 from OER test before beginning test. If necessary open windows and doors, and use mixing fans to increase air exchange.	
Take pictures of the 3 monitoring sites and the exterior and interior of home	
Turn on ozone and carbon dioxide data logging.	
Check cable connections and confirm data logging.	
Record starting time, ozone, carbon dioxide, temperature, and relative humidity readings at each monitoring location (2 indoor, 1 outdoor).	

Test Start Time:		Notes	

	Outdoor:	Indoor location 1:	Indoor location 2 :
CO_2 (ppm)			
Temp (F)			
RH (%)			
O_3 (ppb)			

	TIME
Turn on mixing fans.	
Turn HVAC to Fan On, System Off	
Seed ozone to nearly 100 ppb; ensure concentrations are stable in home before turning off the generator. If concentrations are not stable, but ozone is near 100 ppb, then set ozone generator timer for 15 minute generation after leaving house.	
Seed carbon dioxide to > 4,000 ppm and monitor carbon dioxide concentration	
Move mixing fans about house to increase air mixing.	
When carbon dioxide concentrations differ by less than 10% at each monitoring site, turn off mixing fans.	
Close and lock egress door.	
After 1.5 hour, enter house.	
Record ending ozone, carbon dioxide, temperature, and relative humidity readings at each monitoring location (2 indoor, 1 outdoor) and time that test is ended	

Test End Time:		Notes	
	Outdoor:	Indoor location 1:	Indoor location 2:
CO_2 (ppm)			
Temp (F)			
RH (%)			
O_3 (ppb)			

Confirm successful data logging and that data appears valid and reasonable.	
Calculate AER, ORR & ODR (estimates only) using "early" and "later" concentration values that are more representative of the actual decay (neglecting noise at start and end of test). AER (est): ORR (est): ODR (est):	
Download logged monitor data onto computer hard drives and flash drives. Use at least 2 storage media to ensure data is captured.	
AER & ODR Monitor Operation—Stage 2 Fan Off—90 minutes	
Conduct test if sufficient time of test house occupancy remains to complete test and	
Attach the 2 indoor static monitoring site sampling tubes to monitors. Move monitors as necessary.	
Review ozone monitor conditions and resolve fault errors.	
Log baseline ozone concentration for 30 minutes prior to test release of O3. Need to establish stable background ozone readings.	
Let home return to approximate stable O3 background and CO2 from Stage 1 test before beginning test. If necessary open windows and doors, and use mixing fans to increase air exchange.	
Turn on ozone and carbon dioxide data logging.	
Check cable connections and confirm data logging.	
Record starting time, ozone, carbon dioxide, temperature, and relative humidity readings at each monitoring location (2 indoor, 1 outdoor).	

Test Start Time:		Notes	
	Outdoor:	Indoor location 1 :	Indoor location 2:
CO_2 (ppm)			
Temp (F)			
RH (%)			
O_3 (ppb)			

	TIME
Turn on mixing fans.	
Turn HVAC to Fan Off, System Off	
Turn on ozone and carbon dioxide data logging.	
Check cable connections and confirm data logging.	
Seed carbon dioxide to > 4,000 ppm and monitor carbon dioxide concentration	
Seed ozone to nearly 100 ppb; ensure concentrations are stable (staying within 80 ppb to 100 ppb range for 5	

minutes) in home before turning off the generator. If concentrations are not stable, but ozone is near 100 ppb, then set ozone generator timer for 15 minute generation after leaving house.	
Move mixing fans about house to increase air mixing, after carbon dioxide is >4000 ppm at each air quality monitor.	
When carbon dioxide concentrations differ by less than 10% at each monitoring site, turn off mixing fans.	
Close and lock egress door.	
After 1.5 hour, enter house.	
Record ending time, ozone, carbon dioxide, temperature, and relative humidity readings at each monitoring location (2 indoor, 1 outdoor).	

Test End Time		Notes	
	Outdoor:	Indoor location 1:	Indoor location 2 :
CO_2 (ppm)			
Temp (F)			
RH (%)			
O_3 (ppb)			

Confirm successful data logging and that data appear valid. If unsuccessful, repeat test.	
Calculate AER, ORR & ODR (estimates only) using "early" and "later" concentration values that are more representative of the actual decay (neglecting noise at start and end of test). Calculation of AER, ORR , ODR are provided in protocol narrative) AER (est): ORR(est): ODR (est):	
Download logged monitor data onto computer hard drives and flash drives. Use at least 2 storage media to ensure data is captured.	
Test Take Down Process	
Air out house as necessary to reduce ozone & carbon dioxide concentrations.	
Return HVAC air filters and reset HVAC settings to pre-test settings (Fan Auto, System Heat or Cool)	
Remove air tightening tape and plastic sheeting.	
Remove in-duct test devices that are not part of home. Ensure tight duct seal with air flow smoke tube.	
Return any potential emission sources that were sealed in air tight containers to original locations. Turn on any exhaust fans and other devices that were turned off or unplugged during the test.	
Remove and load equipment & supplies.	
Note any damage resulting from test and take pictures of any damage.	
Sweep up any debris/dirt resulting from test activity.	
Return key as arranged with owner/property manager.	

9.5 California induct device testing checklist for commercial test

Test Name	
Date	
Address	
Test Device	Trane TCACS (Trane Catalytic Air Cleaning System), MERV 13 Filter, Photocatalytic Oxidation, and UV

California Field Test Checklist	
Monitoring Site Selection and Preparation—15 minutes	
Locate monitoring sites so that sampling tubes are 2 m or less in length.	
For AER & ODR tests, locate 1 representative indoor static monitoring locations in center of room, free of obstructions, and 1 to 1.5 meters high. Sites should be away from VOC sources, air vents, partitions including large furniture pieces, and direct sunlight by at least 1 meter.	
Locate 1 outdoor monitoring location. Outdoor monitoring site is 1 to 2 meters from building and 1 to 1.5 meters high, and away from potential ozone sources or sinks sources.	
For OER test, locate an air supply (downstream) monitoring site that has the shortest duct run from the test device.	
Turn on ozone monitoring devices to warm-up for 30 minutes, until test cell temperature is 37.5 degrees C.	
Set-up logging computers for ozone monitors and establish data connection.	
Set-up carbon dioxide monitors within 1 meter of ozone sampling tubes.	
Set-up ozone generators and carbon dioxide cylinder for seeding process. Choose pathway for moving cylinder through room.	
Set-up mixing fans near monitoring sites. Use at least 2 box fans with long extension cords so fans can be moved about room.	
Building Inspection Preparation—30-60 minutes	
Inspect room interior to determine general air tightness. Close and lock all windows and doors, except egress door used in test. .	
Select egress door.	
Affix notification sign on entry doors.	
Measure humidity and temperature at indoor static monitoring sites .	
Use air flow smoke tube to detect significant air leaks.	
Improve room air tightness, if large air leaks are detected. Seal with quick release painters tape and/or polyethylene sheeting (4 mil >) thickness.	
Open connecting doors if any.	
Close closet doors.	
Turn off all exhaust fans.	
Remove HVAC air filters.	
Seal suspected reactive emission sources like candles, personal care products and cleaners in air tight bags or containers.	
Turn off electrical or combustion emission sources, such as stand-alone heaters and air cleaners.	
O3 Concentration Rise due to In-Duct Device Operation (OER)—Device On—4 ½ hours	
HVAC settings; Fan On and System Off.	
Attach the 2 supply and return vent sampling tubes. Move monitors as necessary.	
Review ozone monitor conditions and resolve fault errors.	
Log baseline ozone concentration for 30 minutes prior to test release of O3. Need to establish background ozone readings.	
Start ozone and carbon dioxide data logging.	
Check cable connections and confirm data logging. Confirm correct test cell temperature.	
Record starting time, ozone, carbon dioxide, temperature, and relative humidity readings at each monitoring location (2 indoor, 1 outdoor).	

Test Start Time:		Notes	

	Outdoor:	Supply Vent	Center of Room
CO_2 (ppm)			
Temp (F)			
RH (%)			
O_3 (ppb)			

	TIME
Turn on ozone in-duct device, set to high setting if applicable.	
Turn on mixing fans.	
Seed carbon dioxide to > 4,000 ppm and monitor carbon dioxide concentration	
Move mixing fans about room to increase air mixing.	
When carbon dioxide concentrations differ by less than 10% at each monitoring site, turn off mixing fans.	
Close and lock egress door.	
After 4.5 hours, enter room.	
Record ending time, ozone, carbon dioxide, temperature, and relative humidity readings at each monitoring location (2 indoor, 1 outdoor).	

Test End Time:		Notes	

	Outdoor:	Supply Vent	Center of Room
CO_2 (ppm)			
Temp (F)			
RH (%)			
O_3 (ppb)			

Confirm successful data logging and that data appears valid and reasonable. If unsuccessful, repeat test.	
Download logged monitor data onto computer hard drives and flash drives. Use at least 2 storage media to ensure data is captured.	
Calculate AER & OER(estimates only) using "early" and "later" concentration values that are more representative of the actual test data (neglecting noise at start and end of test).	
AER (est): OER (est):	
AER & ODR Monitor Operation—Stage 1 Fan On—90 minutes	
Calibrate carbon dioxide meter.	
Set ozone logging on 60 second averaging.	
Set carbon dioxide, temperature, and relative humidity logging on 60 second averaging.	
Review ozone monitor conditions and resolve fault errors.	
Log baseline ozone concentration for 30 minutes prior to test release of O3. Need to establish background ozone readings.	
Let room return to approximate (within 30%) O3 background and CO2 from OER test before beginning test. If necessary open windows and doors, and use mixing fans to increase air exchange.	
Take pictures of the 3 monitoring sites and the exterior and interior of building.	
Turn on ozone and carbon dioxide data logging.	
Check cable connections and confirm data logging.	
Record starting time, ozone, carbon dioxide, temperature, and relative humidity readings at each monitoring location (2 indoor, 1 outdoor).	

Test Start Time:		Notes	

	Outdoor:	Indoor location 1 (take picture):	Indoor location 2 (take picture) :
CO_2 (ppm)			
Temp (F)			
RH (%)			
O_3 (ppb)			

	TIME

Turn on mixing fans.	
Turn HVAC to Fan On, System Off	
Seed ozone to nearly 100 ppb; ensure concentrations are stable in room before turning off the generator. If concentrations are not stable, but ozone is near 100 ppb, then set ozone generator timer for 15 minute generation after leaving room.	
Seed carbon dioxide to > 4,000 ppm and monitor carbon dioxide concentration	
Move mixing fans about house to increase air mixing.	
When carbon dioxide concentrations differ by less than 10% at each monitoring site, turn off mixing fans.	
Close and lock egress door.	
After 1.5 hour, enter room.	
Record ending ozone, carbon dioxide, temperature, and relative humidity readings at each monitoring location (2 indoor, 1 outdoor) and time that test is ended	

Test End Time:		Notes	
	Outdoor:	Indoor location 1:	Indoor location 2:
CO_2 (ppm)			
Temp (F)			
RH (%)			
O_3 (ppb)			

Confirm successful data logging and that data appears valid and reasonable.	
Calculate AER, ORR & ODR (estimates only) using "early" and "later" concentration values that are more representative of the actual decay (neglecting noise at start and end of test). AER (est): ORR (est): ODR (est):	
Download logged monitor data onto computer hard drives and flash drives. Use at least 2 storage media to ensure data is captured.	
AER & ODR Monitor Operation—Stage 2 Fan Off—90 minutes	
Conduct test if sufficient time to complete test.	
Attach the 2 indoor static monitoring site sampling tubes to monitors. Move monitors as necessary.	
Review ozone monitor conditions and resolve fault errors.	
Log baseline ozone concentration for 30 minutes prior to test release of O3. Need to establish stable background ozone readings.	
Let room return to approximate stable O3 background and CO2 from Stage 1 test before beginning test. If necessary open windows and doors, and use mixing fans to increase air exchange.	
Turn on ozone and carbon dioxide data logging.	
Check cable connections and confirm data logging.	
Record starting time, ozone, carbon dioxide, temperature, and relative humidity readings at each monitoring location (2 indoor, 1 outdoor).	

Test Start Time:		Notes	
	Outdoor:	Indoor location 1 :	Indoor location 2:
CO_2 (ppm)			
Temp (F)			
RH (%)			
O_3 (ppb)			

	TIME
Turn on mixing fans.	
Turn HVAC to Fan Off, System Off	
Turn on ozone and carbon dioxide data logging.	
Check cable connections and confirm data logging.	
Seed carbon dioxide to > 4,000 ppm and monitor carbon dioxide concentration	
Seed ozone to nearly 100 ppb; ensure concentrations are stable (staying within 80 ppb to 100 ppb range for 5 minutes) in room before turning off the generator. If concentrations are not stable, but ozone is near 100 ppb, then set ozone generator timer for 15 minute generation after leaving room.	
Move mixing fans about room to increase air mixing, after carbon dioxide is >4000 ppm at each air quality monitor.	
When carbon dioxide concentrations differ by less than 10% at each monitoring site, turn off mixing fans.	
Close and lock egress door.	
After 1.5 hour, enter room.	
Record ending time, ozone, carbon dioxide, temperature, and relative humidity readings at each monitoring location (2 indoor, 1 outdoor).	

Test End Time		Notes	
	Outdoor:	Indoor location 1:	Indoor location 2 :
CO_2 (ppm)			
Temp (F)			
RH (%)			
O_3 (ppb)			

Confirm successful data logging and that data appear valid. If unsuccessful, repeat test.	
Calculate AER, ORR & ODR (estimates only) using "early" and "later" concentration values that are more representative of the actual decay (neglecting noise at start and end of test). Calculation of AER, ORR , ODR are provided in protocol narrative) AER (est): ORR(est): ODR (est):	
Download logged monitor data onto computer hard drives and flash drives. Use at least 2 storage media to ensure data is captured.	
Test Take Down Process	
Air out room as necessary to reduce ozone & carbon dioxide concentrations.	
Return HVAC air filters and reset HVAC settings to pre-test settings (Fan Auto, System Heat or Cool)	
Remove air tightening tape and plastic sheeting.	
Remove in-duct test devices that are not part of building. Ensure tight duct seal with air flow smoke tube.	
Return any potential emission sources that were sealed in air tight containers to original locations. Turn on any exhaust fans and other devices that were turned off or unplugged during the test.	
Remove and load equipment & supplies.	
Note any damage resulting from test and take pictures of any damage.	
Sweep up any debris/dirt resulting from test activity.	
Return key as arranged with owner/property manager.	

