EPA United States Environmental Protection Agency

Engineering Issue

Adsorption-based Treatment Systems for Removing Chemical Vapors from Indoor Air

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The U.S. Environmental Protection Agency (EPA) Engineering Issue Papers (EIPs) are a series of technology transfer documents that summarize the latest information on selected waste treatment and site remediation technologies and related issues. EIPs are designed to help remedial project managers, on-scene coordinators, contractors and other site managers understand the type of data and site characteristics needed to evaluate a technology for a particular application at their sites. This EIP may also be useful for building owners/operators and home owners who may have a concern about the indoor air quality at their location(s). Each EPA EIP is developed in conjunction with a small group of engineers and scientists from inside EPA and outside consultants, with a reliance on peer-reviewed literature, EPA reports, Web sources, current ongoing research, and other pertinent information. As such, this EIP assembles, organizes, and summarizes the current knowledge on air treatment technologies that are available for removing volatile organic compounds (VOCs) from indoor air. VOCs are one group of chemicals that can easily become gases, or chemical vapors, which can migrate through soil and enter buildings. Well-known examples of VOCs are petroleum products (e.g., gasoline or diesel fuel), dry cleaning solvents (e.g., perchloroethylene, aka perc) and industrial degreasers (e.g., trichloroethylene, TCE). This EIP does not represent EPA policy or guidance.

1. PURPOSE AND SUMMARY

This EIP summarizes the state of the science on selecting and using indoor treatment technology for VOCs, also known as air treatment units (ATUs). When selected and operated correctly, ATUs remove VOCs from indoor air to keep their concentrations below specified limits. This paper describes the

ACRONYMS AND ABBREVIATIONS

ACH	air exchanges per hour
ATU	air treatment unit
AHAM	Association of Home Appliance Manufacturers
AIC	acid-impregnated carbon
AS	air sparging
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIC	base-impregnated carbon
CADR	Clean Air Delivery Rate (from AHAM room air cleaner test)
CARB	California Air Resource Board
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFM	cubic feet per minute
DQO	data quality objective
EIP	Engineering Issue Paper
EPA	U.S. Environmental Protection Agency
GAC	granular activated carbon
HEPA	high-efficiency particle air filter
HVAC	heating, ventilation, and air conditioning
IH	imminent hazard
ISO	International Standards Organization
MEK	methyl ethyl ketone
NIST	National Institute of Standards and Technology
PCE	perchloroethylene, tetrachloroethylene, or tetrachloroethene, also PERC
PCO	photocatalytic oxidation
PPB	parts per billion
PPIA	potassium permanganate impregnated alumina
PPM	parts per million
RH	relative humidity
RCRA	Resource Conservation and Recovery Act
SSD	subslab depressurization
SVE	soil vapor extraction
TCE	trichloroethylene or trichloroethene
TCLP	EPA's Toxicity Characteristic Leachate Procedure
UV	ultraviolet light
VI	vapor intrusion
VOC	volatile organic compound

different types of commercially available VOC ATUs, how they work, and what factors influence their effectiveness. This EIP also provides information on how to select, install, operate, and monitor VOC ATUs to meet indoor air quality objectives.

2. INTRODUCTION

The focus of this EIP is Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), known also as Superfund, and Resource Conservation and Recovery Act (RCRA) sites with VOCs in indoor air as the contaminants of concern. The ATU technologies described in this EIP can be applied when indoor air VOC concentrations exceed specified limits, including sites where VOCs are entering a building from a subsurface source, commonly known as vapor intrusion (VI). The technology can also be applied when the VOCs are entering the building from groundwater, for example in sumps.

One of the more common applications of VOC ATUs is when a temporary reduction of indoor air VOC concentrations is needed while a longer-term solution is put in place. One example of this situation would be using an ATU while a subslab depressurization mitigation system is installed at a VI site (and ultimately soil and groundwater remediation is implemented to eliminate the need for indoor air mitigation). In these cases, portable ATUs can be deployed for weeks or months while the longer-term solution is designed, permitted, and constructed. Similarly, VOC ATUs can be used to reduce indoor air VOC concentrations while possible sources of the VOCs of concern are investigated.

This EIP surveys the available literature to address five aspects of VOC ATU use: (1) What research has been conducted on VOC ATUs that demonstrate their effectiveness in removing chlorinated VOCs from indoor air? (2) What VOC ATUs are commercially available, how do they work, and what are the recommended protocols, performance goals, and monitoring for their use? (3) Based on available test results, how effective are commercially available VOC ATU technologies at removing or destroying chlorinated VOCs from indoor air? (4) What are the building- and unit (device)-specific factors that influence VOC ATU performance? and (5) How should VOC ATUs be selected, installed, and maintained in a particular building? The paper also identifies knowledge gaps that interfere with the ability to answer these questions and recommends research needs to fill these gaps.