9.6 Description, images, plan drawings and data for California Test houses

9.6.1 California Test House 1

Location: Davis, CA.
Testing conducted: May 22 and 23, 2012.
Device Tested: activTek INDUCT 2000
Description: House area is 150 m^2 and volume is 377 m^3. The house had a high vaulted ceiling, two floors, and an open stair case and balcony overlooking living room area. Living, kitchen, dining, and ½ bath areas located on the first floor. Three bedrooms and two bathrooms located on the second floor. The house had an attached two-car garage. HVAC was a forced air system accessed from the attic. House floor plan with a photograph of the house and the supply sampling site in the master bedroom is below. A rabbit occupied the house. At the request of the occupant their pet rabbit was in the house during the testing.

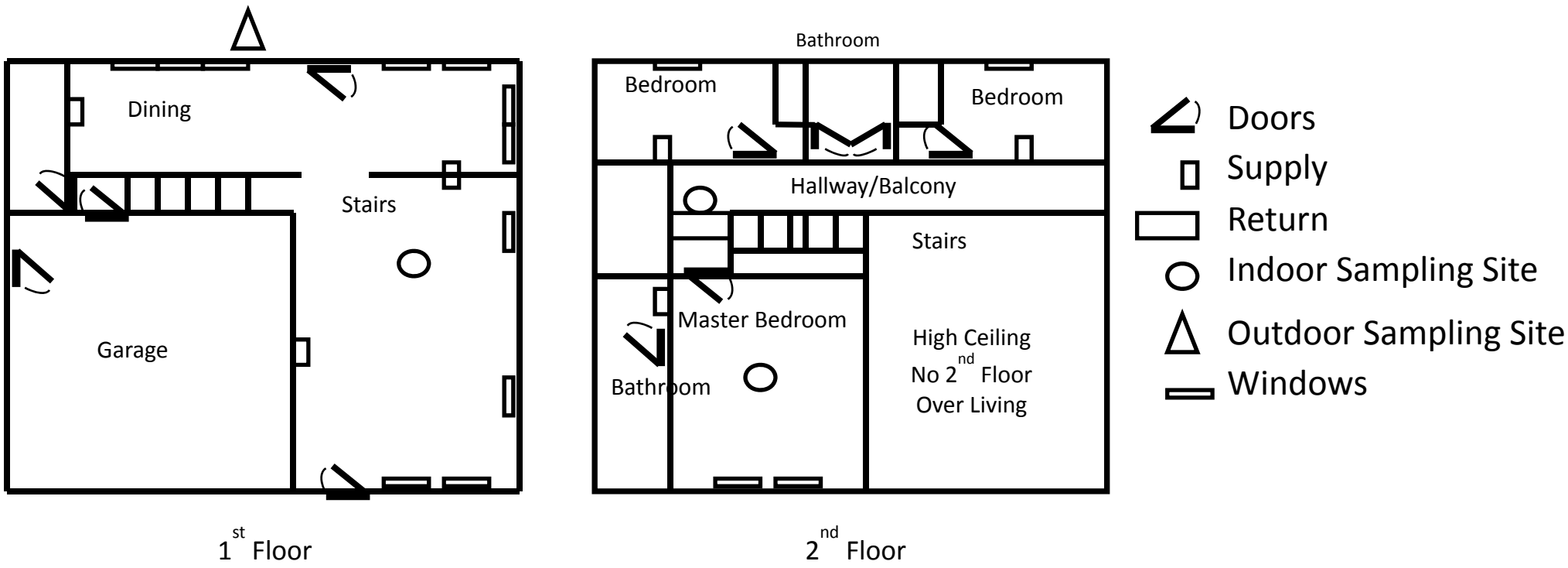

Figure 9.11. Plan drawing of test house 1 including sample locations and location of supply and return vents.

Figure 9.12. Image of front of Test House 1 and location of supply sampling in master bedroom.

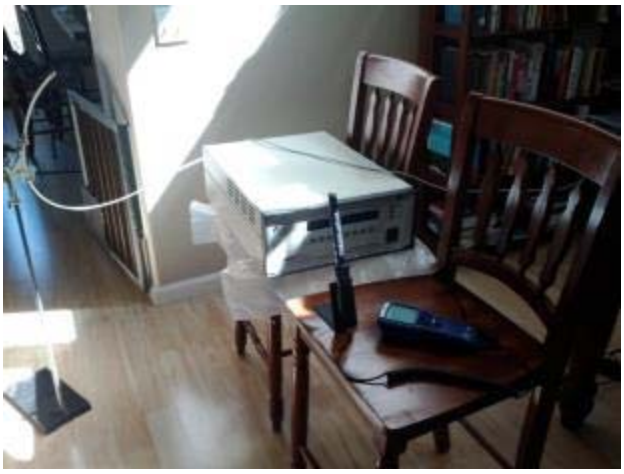

Figure 9.13. Image of location of living room sampling.

Figure 9.14. Image of device tested (activTek INDUCT 2000) as installed in air handling system.

Test House 1 summary data is provided below. Subsequent tables (3) provide test condition data for each test.

Table 9.21. Summary of Test House 1 results including air exchange rates, ozone decay rates, incremental increase in ozone concentration and ozone emission rates.

Date & Start Time	HVAC Status	Test House, Test & In-Duct Device Tested	Air Exchange Rate (1/hr)		Ozone Removal Rate (1/hr)		Ozone Decay Rate (1/hr)		Max Conc. (ppb)	Steady State Conc. (ppb)	Ozone emission rate, OER1, mg/hr	OER2, mg/hr
			Bedroom	Living room	Bedroom	Living room	Bedroom	Living room				
5/22/12 10:30	Stage 1 Fan On	**Test House 1** AER/ODR	0.31±0.01	0.37±0.01	5.0±0.9	7.7±0.2	4.7±0.9	7.4±0.2				
5/22/12 13:26		**Test House 1** AER/ODR/OER activTek INDUCT 2000	0.27±0.01	0.27±0.01	5.0±0.9	7.7±0.2	4.7±0.9	7.5±0.2	5.13±1.5	4.37±0.93	13.5±11.82	9.95±6.12
5/23/12 10:20		**Test House 1** AER/ODR	0.25±0.01	0.14±0.01	2.8±0.2	4.1±0.2	2.52±0.2	4.0±0.2				
5/23/12 12:20		**Test House 1** AER/ODR/OER activTek INDUCT 2000	0.32±0.01	0.31±0.01	2.8±0.2	4.1±0.2	2.52±0.2	3.8±0.2	6.8±1.5	5.83±0.84	5.5±1.5	8.8±4.3

Table 9.22. Test House 1 AER/ODR May 22 10:30, Test Conditions.

Test Start Time:	10:30	Notes	CO_2 Canister ran out during seeding; was able to achieve 4000+ ppm concentration. CO_2 levels above 1000 ppm before seeding. Rabbit left in house per occupant direction.
Test Conditions	Outdoor: Backyard Patio	Indoor location 1: Dining Room/Living Room/Stairs Junction	Indoor location 2 : Master Bedroom
CO_2 (ppm)	408	1194	1076
Temp (F)	74.7	73.4	73.2
RH (%)	49.4	57.7	57.4
O_3 (ppb)	30.2	1.8	2.8
Test End Time:	13:03	Notes	Clear skies; temperature climbing. Purchased CO_2 in Woodland, CA.
CO_2 (ppm)	404	2611	2628
Temp (F)	80.3	76.1	76.3
RH (%)	35.9	51.7	52.0
O_3 (ppb)	42.2	2.1	3.5

Table 9.23. Test House 1 OER May 22 13:26, Test Conditions.

Test Start Time:	13:26	Notes	2B-Tech A Outdoors, 2B Tech B Supply Vent, API Return Vent
Test Conditions	Outdoor: Backyard Patio	Supply Vent: Dining Room/Living Room/Stairs Junction	Return Vent: Top of stair; in front of master bedroom
CO_2 (ppm)	405	2178	2502
Temp (F)	83.4	76.9	76.4
RH (%)	35	52.7	53.0
O_3 (ppb)	46.4	2.4	0.9
Test End Time:	17:00	Notes	Outdoor ozone stable after climbing in morning.
CO_2 (ppm)	414	1997	2261
Temp (F)	93.0	80.8	78.4
RH (%)	23.0	49.5	51.2
O_3 (ppb)	47.1	17.2	6.8

Table 9.24. Test house 1 OER May 23 12:20, test conditions.

Test Start Time:	12:20	Notes	2B-Tech A Outdoors, 2B Tech B Supply Vent, API Return Vent
Test Conditions	Outdoor: Backyard Patio	Supply Vent: Dining Room/Living Room/Stairs Junction	Return Vent: Top of stair; in front of master bedroom
CO_2 (ppm)	397	3939	4513
Temp (F)	74.9	74.2	75.8
RH (%)	33.1	48.8	44.9
O_3 (ppb)	48.4	60.9	36.3
Test End Time:	16:20	Notes	
CO_2 (ppm)	426	3142	4128
Temp (F)	93.3	76.0	77.8
RH (%)	15.3	46.5	43.7
O_3 (ppb)	47.8	21.0	8.1

9.6.2 California Test House 2

Location: Sacramento, CA.
Testing conducted: May 25, 2012.
Device tested: Trane Clean Effects
Description: Testing conducted. House area is 218 m^2 and volume is 531 m^3, but the upper floor with 219 m^3 was sealed off during testing so that only 312 m^3 (downstairs, approximately 127 m^2) was involved in the testing. The 1st and 2nd floors had separate HVAC systems. The downstairs had two bathrooms, three bedrooms, a living room, a den, and a kitchen. The house had a fireplace that was sealed during testing. Attached to the house was a two-car garage. HVAC was forced air systems with a Trane Clean Effects EP installed on the 1st floor system. The HVAC system was accessed in a small 1st floor utility closet. The occupant used 2 Oreck Air Purifiers (table-top, room sized cleaners with EP and filtration); these devices were turned off during testing. Backyard was heavily vegetated with fruit trees and shrubs. The drawing below only shows the first floor of the house because the 2nd floor was not involved in testing.

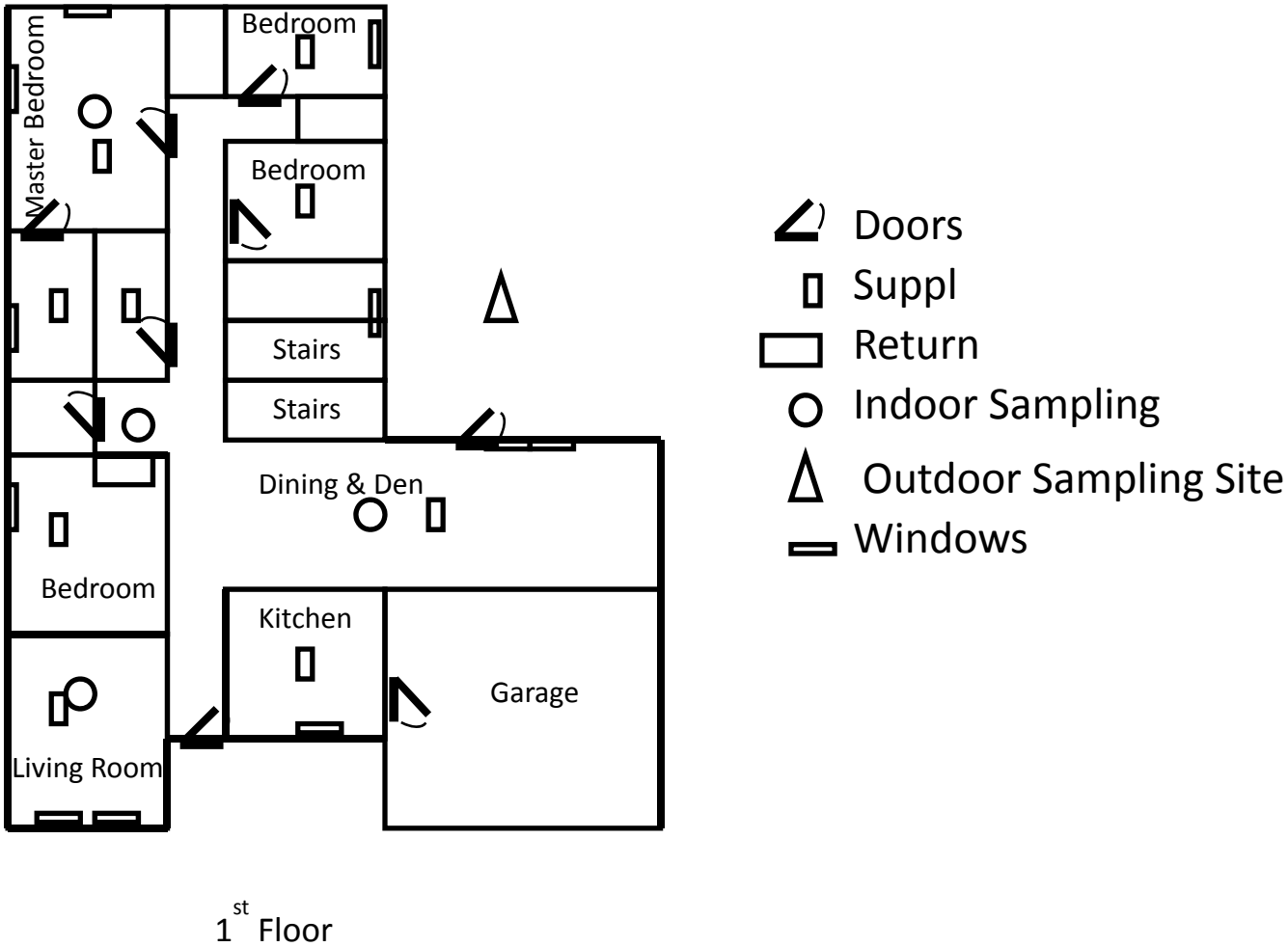

Figure 9.15. Plan drawing of Test House 2 including sample locations and location of supply and return vents (not to scale).

Figure 9.16. Image of front of Test House 2.

Figure 9.17. Image of location of supply sampling.

Figure 9.18. Image of device tested (Trane Clean EffectsTrane Clean Effects) as installed in air handling system.

Test House 2 summary data is provided below. Subsequent tables (2) provide test condition data for each test.

Table 9.25. Summary of Test House 2 results including air exchange rates, ozone decay rates, incremental increase in ozone concentration and ozone emission rates.