3. AIR TREATMENT SYSTEM BASICS

3.1 *Classes of Commercially Available Treatment Units*

ATUs for removing gas phase contaminants from indoor air use many different technologies and come in designs intended for standalone operation (as portable, wall-mounted, or ceiling-mounted units) or for installation in heating, ventilation, and air conditioning (HVAC) ducts. The most common VOC air cleaning technology in either design employs a sorbent bed, or sorbent layer, usually composed of carbon, to remove gas phase contaminants from the air. Reactive ATUs, which use various chemical reactions to change or breakdown the contaminants into other compounds, are also commercially available.

For the removal of the VOCs that are important for VI (i.e., chlorinated compounds like trichloroethylene and perchloroethylene), the most-demonstrated technology at this time—and the primary focus of this document—is carbon sorption, preferably with a large amount of carbon relative to the air flowrate needed. The principles and performance of other commercially available technologies (e.g., photocatalytic oxidation) that may be proposed for VOC control will also be briefly discussed.

Standalone devices use fans to pull room air into the unit, through a sorbent bed, and back into the same room after the air is "cleaned." Portable versions of standalone devices are plugged into wall outlets and can be easily moved. Wall- and ceiling-mounted units that can be hard wired for power are also available.

HVAC ATUs, also called in-duct systems, are normally installed in existing HVAC ducts or outside the duct system but connect to it. The air from the contaminated room enters the HVAC duct, possibly after passing through other rooms on the way to the return air duct inlet, and is decontaminated by the in-duct ATU before being redistributed throughout the building. In-duct devices often do not require a dedicated power supply because the HVAC fan forces the air through the device.

Each class of ATU has its advantages and disadvantages, so it is important to understand your situation, contaminants, humidity variability and range, temperature, airflow needs, and other related factors before choosing an ATU. Many devices are sold without full unit test data and some are sold without any test data. The lack of test data requires the user to understand the principles of operation to evaluate how well the technology, in the configuration being sold, is likely to function for their needs. Without test data, the person selecting the ATU and designing its installation must be knowledgeable of indoor air quality assessment and maintenance. A professional engineer can assist in assessing unit selection.

3.2 *Adsorption Principles and Performance*

3.2.1 Adsorption Principles

Two types of adsorption occur in ATUs: physisorption and chemisorption. In physisorption, compounds collect on the sorbent surface due to van der Waals forces and other relatively weak binding forces, and remain there until they are desorbed. Both the sorbed compound and the sorbing surface remain the same—no irreversible chemical changes occur. Physisorption systems can have single use or regenerable sorbents. Desorption (i.e., release of the chemical) can be intentional in a regeneration process or may occur because of significant changes in conditions (such as temperature, humidity, or chemicals adsorbed) that prevailed after the original adsorption. In chemisorption, the adsorbed compound collects on the surface but reacts with the surface irreversibly so that desorption is not possible. This permanently removes the contaminant from the airstream but also consumes the surface of the sorbent (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE], 1994).

Sorption occurs at a molecular level when VOC molecules contact the sorbent surface due to Brownian (or random) motion, as energetic molecules move from a higher concentration in the air near the sorbents to the relatively low concentration air in the boundary layer at the surface of the sorbent (**Figure 1**). Advective currents (i.e., airflow), whether natural or fan induced, bring contaminants into range where this Brownian motion can become important. Effective sorbents tend to have large surface areas due to the presence of micropores. According to ASHRAE (1994), "one gram of 1.5 mm diameter carbon spheres would have an external surface area of about 0.01 m^2, which is only a small fraction of the total adsorption surface of 1,000 to 1,500 m^2/g."

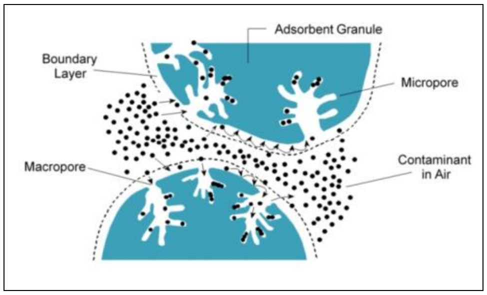

Figure 1. Diagram illustrating sorption of VOCs by solid, porous sorbent granules

The most common sorbent in use for air cleaning is granular activated carbon (GAC). For VOCs, including the chlorinated hydrocarbons most frequently encountered at VI sites, carbon acts as a physisorbent. When the concentration of a compound in the air goes down, the sorbed contaminant may desorb due to the concentration gradient driving force.

Carbon sorbents are usually placed in beds, or layers, where small granules of carbon are held in place in a confined space with mesh to allow airflow and contact with the sorbent surface. Within these beds, the sorbents are often described by their particle size. The particle size is often expressed in "mesh" units that refer to the sieves that pass or retain a given particle size. For example, in 8×30 mesh GAC, at least 96% of the granules by weight are larger than 30 mesh (0.60 mm) and at least 85% of the granules by weight are smaller than 8 mesh (2.36 mm). Other GAC sizes include 12×40 US mesh (0.42 to 1.70 mm) and 6×16 US mesh (1.18 to 3.35 mm).

For a deep enough bed of carbon with a constant VOC input, the downstream concentrations, or breakthrough, has a standard-shaped curve starting at 0% penetration, or entry into the macro- and micro– pores in the sorbent material (**Figure** 1), and rising to 100% if exposed long enough. **Figure 2** shows the typical slow initial breakthrough, followed by an increasing rate, then an asymptotic approach to equal the upstream concentration. Adsorption is followed by desorption when the inflow of the contaminant is eliminated while air is still flowing. Performance measures include efficiency at a specific time, capacity (how much VOC mass is removed) at a specific point, and breakthrough time (how long it takes to reach, for example, 50% of the upstream concentration marked in **Figure 2**).

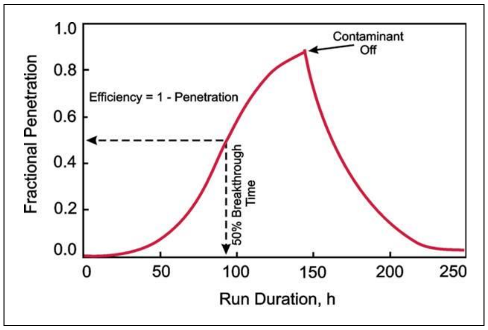

Figure 2. Typical sorbent breakthrough curve for carbon or other solid sorbents

3.2.2 Influences on Adsorption Performance

The efficiency and capacity of an adsorbent, such as activated carbon, can be influenced by several factors including:

- Structure/nature of the target VOC(s)
- Humidity and temperature
- Concentration of the target VOC(s)
- Concentrations of nontarget VOCs and other gases
- Properties of the carbon, such as the material used to manufacture it and the grain (mesh) size.

Different compounds adhere to carbon differently (due to their polarity, van der Walls forces, etc.). More strongly sorbing compounds can compete with and cause more weakly sorbing compounds to desorb from the active sites on the carbon where they are bound. For example, incoming toluene will cause the displacement of isobutanol as the toluene occupies the sorption site (VanOsdell et al., 1996). This is important if the total capacity of the bed is insufficient to hold the more weakly sorbing compounds and the weakly sorbing compounds are of concern. In general, compounds with higher molecular weights sorb better. For activated carbons, moderately adsorbable gases tend to be those with boiling points from -100° to 0°C, lighter gases tend not to adsorb as well, and gases with high molecular weights and boiling points adsorb preferentially (Godish, 1989; Shepherd, 2001). Shepherd (2001) provides relative carbon sorption strengths for various VOCs. **Table 1** shows the relative sorption strength, molecular weights, and boiling points for some selected compounds.

Table 1. Relative VOC Adsorption Rates by Molecular Weight and Boiling Points (Shepherd, 2001)

Relative Sorption Strength	Compound	Molecular Weight	Boiling Point (C)
Strong	NITROBENZENE	123	211
↑	TETRACHLOROETHANE	166	147
	TETRACHLOROETHYLENE (PCE)	165	121
	STYRENE	104	145
	XYLENE	106	138
	NAPATHYLENE	128	217
	TOLUENE	92	111
	BENZENE	78	80
	METHYL TERT-BUTYL ETHER (MTBE)	88	55
	HEXANE	86	68
	ETHYL ACRYLATE	100	57
	DICHLOROETHANE	99	99
	METHYL ETHYL KETONE (MEK)	72	80
	METHYLENE CHLORIDE	84	40
	ACRYLONITRILE	53	74
	ACETONE	58	56
	VINYL CHLORIDE	62	-14
	CHLOROETHANE	64	-12
↓	BROMOTRIFLUOROMETHANE	149	-58
Weak	METHANE	16	-161

For example, Guo et al. (2006) ran sorption performance and desorption experiments (using the methodology of the ASHRAE Standard 145.1-2008) on commercially available activated carbon media for hexane, decane, toluene, PCE, 2-butanone, isobutanol, and D-limonene. VOC concentrations were in the range of 30–100 parts per million (ppm). All the sorbents tested were different types of activated carbon except one carbon/potassium permanganate impregnated alumina (PPIA) blend.