Date & Start Time	HVAC Status	Test House, Test & In-Duct Device Tested	Air Exchange Rate (1/hr)		Ozone Removal Rate (1/hr)		Ozone Decay Rate (1/hr)		Max Conc. (ppb)	Steady State Conc. (ppb)	Ozone emission rate, OER1, mg/hr	OER2, mg/hr
			Den	Living room	Den	Living room	Den	Living room				
5/25/12 15:25	Stage 1 Fan On	**Test House 2** AER/ODR	0.21±0.01	0.30±0.01	1.15±0.08	2.66±0.08	0.94±0.08	2.36±0.08				
5/25/12 10:16		**Test House 2** AER/ODR/OER Trane Clean Effects EP	0.32±0.01	0.30±0.01	1.15±0.08	2.66±0.08	0.85±0.08	2.34±0.08	10.4±1.5	7.11±2.4	2.68±1.12	3.69±4.75

Table 9.26. Test House 2 AER/ODR May 25 15:25, Test Conditions.

Test Start Time:	15:25	Notes	Oreck table top air purifiers turned off 1 hour prior to testing. Not in operation during testing. 2nd floor HVAC system off, fan off during testing to minimize effects; 2nd floor sealed off from first floor to minimize house volume.
Test Conditions	Outdoor: Backyard Patio	Indoor location 1: Living Room	Indoor location 2 : Den; occupants principal living area.
CO_2 (ppm)	245	1597	1626
Temp (F)	70.6	71.5	72.7
RH (%)	30.1	41.0	41.8
O_3 (ppb)	37.3	10	14.6
Test End Time:	17:00	Notes	
CO_2 (ppm)	247	2343	2265
Temp (F)	68.8	72.0	73.1
RH (%)	31.5	40.8	41.8
O_3 (ppb)	37.3	56.4	56.8

Table 9.27. Test House 2 OER May 25 10:16, Test Conditions.

Test Start Time:	10:16	Notes	Confirmed Oreck air purifiers remained off, and turned on Trane Clean Effects device, confirmed operation as indicated in manual. Very heavy vegetation in backyard; numerous trees and shrubs that may reduce outdoor CO_2 near of monitor.	
Test Conditions	Outdoor: Backyard Patio	Supply Vent: Living Room		Return Vent: Hallway off spare bedroom
CO_2 (ppm)	263	705		414
Temp (F)	80.5	68.4		66.1
RH (%)	18.8	45.2		49.7
O_3 (ppb)	28.1	6.0		4.5
Test End Time:	14:25	Notes	Return CO_2 did not log.	
CO_2 (ppm)	247	1780		1779
Temp (F)	69.4	70.7		71.8
RH (%)	32.7	41.5		42.3
O_3 (ppb)	39.2	15.0		10.2

9.6.3 California Test House 3

Location: Sacramento, CA.
Date of tests: May 30, 2012.
Device tested: AirZone Air Duct 2000
Description: House volume is 431 m^3 and area 180 m^2. The house had split HVAC systems for 1st floor and 2nd floor; forced air HVAC system accessed from attic. It was not practical to seal off the 2nd floor of this house due to design of stair case. The upper floor had four bedrooms and two bathrooms, and a small storage room. The 1st floor had a kitchen, dining room, living room, and den. A two car garage was attached to the house.

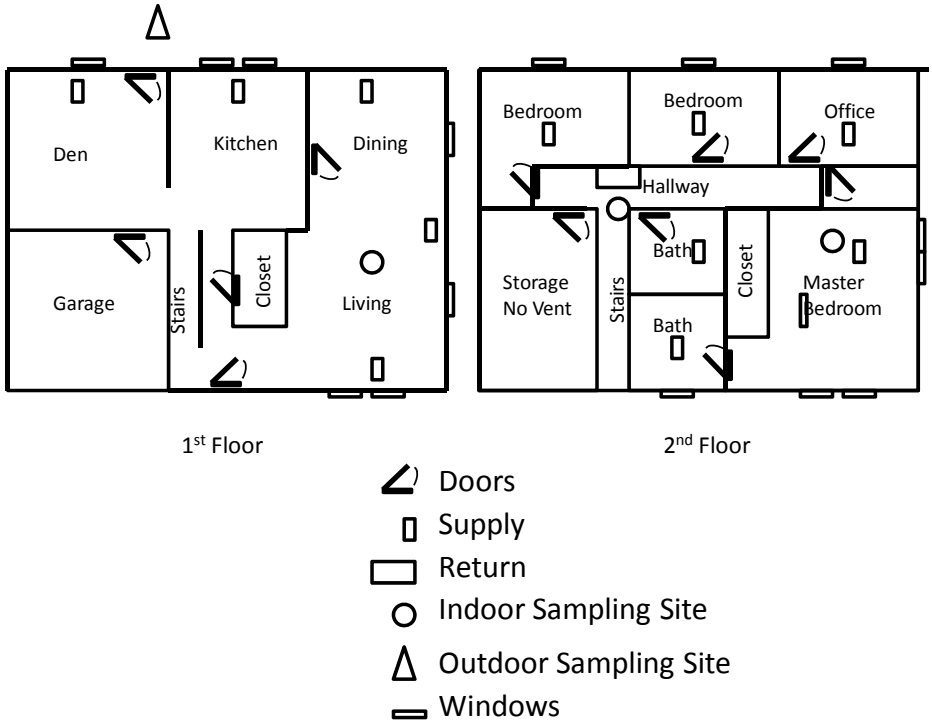

Figure 9.19 Plan drawing of Test House 3 including sample locations and location of supply and return vents (not to scale).

Figure 9.20. Image of front of Test House 3.

Figure 9.21. Image of location of sampling at return.

Figure 9.22. Image of monitoring site in master bedroom.

Test House 3 summary data is provided below. Subsequent tables (2) provide test condition data for each test.

Table 9.28. Summary of Test House 3 results including air exchange rates, ozone decay rates, incremental increase in ozone concentration and ozone emission rates.

Date & Start Time	HVAC Status	Test House, Test & In-Duct Device Tested	Air Exchange Rate (1/hr)		Ozone Removal Rate (1/hr)		Ozone Decay Rate (1/hr)		Max Conc. (ppb)	Steady State Conc. (ppb)	Ozone emission rate, OER1, mg/hr	OER2, mg/hr
			Den	Living room	Den	Living room	Den	Living room				
5/30/12 14:03	Stage 1 Fan On	**Test House 3** AER/ODR	0.73±0.02	0.66±0.02	2.94±0.2	5.78±0.3	2.22±0.2	5.12±0.3				
5/30/12 9:00		**Test House 3** AER/ODR/OER AirZone Air Duct 2000	0.93±0.01	0.53±0.04	2.94±0.2	5.78±0.3	2.02±0.2	5.25±0.3	10.8±1.5	25.2±2.4	61.3±16.2	71.1±17.5

Table 9.29. Test House 3 AER/ODR May 30 14:03, Test Conditions.

Test Start Time:	14:03	Notes	
Test Conditions	Outdoor: Backyard Patio/Pool Deck	Indoor location 1: Den	Indoor location 2 : Living Room
CO_2 (ppm)	387	649	793
Temp (F)	82.1	73.6	74.2
RH (%)	28.0	55.5	54.7
O_3 (ppb)	55.9	10.8	3.4
Test End Time:	16:15	Notes	
CO_2 (ppm)	391	1845	2290
Temp (F)	89.4	74.5	75.3
RH (%)	24.5	53.9	53.5
O_3 (ppb)	60.5	25.1	31.1

Table 9.30. Test House 3 OER May 30 9:05, Test Conditions.

Test Start Time:	9:05	Notes	2 returns in house, upstairs and downstairs; placed monitor on upstairs return.
Test Conditions	Outdoor: Backyard Patio/Pool Deck	Supply Vent: Living Room	Return Vent: Upstairs top of stairs
CO_2 (ppm)	407	934	986
Temp (F)	74.8	74.1	74.5
RH (%)	45.7	49.0	53.2
O_3 (ppb)	16.4	2.5	3.0
Test End Time:	13:03	Notes	
CO_2 (ppm)	391	963	839
Temp (F)	86.6	78.9	73.9
RH (%)	31.4	44.3	52.9
O_3 (ppb)	58.6	13.4	16.1

9.6.4 California Test House 4

Location: Garden Valley, CA.
Date of tests: January 7-8, 2013.
Description: located approximately 30 minutes southeast of Sacramento in the Sierra Nevada foothills. The house is in a remote, rural location in the foothills. The volume is 196 m^3 and the floor area is 93 m^2. The home had non-standard ceiling heights in bedrooms and living room area; approximately 2.3 m rather than 2.44 m. It is a single story house with 2 bedrooms, 2 bathrooms, dining area, living room, and kitchen. The house was tightly sealed and had a forced air HVAC system that was easily accessed in the attic. The house was not constantly occupied, but was fully furnished. The occupant operated the HVAC in an energy saving mode with the thermostat set at 55° F. The house did not have a garage attached. Floor plan for house is shown below.

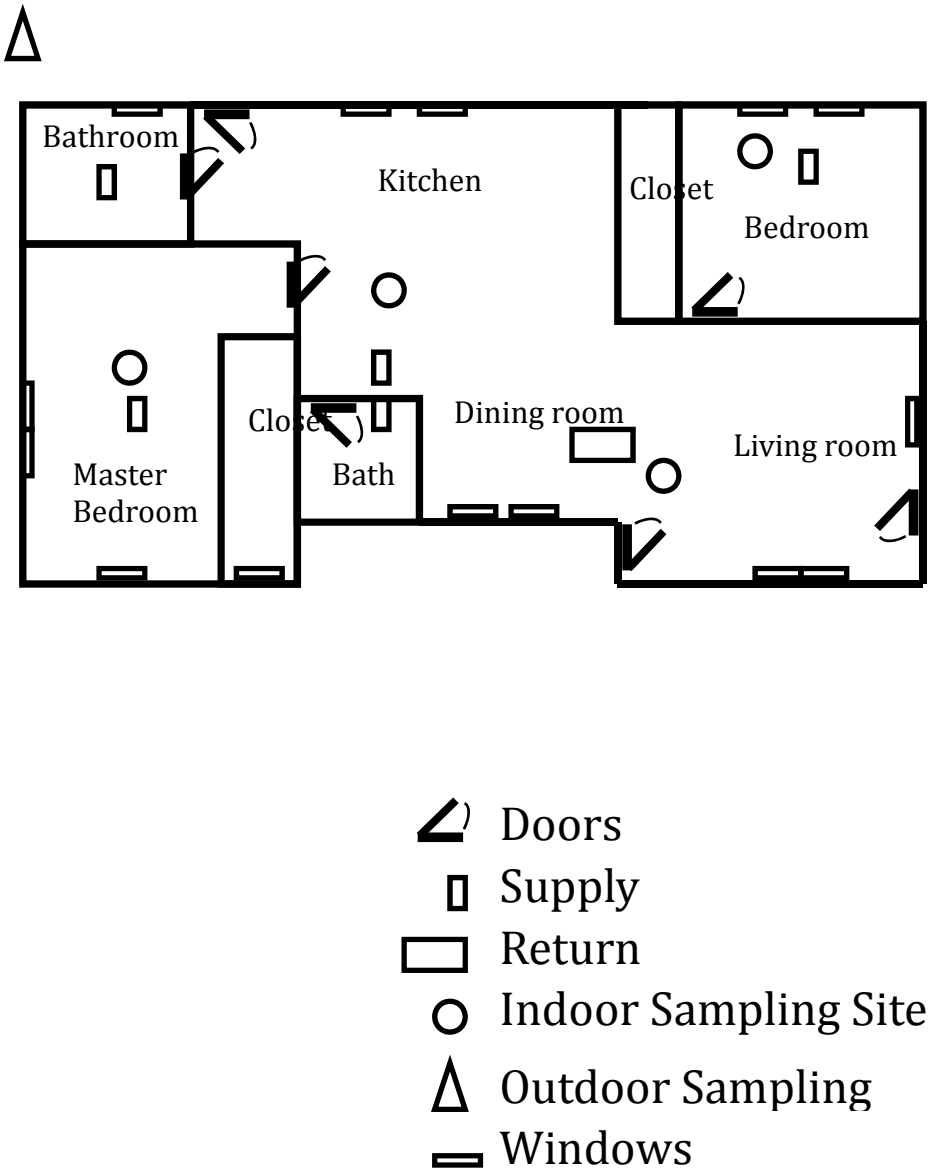

Figure 9.23. Plan drawing of Test House 4 including sample locations and location of supply and return vents (not to scale).

Figure 9.24. Image of front of Test House 4.

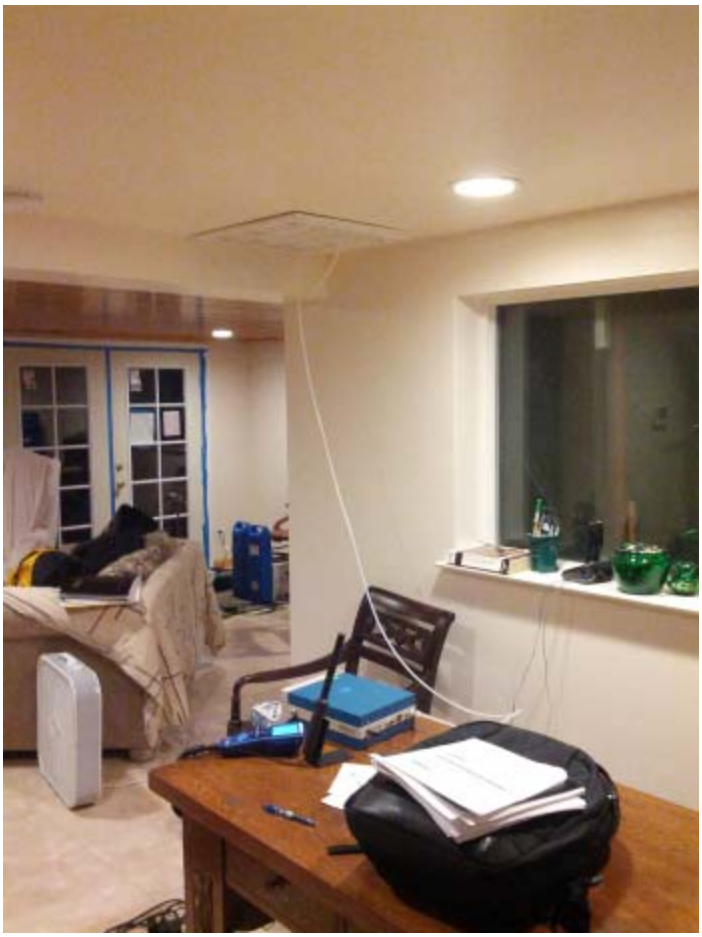

Figure 9.25. Image of location of sampling at return.