Reporting performance as breakthrough time at 50% removal efficiency for a 43-ppm average upstream PCE test, Guo et al. (2006) observed values from 13 to 21 hours across five carbon sorbents showing that the type of carbon can make a substantial difference in performance and that it can be difficult to predict performance beforehand. Both the sorbent with the 21-hour breakthrough time and the sorbent with the 13-hour breakthrough time were bituminous coal-based granular carbons. PCE was in the middle in terms of capture with 2-butanone, toluene, and isobutanol coming through quicker; n-hexane, about the same; n-decane, slower; and d-limonene, much slower. These data suggest that the presence of common longer-chain alkanes, such as n-decane, and naturally occurring terpenes, such as d-limonene, could cause PCE to desorb from carbon beds.

In addition, water vapor is normally present in the atmosphere at much higher levels than VOC contaminants, with water vapor comprising up to 4% of the atmosphere by volume and most organic contaminants a few parts per million or less (U.S. EPA, 2011a). Water vapor competes for sorption sites on carbon. Higher humidity, thus, may result in less sorption (Owen, 1996) and increasing humidity can drive off sorbed contaminants. The influence of humidity can vary by type of contaminant, concentration, and type of carbon (Hines et al., 1990; McDermott and Arnell, 1954; Moyer, 1983; Nelson et al., 1976; Stampfer, 1982; Werner, 1985). The efficiency of benzene sorption, as described by Deitz (1988), steadily decreased as humidity increased. For high concentrations (1,300 and 300 mg/m^3 [240 to 56 ppm]), Werner (1985) reported that increased relative humidity decreased carbon adsorption of TCE significantly for lower TCE concentration tests with decreasing influence as the TCE concentration increased.

Data reported for chlorinated and other hydrocarbons show some evidence of competition between VOCs for active sorption sites. This competition can manifest as a difference in performance between a test of a VOC by itself and that same VOC in a mixture. If two compounds A and B are in a mixture, the strength of their binding to carbon when mixed is not always well predicted by single pure compound tests. VanOsdell et al. (1996) investigated test methods for sorbents and sorbent-based ATUs for removal of VOCs and the acid gases: ozone, SO_2, and NO_2. Gas-phase challenges were single compounds and mixtures. This study clearly showed that gases penetrate sorbents at different rates depending on the challenge mixture and the gas concentrations. PCE was tested as a single gas and as part of a specific test mixture as the representative chlorinated hydrocarbon. One result showed that the 10% breakthrough time versus contaminant concentration curves for PCE and other VOCs were linear across approximately two orders of magnitude of concentration with PCE breaking through more slowly (sorbing better) than either toluene or 1-butanol on the 4x8 mesh GAC. However, toluene sorbed better than PCE (PCE came through more quickly in mixture tests). For a five-VOC mixture, total 1 ppm concentration test, of a full-scale 4x8 mesh GAC with a calculated 0.1 second residence time (about 100 lbs. of GAC at 2,000 cubic feet per minute [cfm]), both toluene and PCE reached only 10% over initial breakthrough in approximately 120 hours, showing that carbon has a substantial PCE capacity. All VOCs were shown to desorb once the challenges were turned off and the concentrations of the VOCs in the influent air decreased. In these tests, methyl ethyl ketone (MEK), 1-butanol, and hexane came through more quickly than toluene or PCE. The presence of acid gases common in urban atmospheres (ozone, SO_2, and NO_2) also decreased the breakthrough time for the VOCs. In addition to shorter breakthrough times for VOCs, ozone has an adverse, non-reversible effect on activated charcoal performance as it attacks the pore structure of activated carbon (Lee and Davidson, 1999).

Because sorption depends on the amount of surface area of the sorbent, ATUs with more carbon are likely to have higher efficiency and capacity. This is only a general rule-of-thumb as carbons can vary by type, pretreatment, and size of pellets/particles. ATU geometry (e.g., accidental or designed bypass of the sorbent bed) will also influence the efficacy of the unit.