Figure 9.26. Image of HVAC UV 560 and activTek INDUCT 2000 installed after air handler.

Test House 4 summary data is provided below. Subsequent tables (2) provide test condition data for each test.

Table 9.31. Summary of Test House 4 results including air exchange rates, ozone decay rates, incremental increase in ozone concentration and ozone emission rates.

Date & Start Time	HVAC Status	Test House, Test & In-Duct Device Tested	Air Exchange Rate (1/hr)	Ozone Removal Rate (1/hr)	Ozone Decay Rate (1/hr)	Max Conc. (ppb)	Steady State Conc. (ppb)		Ozone emission rate, OER1, mg/hr		Alternate OER2, mg/hr	
							Center	Return	Center	Return	Center	Return
1/7 to 1/8/13 15:48	System On, Fan On	**Test House 4** AER/ODR/ OER HVAC UV 560	0.91±0.04	4.74±0.06	3.83±0.07	169±1.5	159±36.3	136±30.7	267±90	227±75	227±50	231±50
1/8/13 17:10	System On, Fan On	**Test House 4** AER/ODR/ OER activTek INDUCT 2000	0.57±0.01	3.99±0.10	3.43±0.10	19.8±1.5	17.8±0.06	16±70.05	23.6±8.21	22±8.87	22.0±4.66	20.5±6.6

Table 9.32. Test House 4 AER/ODR January 7 15:48, Test Conditions.

Test Start Time:	16:05	Notes	
Test Conditions	Outdoor: Near back door	Indoor location 1: Living Room	Indoor location 2 : Master Bedroom
CO_2 (ppm)	344	650	605
Temp (F)	48.6	57.0	57.6
RH (%)	77.6	63.6	62.7
O_3 (ppb)	13.9	0.5	3.5
Test End Time:	17:41	Notes	
CO_2 (ppm)	369	1902	2041
Temp (F)	53.7	58.4	60
RH (%)	66.7	64.2	59.4
O_3 (ppb)	3.3	17.1	20.5

Table 9.33. Test House 4 OER January 7-8 15:48, Test Conditions.

Test Start Time:	18:41	Notes	
Test Conditions	Outdoor: Near back door	Supply Vent: Spare Bedroom	Return Vent: Dining/Kitchen Area
CO_2 (ppm)	369	1419	1238
Temp (F)	39.7	65.7	66.1
RH (%)	93.0	55.4	56.1
O_3 (ppb)	5.4	1.0	3.6
Test End Time:	7:50 Jan 8	Notes	Foggy conditions in morning, noticeable ozone odor/irritation when entered home.
CO_2 (ppm)	382	455	432
Temp (F)	47.6	55.0	56.8
RH (%)	50.4	60	56.6
O_3 (ppb)	28.6	203	168

Table 9.34. Test House 4 OER January 8 17:10, Test Conditions.

Test Start Time:	16:05	Notes	
Test Conditions	Outdoor: Near back door	Supply Vent: Spare Bedroom	Return Vent: Dining/Kitchen Area
CO_2 (ppm)	344	650	636
Temp (F)	48.6	57	57
RH (%)	77.6	63.6	67.5
O_3 (ppb)	13.9	0.5	3.3
Test End Time:	17:10	Notes	
CO_2 (ppm)	369	1902	1996
Temp (F)	53.7	58.4	59.1
RH (%)	66.7	64.2	64.6
O_3 (ppb)	3.3	17.1	20.5

9.6.5 California Test House 5

Location: Davis, CA.
Date of tests: January 9-10, 2013.
Description: The volume is 206 m^3 and the floor area is 92 m^2. The house had 2 bedrooms, open kitchen/dining/living room space, laundry room, and two bathrooms. The house was attached to houses on either side (a modern row house construction). The house had a low slope roof with the HVAC system roof mounted. The system was not easily accessed and installation of the HVAC UV 560 test device required placing the UV lamp fixture completely into the duct distribution plenum, rather than mounting the lamp fixture outside the plenum with the UV lamp penetrating into the duct space (see Figure 10 below). The house had an attached single car garage. A dog and a cat regularly occupied the house. Test House 5 had a large master bedroom that was undergoing renovations and had the flooring removed to expose the concrete subfloor (house slab). Floor plan for the house is shown below.

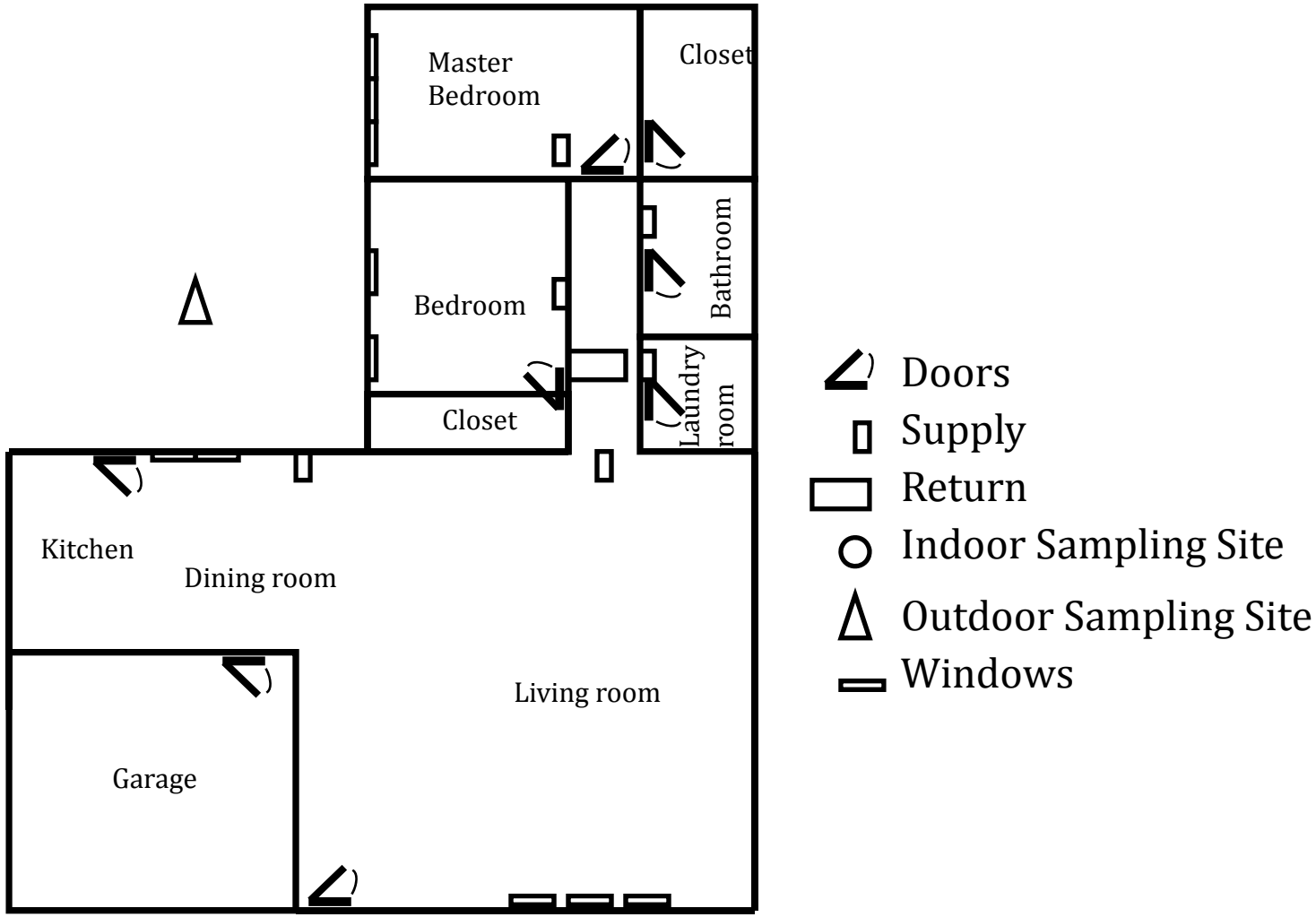

Figure 9.27. Plan drawing of Test House 5 including sample locations and location of supply and return vents (not to scale).

Figure 9.28. Image of front of Test House 5.

Figure 9.29. Image of HVAC UV 560 installed in plenum after fan.

Figure 9.30. Image of monitors in living room.

Test House 5 summary data is provided below. Subsequent tables (2) provide test condition data for each test.

Table 9.35. Summary of Test House 5 results including air exchange rates, ozone decay rates, incremental increase in ozone concentration and ozone emission rates.

Date & Start Time	HVAC Status	Test House, Test & In-Duct Device Tested	Air Exchange Rate (1/hr)	Ozone Removal Rate (1/hr)	Ozone Decay Rate (1/hr)	Max Conc. (ppb)	Steady State Conc. (ppb)		Ozone emission rate, OER1, mg/hr		Alternate OER2, mg/hr	
							Center	Return	Center	Return	Center	Return
1/10/13 9:21	System off, Fan Auto	**Test House 5** AER/ODR/ OER HVAC UV 560	0.44±0.01	6.23±0.51	5.80±0.51	93±1.5	103.2±3.7	87.6±3.9	239±62	202±53	234±33	197±28
1/11/13 9:02	System On, Fan On	**Test House 5** AER/ODR/ OER HVAC UV 560	0.52±0.01	6.23±0.51	5.7±0.51	109±1.5	119±22.4	104±7	280±105	244±81.7	271±64.3	236±35.7

Table 9.36. Test House 5 AER/ODR/OER January 10, 2013 9:21, Test Conditions.

Test Start Time:	9:21	Notes	
Test Conditions	Outdoor: Patio	Supply: Laundry	Return : Hallway, near living room
CO_2 (ppm)	366	992	1007
Temp (F)	69.6	67.1	66.7
RH (%)	34.2	47.2	50.0
O_3 (ppb)	13.7	5.0	2.8
Test End Time:	15:21	Notes	Distinct ozone odor on entry
CO_2 (ppm)	354	740	779
Temp (F)	50.0	63.2	63.8
RH (%)	49.3	51.9	54.0
O_3 (ppb)	33.6	145.2	88.4

Table 9.37. Test House 5 OER January 11 9:10, Test Conditions.

Test Start Time:	9:10	Notes	
Test Conditions	Outdoor: Patio	Supply Vent: Laundry	Return Vent: Hallway, near living room
CO_2 (ppm)	474	1062	1060
Temp (F)	38.7	61.9	60.6
RH (%)	69.3	43.1	49.3
O_3 (ppb)	8.7	5.0	1.4
Test End Time:	11:30	Notes	
CO_2 (ppm)	375	670	701
Temp (F)	47.4	67.4	67.8
RH (%)	48.9	41.3	44.5
O_3 (ppb)	12.0	148.0	104.8

9.6.6 California Test House 6

Location: Citrus Heights, CA.
Date of tests: January 11-13, 2013.
Description: The volume is 199 m^3 and the floor area is 94 m^2. Testing was conducted January 11 to 13, 2013. The house had three bedrooms, a living room, dining area, kitchen and one bathroom. A two-car garage attached to the house. The HVAC system was a forced air system accessed in the attic. A medium sized dog regularly occupied the house, but was not in house during testing. Floor plan is provided below.

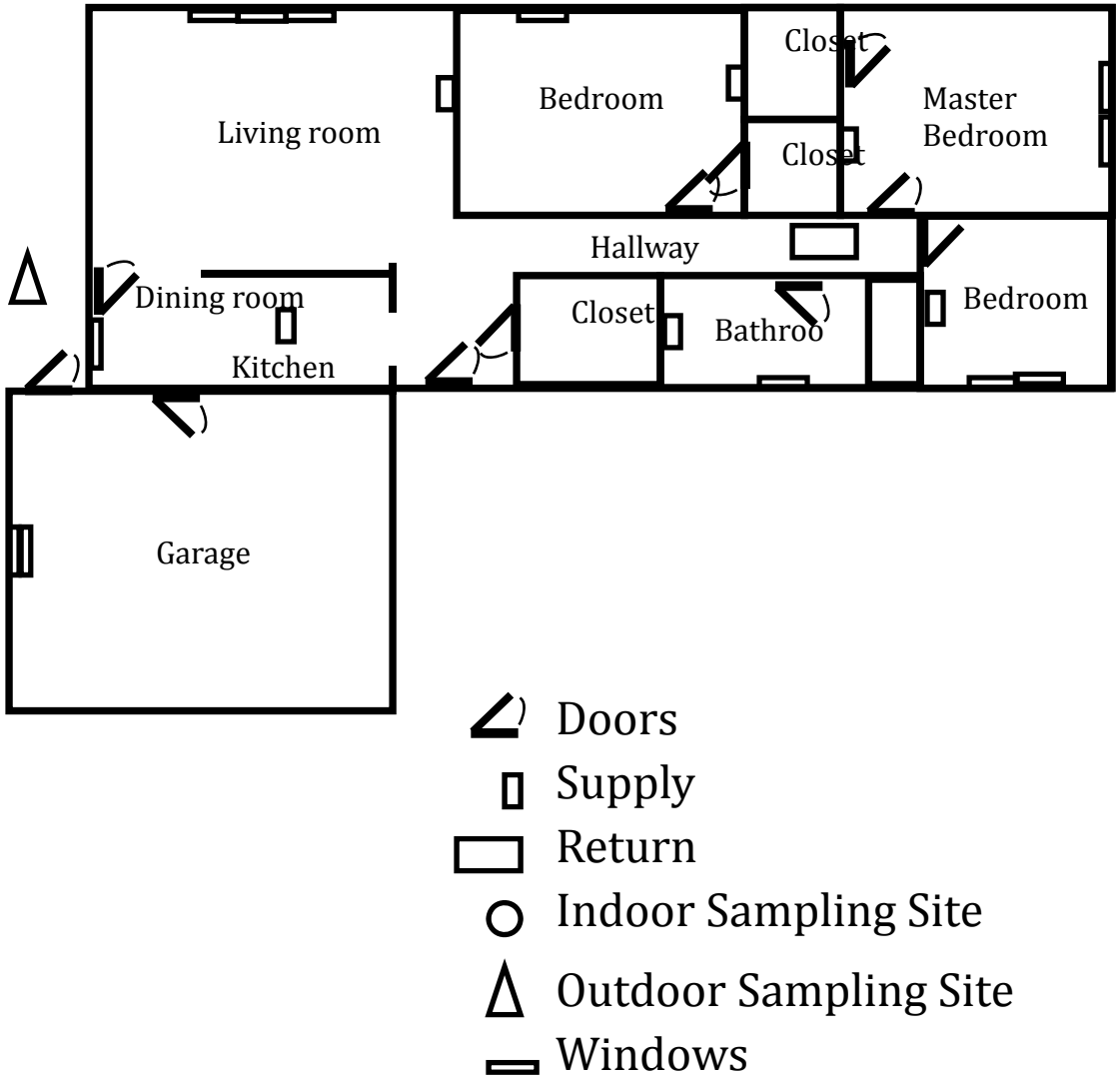

Figure 9.31. Plan drawing of Test House 6 including sample locations and location of supply and return vents (not to scale).

Figure 9.32. Image of front of Test House 6.

Figure 9.33. Image of Honeywell EP installed.

Figure 9.34. Image of monitors in master bedroom.

Test House 6 summary data is provided below. Subsequent tables (2) provide test condition data for each test.

Table 9.38, Summary of Test House 6 results including air exchange rates, ozone decay rates, incremental increase in ozone concentration and ozone emission rates.

Date & Start Time	HVAC Status	Test House, Test & In-Duct Device Tested	Air Exchange Rate (1/hr)	Ozone Removal Rate (1/hr)	Ozone Decay Rate (1/hr)	Max Conc. (ppb)	Steady State Conc. (ppb)		Ozone emission rate, OER1, mg/hr		Alternate OER2, mg/hr	
							Center	Return	Center	Return	Center	Return
1/12/13 9:34	System Off, Fan On	**Test House 6** AER/ODR/ OER Honeywell EP	0.74±0.01	7.28±0.31	6.54±0.31	27.6±1.5	18.7±0.93	16.4±5.41	48±5.8	42±20.5	44±5.8	38±15.3
1/12/ to 1/13/13 20:00	System On, Fan Off	**Test House 6** AER/ODR/ OER Honeywell EP	0.79±0.01	8.05±0.74	7.26±0.74	21.8±1.5	9.2±3.52	13.8±5.62	22.6±18.6	36.8±18.6	20.5±11.1	34.5±17.6
1/13 /13 10:17	System On, Fan On	**Test House 6** AER/ODR/ OER Honeywell EP	0.77±0.01	3.69±0.06	2.9±0.06	35.8±1.5	26.8±1.85	26.6±6.86	31.5±9.8	31.1±12.4	33.3±4.4	33±10

Table 9.39. Test House 6 AER/ODR/OER January 12, 2013 9:21, Test Conditions.

Test Start Time:	14:09	Notes	AER/ODR started at 9:21, OER at 14:09, OER Values Here
Test Conditions	Outdoor: Patio	Supply: Master Bedroom	Return : Hallway
CO_2 (ppm)	361	675	726
Temp (F)	45.6	60	58.1
RH (%)	42.2	49.7	55.4
O_3 (ppb)	15.8	0.9	4.3
Test End Time:	19:15	Notes	
CO_2 (ppm)	393	55.2	613
Temp (F)	34.5	57.2	57.1
RH (%)	66.2	48.8	54.3
O_3 (ppb)	8.8	23.6	14.7

Table 9.40. Test House 6 OER January 12-13 20:00, Test Conditions.

Test Start Time:	20:05	Notes	Overnight test
Test Conditions	Outdoor: Patio	Supply Vent: Laundry	Return Vent: Hallway, near living room
CO_2 (ppm)	443	632	690
Temp (F)	31.8	64.9	58.7
RH (%)	75.0	41.9	53.3
O_3 (ppb)	14.3	1.3	4.9
Test End Time:	7:10 Jan 13	Notes	
CO_2 (ppm)	575	518	562
Temp (F)	21.0	60.7	57.5
RH (%)	100	37.5	45.5
O_3 (ppb)	16.1	16.2	10.7

Table 9.41. Test House 6 OER January 13 10:17, Test Conditions.

Test Start Time:	10:47	Notes	
Test Conditions	Outdoor: Patio	Supply Vent: Master Bedroom	Return Vent: Hallway
CO_2 (ppm)	385	5119	3123
Temp (F)	41.8	72.6	59.7
RH (%)	53.5	32.5	50.3
O_3 (ppb)	9.7	9.1	10.5
Test End Time:	15:39	Notes	
CO_2 (ppm)	358	493	630
Temp (F)	43.7	61	59.1
RH (%)	48.3	41.2	48.3
O_3 (ppb)	25.5	36.2	28.1

9.6.7 California Commercial Test

Location: Sacramento, CA, Grant Union High School, Classroom B-12.
Date of tests: January 14, 2013.
Device tested: Trane TCACS
Description: The classroom was a large, traditional high school design with marker and chalk boards along three walls, a projection screen, classroom and office desks, and windows along the exterior wall. Ceilings were high; approximately 3 m and supply and return air were provided by ceiling mounted ducts. The room volume was 144 m^3 and the floor area is 48 m^2. Floor plan for the classroom is below.

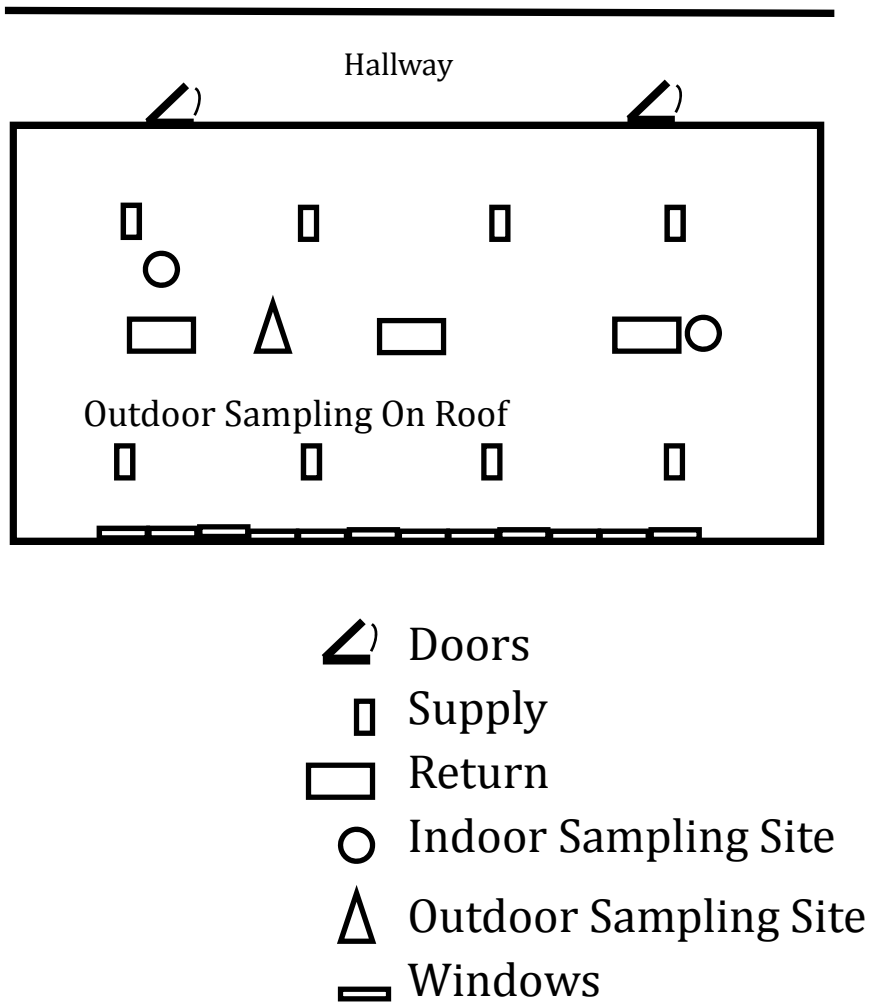

Figure 9.35. Plan drawing of Commerical Test classroom including sample locations and location of supply and return vents (not to scale).

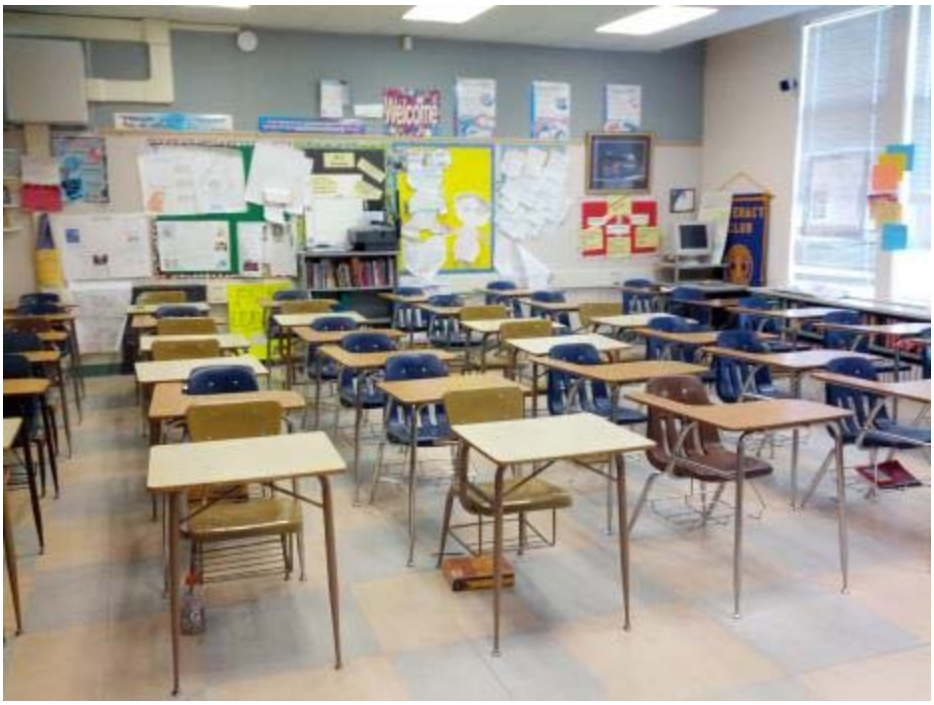

Figure 9.36. Image of Commercial Test classroom.

Figure 9.37. Image of TCACS roof-top unit above classroom.

Figure 9.38. Image of outdoor monitoring sit on classroom roof.

Commercial Test summary data is provided below. Subsequent tables (2) provide test condition data for each test.

Table 9.42. Summary of Commercial Test results including air exchange rates, ozone decay rates, incremental increase in ozone concentration and ozone emission rates.

Date & Start Time	HVAC Status	Test House, Test & In-Duct Device Tested	Air Exchange Rate (1/hr)	Ozone Removal Rate (1/hr)	Ozone Decay Rate (1/hr)	Max Conc. (ppb)	Steady State Conc. (ppb)		Ozone emission rate, OER1, mg/hr		Alternate OER2, mg/hr	
							Center	Return	Center	Return	Center	Return
1/14/13 9:35	System On, Fan On	**Com. Test** OER Trance TCACS	0.75±0.2	5.75±0.2[1]	5.0±0.2[1]	21.6	14.4±6.26	NA	17.9±9.9	NA	17.2±11.5	NA

[1] ORR and ODR are averages of Test Houses 4-6 ORR and ODR.

Table 9.43. Commercial Test AER/ODR/OER January 14, 2013 9:35, Test Conditions.

Test Start Time:	9:51	Notes	Device on 1st 2 hours, then off 2nd 2 hours. Occupied classroom, unable to conduct AER/ODR. Able to use elevated CO_2 due to occupancy to estimate AER.
Test Conditions	Outdoor: Roof above classroom	Supply: Front of classroom	Return : Back of Classroom
CO_2 (ppm)	471	1473	861
Temp (F)	47.1	76.4	85.1
RH (%)	38.1	26.9	15.8
O_3 (ppb)	16.1	2.5	4.4
Test End Time:	14:00	Notes	
CO_2 (ppm)	404	1066	1150
Temp (F)	49.5	73.2	72.9
RH (%)	29.6	22.7	22.7
O_3 (ppb)	12.8	18	19.5

9.7 Tulsa test house detailed results

Table 9.44. Tulsa Test House Data Calculated Values and Uncertainty Estimates.

	Test Date	2/22/2012, 10 am	2/22/2012, 1 pm	2/22/2012, 4 pm	2/23/2012, 9 am	3/5/2012, 2 pm	3/7/2012, 11 am	3/7/2012, 3 pm	4/24/2012, 3 pm
	Test House	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house
	Device Tested	NA	NA	NA	NA	NA	Air zone Air duct 2000	Active tek	NA
	HVAC Status*	System OFF, Fan ON	System Off, Fan Off	System On, Fan ON	System Off, Fan Off	System Off, Fan ON	System OFF, Fan ON	System OFF, Fan ON	System OFF, Fan ON
	Type of Test	AER/ODR	AER/ODR	AER/ODR	AER/ODR	AER/ODR	AER/OER	AER/OER	AER/ODR
Calculated Values	AER	0.55	0.14	0.42	0.20	1.48	0.55	0.55	0.55
	House Volume, m^3	198.40	198.40	198.40	198.40	198.40	198.40	198.40	198.40
	Max return conc., ppb	62.78	153.00	227.70	151.86	218.00	103.62	30.62	123.80
	Ceq_r, average O3, return of room, ppb	NA	NA	NA	NA	NA	99.59	27.63	NA
	Ceq_r, average O3, return of room, mg m^{-3}	NA	NA	NA	NA	NA	0.20	0.05	NA
	Ci,background ozone, ppb	NA	NA	NA	NA	NA	7.48	4.56	NA
	(Ceq_r - Ci)_1, ppb	NA	NA	NA	NA	NA	92.11	23.07	NA
	(Ceq_r - Ci)_1, mg m^{-3}	NA	NA	NA	NA	NA	0.18	0.04	NA
	ORR, h^{-1}	9.30	2.90	3.62	5.05	7.15	11.54	11.54	6.54
	ODR, h^{-1}	8.75	2.76	3.21	4.85	5.67	10.98	10.98	5.99
	O3 Penetration	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	Outdoor O3,ppb	7.25	8.05	18.60	22.25	47.80	36.00	9.45	44.10
	Outdoor O3,mg m^{-3}	0.01	0.02	0.04	0.04	0.09	0.07	0.02	0.09