Chapter 46 of the *ASHRAE Handbook–HVAC Applications* includes information on contaminants, problem assessment, reduction strategies, ventilation, ATU system design, environmental influences, and testing for ATUs for gaseous contaminants (ASHRAE, 2015). Table 7 in ASHRAE (2015) provides recommendations for the type of sorbent media to use for different VOCs. Sorbents included are GAC, PPIA, acid-impregnated carbon (AIC), and base-impregnated carbon (BIC). GAC is the first choice for dichlorobenzene, dichlorofluoromethane, PCE, and 1,1,1 trichloroethane. PPIA is listed second for TCE and as an alternate first for 1,1,1 trichloroethane. However, recent (June and July 2016) contacts with manufacturers by e-mail and at the June 2016 ASHRAE meeting gave only GAC as the recommended sorbent for chlorinated hydrocarbons.

3.3 *Photocatalytic Oxidation*

Photocatalytic oxidation (PCO) refers to a type of reactive ATU that uses light and catalysts to react VOCs in the air into other species. Typically, these devices are called UV-PCO for the ultraviolet light used with photocatalytic oxidation. Specific devices may be designed for different specific wavelengths and this could influence performance. The usual catalyst is titanium dioxide (TiO_2).

PCO technology has been studied extensively at the lab scale and to some extent at full scale (room sized and up to units designed to treat a full building). Although some studies show that—given enough air passes (recirculation) through the devices—many contaminants can be broken down to CO_2 and water, most studies show that intermediate oxidation byproducts are formed, including aldehydes (such as formaldehyde), acetone, and even phosgene. The current commercial implementations of this technology achieve multiple passes by discharge to the room air where the byproducts may be breathed in before re-entrainment to the device of some of the room air (Hodgson et al., 2005; Jo and Park, 2004; Mo et al., 2009).

In real-world situations, it is impossible to know ahead of time exactly what VOCs and other gases will be present in the indoor air to be treated. Reactions in the PCO devices may result from compounds in the air other than the targeted VI compounds. VOCs like chlorinated solvents, benzene, and other petroleum hydrocarbons are always present in the indoor and ambient atmosphere even in rural areas and remote sites (Kesselmeier and Staudt, 1999; Weisel et al., 2008). Thus, it is nearly impossible to predict which intermediaries will be formed without sampling and analyzing the indoor air. Because intermediate products become part of the breathing air in the room or building being treated, and may have low indoor-air screening levels, they must be considered potentially as dangerous or more dangerous than the original contaminants of concern (Alberici et al., 1998; Hodgson et al., 2005, 2007; Kropp, 2014). In short, there have not been enough field demonstrations in complex real indoor atmospheres to fully evaluate whether any observed destruction of target VOCs outweighs the formation of undesirable reaction byproducts by PCO devices.

Some PCO devices are ineffective or produce excessive ozone. California maintains lists of ATUs that are "potentially hazardous" because of ozone generation along with the devices that they certify. Kropp (2014) studied on-the-market PCO devices in a small (580 L) chamber. Of the five devices studied, three did not appreciably reduce the concentration of the target contaminant. The fourth removed contaminants, but the sorbent bed it contained performed similarly with the UV light function turned off. The fifth device destroyed dichlorobenzene over time and did not make phosgene. Byproducts formed by these devices included acetone, acetaldehyde, and formaldehyde.

A lab-scale study by Alberici et al. (1998) also showed destruction of compounds and creation of intermediate byproducts. They examined byproducts of UV-PCO (TiO_2/UV) degradation of TCE, PCE, chloroform, and dichloromethane at various humidity levels. Among the byproducts they detected were phosgene for TCE, PCE, and chloroform; dichloroacetyl chloride for TCE; and trichloroacetyl chloride for PCE. Chlorine gas (Cl_2) was also detected as a final product. Alberici et al. (1998) also showed that increasing the relative humidity (RH) from 20% to 80% decreased the destruction from close to 100% to 70% for a 30-minute exposure.

Hodgson et al. (2005) generated extensive data on the destruction of low concentration multicomponent VOC mixtures by UV-PCO in a 20 m^3 chamber. Byproducts found included formaldehyde, acetaldehyde, acetone, formic acid, and acetic acid. These compounds were found at low levels, given that the inlet concentrations were also low level. In a study with a gas mixture intended to be similar to the Hodgson et al. (2005) study, but done in an HVAC test duct, RTI (2009) tested a different UV-PCO unit and showed very small statistically significant differences between upstream and downstream VOC concentrations with some removal of several compounds. In a follow-on study, Hodgson et al. (2007) looked at chemisorbent scrubbers downstream of the UVPCO device to reduce the production of formaldehyde and acetaldehyde and found that the combination "effectively counteracted the generation of formaldehyde and acetaldehyde due to incomplete oxidation of VOCs in the UVPCO reactor."