	Test Date	2/22/2012, 10 am	2/22/2012, 1 pm	2/22/2012, 4 pm	2/23/2012, 9 am	3/5/2012, 2 pm	3/7/2012, 11 am	3/7/2012, 3 pm	4/24/2012, 3 pm
	Test House	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house
	Device Tested	NA	NA	NA	NA	NA	Air zone Air duct 2000	Active tek	NA
	HVAC Status*	System OFF, Fan ON	System Off, Fan Off	System On, Fan ON	System Off, Fan Off	System Off, Fan ON	System OFF, Fan ON	System OFF, Fan ON	System OFF, Fan ON
	Type of Test	AER/ODR	AER/ODR	AER/ODR	AER/ODR	AER/ODR	AER/OER	AER/OER	AER/ODR
	OER, mg h^{-1}	NA	NA	NA	NA	NA	441.36	113.00	NA
	Alternate OER, mg m^{-3}	NA	NA	NA	NA	NA	413.97	95.71	NA
	Conc temperature conversion	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
Uncertainty	AER, h^{-1}	0.02	0.01	0.01	0.01	0.04	0.04	0.04	0.04
	House Volume, m^{-3}	19.84	19.84	19.84	19.84	19.84	19.84	19.84	19.84
	Equilibrium O3, return of room, ppb	NA	NA	NA	NA	NA	5.31	2.87	NA
	Equilibrium O3, return of room, mg m^{-3}	NA	NA	NA	NA	NA	0.01	0.01	NA
	Ci,background ozone, ppb	NA	NA	NA	NA	NA	3.12	3.03	NA
	(Ceq_r - Ci)_1, ppb	NA	NA	NA	NA	NA	6.16	4.17	NA
	(Ceq_r - Ci)_1, mg m^{-3}	NA	NA	NA	NA	NA	0.01	0.01	NA
	ORR, h^{-1}	0.88	1.35	1.92	3.48	2.26	2.58	2.58	1.17
	ODR, h^{-1}	0.88	1.35	1.92	3.48	2.26	2.58	2.58	1.17
	O3 Penetration	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	Outdoor O3, ppb	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
	Outdoor O3, mg m^{-3}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	OER, mg hr^{-1}	NA	NA	NA	NA	NA	149.51	42.70	NA
	Alternate OER, mg hr^{-1}	NA	NA	NA	NA	NA	105.16	29.14	NA

Table Continued: Tulsa Test House Data Calculated Values and Uncertainty Estimates

	Test Date	4/25/2012, 2 pm	4/25/2012, 4 pm	4/26/2012, 11 am	4/26/2012, 4 pm	4/27/2012, 10 am	4/27/2012, 3 pm	5/2/2012, 1 pm	5/3/2012, 9 am
	Test House	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house
	Device Tested	NA	Air guardian	Active tek In duct 2000	Active tek In duct 2000	NA	Air zone Air duct 2000	Air guardian	Air zone Air duct 2000
	HVAC Status*	System OFF, Fan ON	System OFF, Fan ON	System On, Fan ON	System OFF, Fan ON	System OFF, Fan ON	System OFF, Fan ON	System ON, Fan ON	System OFF, Fan ON
	Type of Test	AER/ODR	AER/OER	AER/OER	AER/OER	AER/ODR	AER/OER	AER/OER	AER/OER
Calculated Values	AER, h^{-1}	0.50	0.50	0.50	0.79	0.79	0.72	0.57	0.55
	House Volume, m^{-3}	198.40	198.40	198.40	198.40	198.40	198.40	198.40	198.40
	Max Return Conc. ppb	168.34	3.30	4.47	102.03	78.91	23.40	60.10	123.80
	Ceq_r, average O3, return of room, ppb	NA	1.73	2.74	NA	51.59	3.24	58.70	NA
	Ceq_r, average O3, return of room, mg m^{-3}	NA	0.00	0.00	NA	0.10	0.01	0.11	NA
	Ci,background ozone, ppb	NA	0.10	2.43	NA	1.89	4.00	3.30	NA
	(Ceq_r - Ci)_1, ppb	NA	1.63	0.31	NA	49.70	0.00	55.40	NA
	(Ceq_r - Ci)_1, mg m^{-3}	NA	0.00	0.00	NA	0.09	0.00	0.10	NA
	ORR, h^{-1}	6.96	6.96	6.96	8.44	8.44	8.44	7.12	6.54
	ODR, h^{-1}	6.46	6.46	6.46	7.65	7.65	7.72	6.55	5.99
	O3 Penetration	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	Outdoor O3, ppb	28.80	26.10	68.60	15.90	26.20	23.90	23.90	44.10
	Outdoor O3, mg m^{-3}	0.05	0.05	0.12	0.03	0.05	0.04	0.04	0.09
	OER, mg hr^{-1}	NA	0.62	0.00	NA	163.11	4.96	146.50	NA
	Alternate OER, mg hr^{-1}	NA	4.43	0.84	NA	151.31	0.00	141.89	NA
	Conc temperature conversion	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018

	Test Date	4/25/2012, 2 pm	4/25/2012, 4 pm	4/26/2012, 11 am	4/26/2012, 4 pm	4/27/2012, 10 am	4/27/2012, 3 pm	5/2/2012, 1 pm	5/3/2012, 9 am
	Test House	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house
	Device Tested	NA	Air guardian	Active tek In duct 2000	Active tek In duct 2000	NA	Air zone Air duct 2000	Air guardian	Air zone Air duct 2000
	HVAC Status*	System OFF, Fan ON	System OFF, Fan ON	System On, Fan ON	System OFF, Fan ON	System OFF, Fan ON	System OFF, Fan ON	System ON, Fan ON	System OFF, Fan ON
	Type of Test	AER/ODR	AER/OER	AER/OER	AER/OER	AER/ODR	AER/OER	AER/OER	AER/OER
Uncertainty	AER, h^{-1}	0.02	0.02	0.02	0.02	0.21	0.21	0.02	0.02
	House Volume, m^{-3}	19.84	19.84	19.84	19.84	19.84	19.84	19.84	19.84
	Ceq_r, average O3, return of room, ppb	NA	1.75	1.24	2.36	NA	1.08	1.56	6.64
	Ceq_r, average O3, return of room, mg m^{-3}	NA	0.01	0.00	0.00	NA	0.00	0.00	0.01
	Ci,background ozone, ppb	NA	0.81	1.86	1.59	NA	0.73	2.33	0.85
	(Ceq_r - Ci)_1, ppb	NA	1.92	2.23	2.85	NA	1.30	2.80	6.70
	(Ceq_r - Ci)_1, mg m^{-3}	NA	0.00	0.02	0.01	NA	0.00	0.01	0.01
	ORR, h^{-1}	1.82	1.82	1.82	1.82	0.17	0.17	0.17	0.33
	ODR, h^{-1}	1.82	1.82	1.82	1.82	0.27	0.27	0.17	0.33
	O3 Penetration	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	Outdoor O3, ppb	1.82	1.50	1.50	1.50	1.50	1.50	1.50	1.50
	Outdoor O3, mg m^{-3}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	OER, mg hr^{-1}	NA	2.35	0.00	0.00	NA	58.51	2.68	40.15
	Alternate OER, mg hr^{-1}	NA	5.36	6.05	NA	NA	15.92	NA	23.20

Table Continued: Tulsa Test House Data Calculated Values and Uncertainty Estimates

	Test Date	5/3/2012, 2 pm	11/1/2012[1]	11/2/2012[1]	11/5/2012[1]	11/21/2012, 10:00	11/21/2012, 19:20
	Test House	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house
	Device Tested	NA	HVAC UV 560	HVAC UV 560	HVAC UV 560	HVAC UV 561	HVAC UV 562
	HVAC Status*	System Off, Fan Off	System OFF, Fan ON	System OFF, Fan ON	System OFF, Fan ON	System OFF, Fan ON	System OFF, Fan ON
	Type of Test	AER/ODR	AER/OER	AER/OER	AER/OER	AER/OER	AER/OER
Calculated Values	AER, h^{-1}	0.43	0.70	0.70	0.70	0.77	0.59
	House Volume, m^{-3}	198.40	198.40	198.40	198.40	198.40	198.40
	Max Return Conc. ppb	53.05	145.00	137.00	508.00	99.14	104.14
	Average O3, return of room, ppb	NA	NA	133.57	NA	105.87	101.51
	Average O3, return of room, mg m^{-3}	NA	NA	0.26	NA	0.19	0.19
	Ci,background ozone, ppb	NA	10.20	12.00	17.10	11.86	17.24
	(Ceq_r - Ci)_1, ppb	NA	NA	121.57	NA	94.00	84.27
	(Ceq_r - Ci)_1, mg m^{-3}	NA	NA	0.24	NA	0.17	0.15
	ORR, h^{-1}	7.12	7.02	7.02	7.02	2.86	2.86
	ODR, h^{-1}	6.70	6.32	6.32	6.32	2.09	2.27
	O3 Penetration	0.80	0.80	0.80	0.80	0.80	0.80
	Outdoor O3, ppb	31.60	49.50	33.70	18.30	38.00	32.00
	Outdoor O3, mg m^{-3}	0.06	0.10	0.07	0.04	0.07	0.06
	OER, mg hr^{-1}	NA	NA	357.91	NA	101.29	99.79
	AER, h^{-1}	NA	NA	332.41	NA	98.07	87.90
	Conc temperature conversion	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018

	Test Date	5/3/2012, 2 pm	11/1/2012[1]	11/2/2012[1]	11/5/2012[1]	11/21/2012, 10:00	11/21/2012, 19:20
	Test House	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house	Tulsa test house
	Device Tested	NA	HVAC UV 560	HVAC UV 560	HVAC UV 560	HVAC UV 561	HVAC UV 562
	HVAC Status*	System Off, Fan Off	System OFF, Fan ON	System OFF, Fan ON	System OFF, Fan ON	System OFF, Fan ON	System OFF, Fan ON
	Type of Test	AER/ODR	AER/OER	AER/OER	AER/OER	AER/OER	AER/OER
Uncertainty	AER	0.02	0.02	0.02	0.02	0.01	0.01
	House volume, m^3	19.84	19.84	19.84	19.84	19.84	19.84
	Equilibrium O3, return of room, ppb	NA	5.15	NA	NA	7.44	2.57
	Equilibrium O3, return of room, mg m^{-3}	NA	0.01	NA	NA	0.01	0.00
	Ci,background ozone, ppb	1.15	1.50	1.50	1.15	7.27	1.12
	(Ceq_r - Ci)_1	NA	5.36	NA	NA	10.40	2.80
	(Ceq_r - Ci)_1,mg m^{-3}	NA	0.01	NA	NA	0.02	0.01
	ORR, h^{-1}	1.22	1.22	1.22	1.22	0.24	0.24
	ODR, h^{-1}	1.22	1.22	1.22	1.22	0.24	0.24
	O3 Penetration	0.15	0.15	0.15	0.15	0.15	0.15
	Outdoor O3,ppb	1.50	1.50	1.50	1.50	1.50	1.50
	Outdoor O3, mg/m3	0.00	0.00	0.00	0.00	0.00	0.00
	OER, mg hr^{-1}	NA	107.01	NA	NA	26.57	25.54
	Alternate OER, mg hr^{-1}	NA	68.27	NA	NA	16.85	11.92

[1] The November 1-5, 2012 HVAC UV 560 tests involved operating the device in a "shock" mode intended for temporary use to reduce strong odors or sanitize excessive contamination. Operation in shock mode showed potential upper ozone generation limits of the device, and to ensure the lamp underwent a break-in period. The November 1 and 5 tests, measured ozone at the supply so an OER was not estimated.

Table 9.45. California May Field Test Calculated Values and Uncertainty Estimates.

	Test Date	5/22/2012, 10.30 am	5/22/2012, 1.26 pm	5/23/2012, 10.20 am	5/23/2012, 1.26 pm	5/25/2012, 3.25 pm	5/25/2012, 10.16 am	5/30/2012, 2.03 pm	5/30/2012, 9.00 am
	Test House	California field test 1	California field test 1	California field test 1	California field test 1	California field test 2	California field test 2	California field test 3	California field test 3
	Device Tested	NA	Active tek In duct 2000	NA	Active tek In duct 2000	NA	Trane Clean Effects EP Device	NA	Air Zone Air Duct 2000 Device
	HVAC Status*	System off, Fan on	System off, Fan on	System off, Fan on	System off, Fan on	System off, Fan on	System off, Fan on	System off, Fan on	System off, Fan on
Measured and Calculated Values	AER, h^{-1}	0.34	0.27	0.19	0.31	0.26	0.31	0.69	0.73
	House Volume, m^{-3}	377.00	377.00	377.00	377.00	312.00	312.00	434.00	434.00
	Max Conc. ppb	154.40	5.13	188.10	6.80	331.00	10.42	124.40	29.81
	Ceq_r,average O3, return of room, ppb	NA	4.37	NA	5.83	NA	7.11	NA	25.20
	Ceq_r,average O3, return of room, mg m^{-3}	NA	0.01	NA	0.01	NA	0.01	NA	0.05
	Ci, background ozone, ppb	NA	2.08	NA	2.40	NA	3.68	NA	4.45
	(Ceq_r - Ci)_1,ppb	NA	2.30	NA	3.43	NA	3.44	NA	20.75
	(Ceq_r - Ci)_1,mg m^{-3}	NA	0.00	NA	0.01	NA	0.01	NA	0.04
	ORR, h^{-1}	6.36	6.36	3.45	3.45	1.90	1.90	4.36	4.36
	ODR, h^{-1}	6.02	6.09	3.26	3.13	1.65	1.60	3.67	3.63
	O3 Penetration	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	Outdoor O3, ppb	36.64	36.64	46.15	50.43	42.98	35.09	58.50	56.10
	Outdoor O3, mg/m^3	0.07	0.07	0.08	0.10	0.08	0.06	0.11	0.10
	OER1, mg h^{-1}	NA	13.55	NA	5.50	NA	2.68	NA	61.25
	OER2, mg h^{-1}	NA	0.01	NA	0.00	NA	0.00	NA	0.00

	Test Date	**5/22/2012, 10.30 am**	**5/22/2012, 1.26 pm**	**5/23/2012, 10.20 am**	**5/23/2012, 1.26 pm**	**5/25/2012, 3.25 pm**	**5/25/2012, 10.16 am**	**5/30/2012, 2.03 pm**	**5/30/2012, 9.00 am**
	Test House	**California field test 1**	**California field test 1**	**California field test 1**	**California field test 1**	**California field test 2**	**California field test 2**	**California field test 3**	**California field test 3**
	Device Tested	**NA**	**Active tek In duct 2000**	**NA**	**Active tek In duct 2000**	**NA**	**Trane Clean Effects EP Device**	**NA**	**Air Zone Air Duct 2000 Device**
	HVAC Status*	**System off, Fan on**	**System off, Fan on**	**System off, Fan on**	**System off, Fan on**	**System off, Fan on**	**System off, Fan on**	**System off, Fan on**	**System off, Fan on**
Uncertainty Estimates	AER, h^{-1}	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
	House Volume, m^{-3}	37.70	37.70	37.70	37.70	31.20	31.20	43.40	43.40
	Ceq_r,average O3, return of room, ppb		0.93		0.66		2.39		2.39
	Ceq_r,average O3, return of room, mg m^{-3}		0.01		0.00		0.00		0.00
	Ci, background ozone, ppb		1.04		1.50		3.71		3.77
	(Ceq_r - Ci)_1,ppb		1.39		1.64		4.42		4.46
	(Ceq_r - Ci)_1,mg m^{-3}		0.00		0.00		0.01		0.01
	ORR, h^{-1}	0.16	0.16	0.17	0.17	0.08	0.08	0.29	0.29
	ODR, h^{-1}	0.17	0.16	0.17	0.17	0.08	0.08	0.29	0.29
	O3 Penetration	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	Outdoor O3, ppb	14.34	4.25	4.11	4.11	4.12	1.77	2.46	1.50
	Outdoor O3, mg/m^3	0.03	0.01	0.01	0.01	0.01	0.00	0.00	0.00
	OER1, mg h^{-1}		11.82		1.52		1.12		16.23
	OER2, mg h^{-1}		6.12		4.29		4.75		17.51

Table 9.46. California January Field Tests Calculated Values and Uncertainty Estimates.

	Test Date	1/7 to 1/8 2013	1/8/2013	1/10/2013	1/11/2013	1/12/2013	1/12/2013 to 1/13/2013	1/13/2013	1/14/2013
	Test House	Test House 4	Test House 4	Test House 5	Test House 5	Test House 6	Test House 6	Test House 6	Commercial Test 1
	Device Tested	HVAC UV 560	activTek 2000	HVAC UV 560	HVAC UV 560	Honeywell EP F300E 1027	Honeywell EP F300E 1027	Honeywell EP F300E 1027	Trane TCACS
	HVAC Status*	System ON, Fan ON	System ON, Fan ON	System OFF, Fan AUTO	System ON, Fan ON	System OFF, Fan ON	System ON, Fan AUTO	System ON, Fan ON	System On, Fan AUTO
Measured and Calculated Values	AER, h^{-1}	0.91	0.57	0.44	0.52	0.74	0.79	0.77	0.75
	House Volume, m^{-3}	196.00	196.00	206.00	206.00	199.00	199.00	199.00	144.00
	Max Conc. Ppb	169.30	19.80	93.00	109.30	27.60	21.80	35.80	21.60
	Ceq_1,equilibrium O3, center of room 1, ppb	159.14	17.78	103.18	118.83	18.65	9.15	26.87	14.41
	Ceq_1,equilibrium O3, center of room 1, mg m^{-3}	0.30	0.03	0.19	0.22	0.03	0.02	0.05	0.03
	Ceq_r,average O3, return of room, ppb	136.44	16.71	87.55	104.40	16.37	13.82	26.47	NA
	Ceq_r,average O3, return of room, mg m^{-3}	0.25	0.03	0.16	0.19	0.03	0.03	0.05	NA
	Ci, background ozone, ppb	2.93	2.63	4.18	4.18	2.27	2.27	2.27	3.21
	(Ceq_1 - Ci)_1,ppb	156.20	15.14	99.00	114.65	16.38	6.88	24.60	11.20
	(Ceq_1 - Ci)_1,mg/m3	0.29	0.03	0.18	0.21	0.03	0.01	0.05	0.02
	(Ceq_r - Ci)_1,ppb	133.50	14.07	83.38	100.23	14.11	11.55	24.21	NA
	(Ceq_r - Ci)_1,mg m^{-3}	0.25	0.03	0.15	0.18	0.03	0.02	0.04	NA
	ORR, h^{-1}	4.74	3.99	6.23	6.23	7.28	8.05	3.69	5.74
	ODR, h^{-1}	3.83	3.43	5.80	5.71	6.54	7.26	2.92	4.99
	O3 Penetration	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	Outdoor O3, ppb	33.54	13.51	34.60	9.49	10.28	18.04	21.22	26.23
	Outdoor O3, mg/m^3	0.06	0.03	0.06	0.02	0.02	0.04	0.04	0.05

	Test Date	1/7 to 1/8 2013	1/8/2013	1/10/2013	1/11/2013	1/12/2013	1/12/2013 to 1/13/2013	1/13/2013	1/14/2013
	Test House	Test House 4	Test House 4	Test House 5	Test House 5	Test House 6	Test House 6	Test House 6	Commercial Test 1
	Device Tested	HVAC UV 560	activTek 2000	HVAC UV 560	HVAC UV 560	Honeywell EP F300E 1027	Honeywell EP F300E 1027	Honeywell EP F300E 1027	Trane TCACS
	HVAC Status*	System ON, Fan ON	System ON, Fan ON	System OFF, Fan AUTO	System ON, Fan ON	System OFF, Fan ON	System ON, Fan AUTO	System ON, Fan ON	System On, Fan AUTO
	OER1, mg h^{-1} Center of Room	266.50	23.55	239.13	280.09	48.04	26.78	39.00	17.9
	OER1, mg h^{-1} Return	227.23	22.04	202.37	244.81	41.89	42.90	38.49	NA
	OER2, mg h^{-1} Center of Room	270.68	22.01	233.91	271.76	44.25	23.53	40.28	17.2
	OER2, mg h^{-1} Return	231.40	20.50	197.15	236.52	38.10	39.63	39.76	NA
	Conc temperature conversion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Uncertainty Estimates	AER, h^{-1}	0.04	0.00	0.01	0.00	0.01	0.01	0.01	0.16
	House Volume, m^{-3}	19.60	19.60	20.60	20.60	19.90	19.90	19.90	14.40
	Ceq_1,equilibrium O3, center of room 1, ppb	31.93	1.27	3.73	22.43	0.93	3.52	1.85	6.26
	Ceq_1,equilibrium O3, center of room 1, mg m^{-3}	0.06	0.00	0.01	0.04	0.00	0.01	0.00	0.01
	Ceq_r,average O3, return of room, ppb	25.68	3.53	3.89	6.95	5.41	5.62	6.86	NA
	Ceq_r,average O3, return of room, mg m^{-3}	0.05	0.01	0.01	0.01	0.01	0.01	0.01	NA
	Ci, background ozone, ppb	2.39	2.49	3.68	3.68	0.78	0.78	0.78	3.93
	(Ceq_1 - Ci)_1,ppb	32.02	2.80	5.24	22.73	1.22	3.61	2.01	7.39
	(Ceq_1 - Ci)_1,mg/m3	0.06	0.01	0.01	0.04	0.00	0.01	0.00	0.01
	(Ceq_r - Ci)_1,ppb	25.80	4.32	5.35	7.86	5.47	5.68	6.91	NA
	(Ceq_r - Ci)_1,mg m^{-3}	0.05	0.01	0.01	0.01	0.01	0.01	0.01	NA
	ORR, h^{-1}	0.06	0.10	0.51	0.51	0.31	0.74	0.06	0.00
	ODR, h^{-1}	0.07	0.10	0.51	0.51	0.31	0.74	0.06	0.16

	Test Date	1/7 to 1/8 2013	1/8/2013	1/10/2013	1/11/2013	1/12/2013	1/12/2013 to 1/13/2013	1/13/2013	1/14/2013
	Test House	**Test House 4**	**Test House 4**	**Test House 5**	**Test House 5**	**Test House 6**	**Test House 6**	**Test House 6**	**Commercial Test 1**
	Device Tested	**HVAC UV 560**	**activTek 2000**	**HVAC UV 560**	**HVAC UV 560**	**Honeywell EP F300E 1027**	**Honeywell EP F300E 1027**	**Honeywell EP F300E 1027**	**Trane TCACS**
	HVAC Status*	**System ON, Fan ON**	**System ON, Fan ON**	**System OFF, Fan AUTO**	**System ON, Fan ON**	**System OFF, Fan ON**	**System ON, Fan AUTO**	**System ON, Fan ON**	**System On, Fan AUTO**
	O3 Penetration	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	Outdoor O3, ppb	4.27	3.33	1.96	1.95	2.79	2.91	4.07	2.97
	Outdoor O3, mg/m^3	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01
	OER1, mg h^{-1} Center of Room	89.95	8.21	61.77	104.75	17.52	13.07	12.15	9.9
	OER1, mg h^{-1} Return	75.05	8.85	52.53	80.70	20.51	21.68	15.37	NA
	OER2, mg h^{-1} Center of Room	61.84	4.66	32.65	64.30	5.82	12.75	5.24	11.5
	OER2, mg h^{-1} Return	50.43	6.64	28.44	35.74	15.34	20.21	12.04	NA

9.8 Example steady state model calculations

Equation (2) is the basis for calculating indoor concentrations of ozone that result from in-duct ozone sources:

$$C = \frac{S + V\lambda C_o P_b}{\left(\lambda + \sum_{i=1}^{n} \frac{k_i C_i}{V} + \sum_{j=1}^{m} v_{d,i} \frac{A_i}{V} + (1 - P_r)\lambda_r\right) V}$$

The overall ozone removal rate indoors due to all sinks (excepting air exchange) is replaced by a single value, k_d, that is based on field results. See Table XX for ranges of parameters.

For the Standard house, the indoor concentration is,

$$C = \frac{100\frac{mg}{h} + \left(350\ m^3 * 0.5\frac{1}{h} * 0\frac{mg}{m^3} * 0.8\right)}{\left(0.5\frac{1}{h} + 4\frac{1}{h} + (1 - 0.85) * 5.7\frac{1}{h}\right) * 350\ m^3} = 0.0534\ \frac{mg}{m^3}$$

At 25C and 1 atm, this is equal to 27.2 ppb.

For the At Risk House,

$$C = \frac{50\frac{mg}{h} + \left(150\ m^3 * 0.1\frac{1}{h} * 0\frac{mg}{m^3} * 1\right)}{\left(0.1\frac{1}{h} + 1.5\frac{1}{h} + (1 - 0.95) * 2\frac{1}{h}\right) * 150\ m^3} = 0.1961\ \frac{mg}{m^3}$$

At 25C and 1 atm, this is equal to 99.9 ppb.

9.9 Example CONTAM project file

The following project file code is for a baseline simulation of the ozone concentration within a home. The wind is from the north (0º) at 5 m/s. The air handler and ozone emitting device are operating on a 50% slow duty cycle (1 hour on/1 hour off). Note that a number of possible schedules (for the air handler or for the ozone emitting device) are imbedded in the project file, but only one or several are specified in any given simulation.

```
ContamW 3.0a 0

! rows cols ud uf    T   uT     N     wH  u  Ao    a
   58   76  1  1 296.150 3    0.00  2.44 1 0.600 0.280
! Ta       Pb      Ws    Wd    rh  day u..
293.150 101325.0  5.000   0.0 0.000 1 2 0 0 1 ! steady simulation
293.150 101325.0  1.000 270.0 0.000 1 2 0 0 1 ! wind pressure test
null ! no weather file
R:\Research\Civil\gcm\Evil Overlord\Cal ARB CONTAM Simulations\CTM_ozone.ctm ! contaminant file
null ! no continuous values file
null ! no discrete values file
null ! no WPC file
null ! no EWC file
WPC description
!  Xref    Yref    Zref   angle u
  0.000   0.000   0.000   0.00 0
! epsP epsS  tShift  dStart dEnd wp mf
  0.01 0.01 00:00:00   1/1   1/1  0  0
! latd  longtd   tznr  altd  Tgrnd u..
 40.00  -90.00  -6.00     0 283.15 2 0
!sim_af afcalc afmaxi afrcnvg afacnvg afrelax uac Pbldg uPb
    1     1     30  1e-005  1e-006    0.75   0 50.00   0
!   slae rs aflmaxi aflcnvg aflinit Tadj
     0   1    100  1e-006      1    0
!sim_mf slae rs maxi   relcnvg   abscnvg relax gamma ucc
   2           30 1.00e-004 1.00e-015 1.250        0 ! (cyclic)
        0   1  100 1.00e-006 1.00e-015 1.100 1.000   0 ! (non-trace)
        0   1  100 1.00e-006 1.00e-015 1.100 1.000   0 ! (trace)
!sim_sts sim_1dz sim_1dd celldx sim_vjt udx
    0      1      0    0.100     0    0
!tsdens relax tsmaxi
    0   0.75    20
!date_st time_st  date_0 time_0   date_1 time_1    t_step   t_list   t_scrn
  Jan01 00:00:00  Jan01 00:00:00  Jan01 24:00:00  00:00:10 00:01:00 01:00:00
!restart  date  time
     0  Jan01 00:00:00
!list doDlg pfsave zfsave zcsave
   1     1      1      1      1
!vol ach -bw cbw exp -bw age -bw
  0   1   0   0   0   0   0   0
!...
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

```
2 ! rvals:
1.2041 9.8055
!valZ valD valC
   0    0    0
!ctype conv var zref imax dtcmo
   0 0.010000    0    0 1000    1
-999
1 ! contaminants:
   1
1 ! species:
! # s t   molwt    mdiam       edens       decay       Dm          CCdef       Cp    u...  name
  1 1 0  48.0000 0.0000e+000 2.0000e+000 5.5500e-004 1.5000e-005 0.0000e+000 1000.000 1 0 0 0 0
Ozone

-999
2 ! levels plus icon data:
! #  refHt   delHt  ni  u  name
  1   2.438   2.438 48 1 1 firstfloor
!icn col row  #
 130  31   5   1
  14  19   9   0
  23  27   9   7
  19  33   9   0
  23  39   9   8
  19  45   9   0
  23  51   9   9
  15  57   9   0
   5  20  10   2
 128  21  10  10
   5  34  10   3
 128  35  10  11
  23  57  11  12
  23  19  14  13
  23  33  14  14
  23  45  14  15
   7  13  15  -1
 133  28  16   3
 133  38  16   4
 133  47  16   5
  18  19  19   0
  19  27  19   0
  23  29  19  16
  21  33  19   0
  16  45  19   0
   5  20  20   4
 128  21  20  17
  17  27  25   0
  23  33  25  18
  19  37  25   0
  15  45  25   0
   5  38  26   5
 128  39  26  19
  23  19  27  20
```