UV-PCO units are often not tested for efficacy or byproduct formation, in part due to the lack of standard test methods. Devices may be sold based on lab-scale or similar device testing, or performance expectations may simply be based on the presence of the catalyst and UV light. Therefore, a UV-PCO device should not be used for VI remediation in occupied spaces unless test results are available that demonstrate efficiency and the lack of toxic byproduct formation for the conditions in the indoor spaces being treated. Other reactive devices (such as bipolar ionization and plasma-based units) have essentially the same positives and negatives as the UV-PCO units discussed above.

3.4 *Other Air Treatment Unit Types*

Other types of ATUs based on ozone generation, chemisorption, or biofiltration are available for use for indoor air VOC mitigation but further testing is required because they are mechanistically unsuitable, lack reliable performance data, or may have negative effects. They are presented in short form in this section to cover devices that might be proposed or considered for use at sites with VI applications. As described below, these technologies have not been adequately tested for VOCs nor for the applications described in this document.

Although ozone generators may remove contaminants by oxidation, they are concerns with their use because of the dangers of ozone itself. As stated in a previous EPA EIP (U.S. EPA, 2008): "regulatory agencies have taken strong positions to warn of potential problems with air cleaners dependent on ozone generation…Methods that inject ozone into the breathing space of the indoor environment cannot be recommended as an air cleaning technique, as ozone is a criteria pollutant. The state of California has banned the sale of residential ozone producing air cleaners effective in 2009." The California Air Resource Board (CARB) has a long list of devices under the heading "Potentially Hazardous Ozone Generators Sold as Air Purifiers."[1] CARB also certifies other air cleaning devices as being electrically safe and having low ozone generation (CARB, 2016).[2]

Some ATUs are marketed as "ion generators." The most common application of the ion generator concept is particulate removal (Shaughnessy et al., 1994), which is beyond the scope of this document.

Chemisorbent beds of permanganate, usually in the form of PPIA, oxidize some airborne contaminants. However, PPIA is not recommended for use with chlorinated hydrocarbons, in part, because of potential byproducts including hydrochloric acid (Aguado et al., 2004; ASHRAE, 1994; VanOsdell et al., 1996).

Biofiltration works by having plants or microbes digest contaminants. These devices need to be specifically planned for the specific compounds to be removed from air, usually need stabilizing time for

[1] https://www.arb.ca.gov/research/indoor/o3g-list.htm

[2] https://www.arb.ca.gov/research/indoor/aircleaners/certified.htm

microbes to self-select for ones that thrive on particular contaminants, and may be slow working (Guieysse et al., 2008). They have not been tested for the applications discussed in this document.

3.5 *Multiple Technology Air Treatment Units*

Many commercially available ATUs include multiple technologies and address both particulates and gases. Frequently, a gas-phase device will add a particle filter before and/or after a sorbent bed. Sorbent media may also be affixed to fibers in combination gas-particle filters. Multiple technology systems should be evaluated based on an understanding of the effects of their component parts. ATUs with particle filtration before a carbon bed would be expected to behave for VOCs as well or better as systems with carbon beds alone, as the filters can prevent the carbon bed from being fouled by particulate matter. Technologies that use particle filtration ahead of UV-PCO would be expected to be subject to most of the same weaknesses as UV-PCO–only systems in VOC removal applications because background VOCs would be not be filtered out and could form reaction byproducts in the UV-PCO unit. A unit with a reaction chamber, such as UV-PCO, ahead of a carbon bed is likely to be acceptable if there is sufficient carbon or other sorbent(s) to adsorb the reaction byproducts (e.g., formaldehyde, acetone, acetic acid, and acetaldehyde).

3.6 *System Sizes and Geometries*

Air treatment units are available in a wide variety of capacities and configurations. Treatment capacity is typically rated as the airflow rate in cubic feet per minute. However, units with similar airflow ratings may differ in air treatment capacity due to different treatment efficiencies resulting from such factors as the type of sorbent material and air-sorbent contact time within the units. At present, manufacturers do not publish information on treatment efficiency using a standardized method so comparisons are difficult. For comparison within this EIP, treatment capacity is assessed as airflow through the device.

Attachment A summarizes information about a wide range of ATU equipment. The listed ATUs fall into the following main categories: portable units and built-in units intended for permanent or semipermanent installation. Built-in units are connected to existing HVAC duct work while portable units are generally freestanding units that withdraw air from the room, treat it, and discharge it into the same room. Various systems are available within each of these categories.

3.6.1 Sizing an Air Treatment Unit

The size of an ATU needs to be understood in the context of the air exchange rate of the room, zone, or building into which it is being installed. The air exchange rate is the ratio of the airflow through the building to the building volume, and is generally expressed in units per hour, the number of air exchanges per hour (ACH). EPA gives a 50th percentile air exchange rate for residences of 0.45 ACH (U.S. EPA, 2011b). Commercial and institutional buildings have design requirements for air exchange that are expressed per person or per unit area of building (International Code Council, 2009). Those requirements typically result in air exchange rates above four for many types of commercial and institutional buildings (Engineering Toolbox, n.d.).

Larger buildings are typically divided into multiple zones for heating or cooling, often defined as areas in which temperature can be separately controlled often by a single thermostat (Grondzik and Furst, 2000). Building mechanical system designers generally seek to create a "well-mixed" condition within each zone for thermal comfort, which also plays an important role in determining the effectiveness of a localized ATU device within the zone (Howard-Reed et al., 2008a, b; Int-Hout, 2015).

3.6.2 Portable Air Treatment Units

Most of the portable units listed in Attachment A are smaller types weighing less than 100 pounds. These units run off 110-volt current and have wall plugs. Airflows range from less than 100 cfm up to approximately 600 cfm. Assuming a residential example, with a normal air exchange rate of one exchange per hour or less, a targeted treatment air exchange rate through the ATU of four exchanges/hour might be selected if significant subslab or indoor sources of VOCs are expected to be present. Thus, in a 10-ft ceiling space up to 900 ft^2, a 600-cfm unit could be used (see Section 5.3 for further information on these types of calculations).

When selecting air flows, attention should also be paid to a comfortable air velocity through the room (ASHRAE, 2009) as well as the need for complete mixing within the zone if the entire zone is to be treated by a portable unit. This estimate will differ from the treatment area estimates provided by the manufacturers, but currently there are no standard methods by which manufacturers estimate and report this information.

Some larger portable units are listed in Attachment A. These wheel- or cart-mounted units also run off 110-volt current and have wall plugs. The listed airflows are up to 2,000 cfm. Using the assumption applied above, a 2,000-cfm unit could treat up to 3,000 ft^2 in a single well-mixed zone with a normal air exchange rate of one per hour or less. One of the larger portable units is optionally ductable, allowing placement of the unit outside of the space being treated. Alternatively, a large space could be treated with multiple smaller units.

3.6.3 Built-in Air (Ducted) Air Treatment Units

Many types of built-in units are commercially available (Attachment B). These devices are intended for placement outside the space being treated, for example in a drop-ceiling space or utility room, and connected to an HVAC duct system or separately ducted for outdoor discharge. The units with separate ducts are hard-wired into the building's electrical system and run off 110- or 220-volt current depending on the model. Airflows range from less than 100 cfm up to 10,000 cfm. HVAC-mounted units are approximately the cross section of the ductwork and 1–12 inches in depth. The airflow will depend on the fan in the HVAC system and, thus, no separate power source is required.

4. PERFORMANCE DATA AND SPECIFICATIONS

Information that a user should consider for ATU design includes airflow (for portable units), pressure drop (for duct-mounted units), VOC removal efficiency, sorbent capacity/lifetime, reliability and uptime, noise levels, power usage, physical dimensions, and weight. Many of these details are cited on sales Websites and on the product's packaging. Care is needed in interpreting data that may not have been measured in the same way. Available specification data for the reviewed devices are summarized in Attachments A and B. Key testing criteria include:

Total Airflow: For portable and many wall-mounted devices, total air flow is the volumetric flow rate (in cubic feet per minute) at which air is pulled from, treated, and returned to the room. For duct-connected devices with their own fan, this is the volumetric flow rate at which air is treated. For HVAC-mounted devices that do not have their own fan, the airflow is usually determined at the air handler of the HVAC system that the device is installed in. Total airflow information should be available for any portable device in any standard catalog listing, from the packaging, and from distributors. Important considerations for the user include being sure that the flow configuration of a device fits the needs of the project and that device inlets and outlets are not obstructed.

Clean Air Delivery Rate (CADR): For portable devices, CADR is the amount of 100% clean air that is delivered by an ATU when tested using the Association of Home Appliance Manufacturers (AHAM, 2015) test method for specific types of particles. An ATU with an airflow of 100 cfm and an efficiency of 50% would have a CADR of 50 cfm. The particulate CADR does not indicate whether a unit can clean VOCs from the air. However, unit testing for VOC removal can provide a VOC CADR-like value based on similar measurements and calculations.