```
  23  57  28  21
 133  30  31   6
  23  37  31  22
  23  45  31  23
 133  39  32   7
 128  55  36  24
   5  56  36   6
  17  19  37   0
  23  29  37  25
  21  37  37   0
  23  41  37  26
  21  45  37   0
  23  51  37  27
  16  57  37   0
  2   4.876   0.101 13 1 1 attic
!icn col row  #
  14  19   9   0
  15  57   9   0
   5  20  10   1
  23  25  15   1
  23  37  15   2
  23  47  21   3
 133  28  22   1
 133  43  22   2
  23  24  29   4
  23  38  29   5
 129  47  32   6
  17  19  37   0
  16  57  37   0
-999
6 ! day-schedules:
! # npts shap utyp ucnv name
  1    2    0    1    0 AHS0
no fraction of outdoor air to AHS or Supply/Return is off whole day
 00:00:00 0
 24:00:00 0
  2    4    0    1    0 Schedule1
on-off every 8 hours
 00:00:00 1
 08:00:00 0
 16:00:00 1
 24:00:00 0
  3   13    0    1    0 Schedule2
on-off every 2 hours
 00:00:00 1
 02:00:00 0
 04:00:00 1
 06:00:00 0
 08:00:00 1
 10:00:00 0
 12:00:00 1
 14:00:00 0
 16:00:00 1
```

18:00:00 0
20:00:00 1
22:00:00 0
24:00:00 1
4 25 0 1 0 Schedule3
on-off every an hour
00:00:00 1
01:00:00 0
02:00:00 1
03:00:00 0
04:00:00 1
05:00:00 0
06:00:00 1
07:00:00 0
08:00:00 1
09:00:00 0
10:00:00 1
11:00:00 0
12:00:00 1
13:00:00 0
14:00:00 1
15:00:00 0
16:00:00 1
17:00:00 0
18:00:00 1
19:00:00 0
20:00:00 1
21:00:00 0
22:00:00 1
23:00:00 0
24:00:00 1
5 49 0 1 0 Schedule5
on-off 0.5 hour
00:00:00 1
00:30:00 0
01:00:00 1
01:30:00 0
02:00:00 1
02:30:00 0
03:00:00 1
03:30:00 0
04:00:00 1
04:30:00 0
05:00:00 1
05:30:00 0
06:00:00 1
06:30:00 0
07:00:00 1
07:30:00 0
08:00:00 1
08:30:00 0
09:00:00 1
09:30:00 0

```
 10:00:00 1
 10:30:00 0
 11:00:00 1
 11:30:00 0
 12:00:00 1
 12:30:00 0
 13:00:00 1
 13:30:00 0
 14:00:00 1
 14:30:00 0
 15:00:00 1
 15:30:00 0
 16:00:00 1
 16:30:00 0
 17:00:00 1
 17:30:00 0
 18:00:00 1
 18:30:00 0
 19:00:00 1
 19:30:00 0
 20:00:00 1
 20:30:00 0
 21:00:00 1
 21:30:00 0
 22:00:00 1
 22:30:00 0
 23:00:00 1
 23:30:00 0
 24:00:00 1
  6    2    0    1    0 Schedule6
On all the time
 00:00:00 1
 24:00:00 1
-999
7 ! week-schedules:
! # utyp ucnv name
  1    1    0 AHS0
no fraction of outdoor air in AHS or Supply/Return is off whole day
 1 1 1 1 1 1 1 1 1 1 1 1
  2    1    0 Schedule1
on-off every 8 hours whole week
 2 2 2 2 2 2 2 2 2 2 2 2
  3    1    0 Schedule2
on-off every 2 hours for whole week
 3 3 3 3 3 3 3 3 3 3 3 3
  4    1    0 Schedule3
on-off every an hour for a week
 4 4 4 4 4 4 4 4 4 4 4 4
  5    1    0 Schedule4
mixed schedule
 1 2 3 4 2 3 4 1 1 1 1 1
  6    1    0 Schedule5
on-off 0.5 hour
```

```
 5 5 5 5 5 5 5 5 5 5 5
  7    1    0 Schedule6
On all the time
 6 6 6 6 6 6 6 6 6 6 6
-999
2 ! wind pressure profiles:
1 13 2 low_rise_WPP
low rise from ASHRAE Fundamentals and Swami and Chandra 1987
   0.0  0.550
  30.0  0.450
  60.0  0.100
  90.0 -0.400
 120.0 -0.500
 150.0 -0.450
 180.0 -0.400
 210.0 -0.450
 240.0 -0.500
 270.0 -0.400
 300.0  0.100
 330.0  0.450
 360.0  0.550
2 2 1 roof_WPP
Roof wind pressure profile
   0.0 -0.500
 360.0 -0.500
-999
0 ! kinetic reactions:
-999
0 ! filter elements:
-999
0 ! filters:
-999
11 ! source/sink elements:
1 Ozone ccf ozone_source
100 mg/hour ozone source rate
 2.78e-008 0 6 4
2 Ozone dvs sink_BR1

 0.0002 61.6876 0 1
3 Ozone dvs sink_BR2

 0.0002 106.653 0 1
4 Ozone dvs sink_KTCH

 0.0002 54.9986 0 1
5 Ozone dvs sink_LIV

 0.0002 178.374 0 1
6 Ozone dvs sink_bath

 0.0002 38.2761 0 1
7 Ozone ccf source_BR1
```

```
 6.74167e-009 0 29 0
8 Ozone ccf source_BR2

 1.11611e-008 0 29 0
9 Ozone ccf source_KTCH

 5.84722e-009 0 29 0
10 Ozone ccf source_bath

 3.48333e-009 0 29 0
11 Ozone dvs source_sink

 0.0001 80 0 0
-999
14 ! flow elements:
1 30 fan_cmf Fan1

 0.0744436 1
2 30 fan_cmf Fan2

 0.0858091 1
3 31 fan_cmf Fan3

 0.142068 1
4 31 fan_cmf Fan4

 0.0443252 1
5 25 plr_orfc attic_vent

 0.00174493 0.136377 0.5 0.160722 0.452369 0.6 30 1 1
6 23 plr_leak1 bsmt_door

 5.00507e-007 0.00244561 0.65 1 4 0.00212903 0 0 3 1 1 0
7 25 plr_orfc crlsp_vent

 0.00438972 0.252259 0.5 0.29729 0.615241 0.6 30 1 1
8 23 plr_leak1 ext_door

 2.48369e-007 0.00140807 0.65 1 4 0.0012258 0 0 3 2 2 0
9 23 plr_leak3 extwall

 3.86324e-007 0.00199427 0.65 1 4 0 0 0.00173611 1 1 1 0
10 23 plr_leak1 garage_door

 5.00507e-007 0.00244561 0.65 1 4 0.00212903 0 0 3 2 2 0
11 23 plr_leak3 garage_wall

 4.25925e-008 0.000350991 0.65 1 4 0 0 0.000305556 1 1 1 0
12 23 plr_leak3 intwall

 4.24348e-007 0.00239312 0.65 0.6 4 0 0 0.00347222 2 2 1 0
13 25 plr_orfc open_door
```

```
 0.0737975 1.65545 0.5 1.95096 1.57608 0.6 30 1 1
14 25 plr_stair stair

 0.0510805 1.40398 0.5 2.4384 8.17547 0 0 1 1
-999
0 ! duct elements:
-999
0 ! control super elements:
-999
0 ! control nodes:
-999
1 ! simple AHS:
! # zr# zs# pr# ps# px# name
  1   7   8  28  29  30 AHS

-999
8 ! zones:
! Z#  f  s#  c#  k#  l#  relHt    Vol  T0  P0  name  clr u..  axs  1-D data:
   1  3   0   0   0   2   0.000 9.68096 296.15 0 Source_zone -1 1 3 1 1 0 0
   2  3   0   0   0   1   0.000 31.7097 296.15 0 bedroom1 -1 1 3 1 1 0 0
   3  3   0   0   0   1   0.000 27.5648 296.15 0 kitchen -1 1 3 1 1 0 0
   4  3   0   0   0   1   0.000 52.4795 296.15 0 bedroom2 -1 1 3 1 1 0 0
   5  3   0   0   0   1   0.000 15.8548 296.15 0 bathroom -1 1 3 1 1 0 0
   6  3   0   0   0   1   0.000 106.907 296.15 0 Living_room -1 1 3 1 1 0 0
   7 10   0   0   0   1   0.000 1.03073 296.15 0 AHS(Rec) -1 1 3 1 1 0 0
   8 10   0   0   0   1   0.000 1.03073 296.15 0 AHS(Sup) -1 1 3 1 1 0 0
-999
8 ! initial zone concentrations:
! Z#      Ozone
   1 0.000e+000
   2 0.000e+000
   3 0.000e+000
   4 0.000e+000
   5 0.000e+000
   6 0.000e+000
   7 0.000e+000
   8 0.000e+000
-999
30 ! flow paths:
! P#    f  n#  m#  e#  f#  w#  a#  s#  c#  l#    X       Y      relHt  mult wPset wPmod wazm Fahs Xmax Xmin icn dir
u..
   1    0   2   1   9   0   0   0   0   0   2   0.000   0.000   0.000 1 0 0 -1 0 0 0  23  3 1 1 1 1 0
   2    0   3   1   9   0   0   0   0   0   2   0.000   0.000   0.000 1 0 0 -1 0 0 0  23  3 1 1 1 1 0
   3    0   6   1   9   0   0   0   0   0   2   0.000   0.000   0.000 1 0 0 -1 0 0 0  23  3 1 1 1 1 0
   4    0   4   1   9   0   0   0   0   0   2   0.000   0.000   0.000 1 0 0 -1 0 0 0  23  3 1 1 1 1 0
   5    0   5   1   9   0   0   0   0   0   2   0.000   0.000   0.000 1 0 0 -1 0 0 0  23  3 1 1 1 1 0
   6    8   1   7   0   0   0   1   4   0   2   0.000   0.000   0.000 1 0 0 0 0.706362 0 0 129  5 0 0 0 1 0
   7    1  -1   2   9   0   1   0   0   0   1   0.000   0.000   2.042 2.48051 0 0.163396 0 0 0 0  23  4 1 1 1 1 0
   8    1  -1   3   9   0   1   0   0   0   1   0.000   0.000   2.042 3.46528 0 0.163396 0 0 0 0  23  4 1 1 1 1 0
   9    1  -1   6   9   0   1   0   0   0   1   0.000   0.000   2.042 2.48051 0 0.163396 0 0 0 0  23  4 1 1 1 1 0
  10    8   8   2   0   0   0   1   4   0   1   0.000   0.000   0.000 1 0 0 0 0.0858019 0 0 128  2 0 0 0 1 0
  11    8   8   3   0   0   0   1   4   0   1   0.000   0.000   0.000 1 0 0 0 0.0744374 0 0 128  2 0 0 0 1 0
  12    1  -1   6   8   0   1   0   0   0   1   0.000   0.000   1.219 1 0 0.163396 90 0 0 0  23  5 1 1 1 1 0
```

```
 13   1 -1   2   9   0   1   0   0   0   1   0.000   0.000   2.042 2.48051 0 0.163396 270 0 0 0  23  2 1 1 1 1 0
 14   0   2   3  12   0   0   0   0   0   1   0.000   0.000   1.219 7.43224 0 0 -1 0 0 0  23  2 1 1 1 1 0
 15   0   3   6  12   0   0   0   0   0   1   0.000   0.000   1.219 7.43224 0 0 -1 0 0 0  23  2 1 1 1 1 0
 16   0   6   2  12   0   0   0   0   0   1   0.000   0.000   1.219 7.43224 0 0 -1 0 0 0  23  1 1 1 1 1 0
 17   8   8   4   0   0   0   1   4   0   1   0.000   0.000   0.000 1 0 0 0 0.142056 0 0 128  2 0 0 0 1 0
 18   0   4   6  12   0   0   0   0   0   1   0.000   0.000   1.219 7.43224 0 0 -1 0 0 0  23  1 1 1 1 1 0
 19   8   8   5   0   0   0   1   4   0   1   0.000   0.000   0.000 1 0 0 0 0.0431851 0 0 128  2 0 0 0 1 0
 20   1 -1   4   9   0   1   0   0   0   1   0.000   0.000   2.042 3.46528 0 0.163396 270 0 0 0  23  2 1 1 1 1 0
 21   1 -1   6   9   0   1   0   0   0   1   0.000   0.000   2.042 2.48051 0 0.163396 90 0 0 0  23  5 1 1 1 1 0
 22   0   4   5  12   0   0   0   0   0   1   0.000   0.000   1.219 7.43224 0 0 -1 0 0 0  23  2 1 1 1 1 0
 23   0   5   6  12   0   0   0   0   0   1   0.000   0.000   1.219 7.43224 0 0 -1 0 0 0  23  2 1 1 1 1 0
 24   8   8   6   0   0   0   1   4   0   1   0.000   0.000   0.000 1 0 0 0 0.289819 0 0 128  2 0 0 0 1 0
 25   1 -1   4   9   0   1   0   0   0   1   0.000   0.000   2.042 2.48051 0 0.163396 180 0 0 0  23  1 1 1 1 1 0
 26   1 -1   5   9   0   1   0   0   0   1   0.000   0.000   2.042 3.46528 0 0.163396 180 0 0 0  23  1 1 1 1 1 0
 27   1 -1   6   9   0   1   0   0   0   1   0.000   0.000   2.042 2.48051 0 0.163396 180 0 0 0  23  1 1 1 1 1 0
 28  16   7   8   0   0   0   0   1   0   1   0.000   0.000   1.219 1 0 0 -1 0 0 0   0  6 1 1 1 1 0
 29  32  -1   8   0   0   0   0   0   0   1   0.000   0.000   1.219 1 0 0 -1 0 0 0   0  6 1 1 1 1 0
 30  64   7  -1   0   0   0   0   0   0   1   0.000   0.000   1.219 1 0 0 -1 0 0 0   0  6 1 1 1 1 0
-999
0 ! duct junctions:
-999
0 ! initial junction concentrations:
-999
0 ! duct segments:
-999
7 ! source/sinks:
! #  z#  e#  s#  c#  mult   CC0  (X, Y, H)min  (X, Y, H)max u
 1   1  11   0   0    1    0  0 0 0  0 0 0  0 0
 2   1   1   4   0    1    0  0 0 0  0 0 0  0 0
 3   2   2   0   0    1    0  0 0 0  0 0 0  0 0
 4   3   4   0   0    1    0  0 0 0  0 0 0  0 0
 5   6   5   0   0    1    0  0 0 0  0 0 0  0 0
 6   4   3   0   0    1    0  0 0 0  0 0 0  0 0
 7   5   6   0   0    1    0  0 0 0  0 0 0  0 0
-999
0 ! occupancy schedules:
-999
0 ! exposures:
-999
0 ! annotations:
-999
* end project file.
```