Pressure Drop (or Resistance): For HVAC-mounted devices, this is a measure of how difficult it is to push or pull air through the device. A higher-pressure drop may reduce airflow and increase energy costs. Pressure drop is usually reported in inches of water (in. H_2O) in the United States. HVAC devices intended for commercial buildings will have rated airflow and pressure drop. These are usually on the product label and will be available from the distributor or manufacturer.

Removal Efficiency: Removal efficiency is the percentage of a contaminant that is removed by the device (outlet ÷ inlet × 100). Removal efficiency may change over time, with temperature and humidity changes, and for different concentrations of VOCs in the inlet air. Penetration is the inverse of efficiency: efficiency = 100% × (1 − penetration). Removal efficiency across the unit is not the same as the achieved change in concentration in the indoor environment in which the unit is operating.

Capacity: The mass of a compound that a device can remove under specific conditions.

Reliability and Uptime: A typical metric of reliability is the mean time between failures (Myrefelt, 2004) or availability as a percentage as uptime divided by total time (Murphy and Morgan, 2006).

Noise Level: How loud a device will be, usually reported for the highest airflow setting in decibels.

Power Usage: How much power the device requires, often measured in watts or kilowatt hours. Some devices report this as likely annual usage.

Dimensions: How wide, deep, and tall a device is.

Weight: For portable units, this could be the unit without the filters, with filter weight reported separately.

4.1 *Laboratory and Chamber Tests for Efficiency and Capacity*

Standardized laboratory test methods for ATUs fall into two main categories: HVAC/in-duct and room.

ASHRAE 145.2-2011 *Laboratory Test Method for Assessing the Performance of Gas-Phase Air-Cleaning Systems: Air-Cleaning Devices* (ASHRAE, 2011) specifies how to test HVAC/in-duct sorbent devices. Each test uses a single contaminant in otherwise clean air as the challenge. The initial efficiency, 1-hour, low concentration, section is followed by the 4-hr, high concentration, capacity test. After the challenge gas is turned off, potential desorption is monitored for up to 30 minutes. This test is performed at one temperature/RH combination. This test allows comparison of ATUs under controlled conditions for pressure drop (resistance), clean filter efficiency, capacity, and presence of desorption (ASHRAE, 2011). This test has recommended compounds for many chemical categories. ASHRAE 145.2 does not have a suggested gas mixture test, and it does not require testing for reaction products. Standing Standard Project Committee 145, the committee responsible for ASHRAE 145.2, is currently considering changes to add reactive devices and reaction product analysis. However, this is likely to take years to incorporate and get approved as a new version of the method. International Standards Organization (ISO) 10121 is a similar test to the current ASHRAE 145.2 with somewhat different concentration levels suggested (ISO, 2014). These tests are performed at the manufacturer's stated airflow, so the airflow for a given pressure drop is reported. In addition, a description of the device, including dimensions, is required.

For portable and wall- or ceiling-mounted room ATUs, the U.S. standard for particle removal is usually the AHAM standard (AHAM, 2015). A room unit is placed in a closed chamber with no airflow through the chamber. The change in concentration (the decay rate) is determined with the device on and off (as a control). Comparison of these values and accounting for the size of the room, leads to a CADR as the output.

The methodology used in this test can be used to test gas-phase filters if a gaseous contaminant and analyzer are substituted in place of the particles and particle analyzer. The National Research Council Canada: NRCC-54013 *Method for Testing Portable Air Cleaners* (NRCC, 2011) and the Professional Standard of the Republic of China: *Test of Pollutant Cleaning Performance of Air Cleaners* (PRC, 2010) implement this approach. Some of the specifics are different, but the essence of on/off decay rate comparisons is the basis for this method. Other than the inclusion of ozone testing in the Chinese method, these methods do not call for testing reaction byproducts. However, it is simple to add analysis for expected reaction byproducts (although it may be difficult to predict which compounds to look for). As an example of this approach to testing, Chen et al. (2005) used this approach in addition to single-pass efficiency reporting. Output from tests of these types can be used in modeling, as discussed later in this document, either as the amount of clean air entering the room or by separating the information into a device airflow amount and a removal efficiency. Note that the clean air rate and the efficiency will change over time in long-term operations even if this is not observed in a short-term laboratory test.

Filter/technology combinations from room ATUs may also be tested for single-pass efficiency in a test duct. This can be done by removing the filter/technology from the housing and fan assembly or by installing the whole device in a duct and matching the duct airflow to the device's airflow rate. This would be a non-standard use of a test method, but can give useful data on the device. Some devices can use different filters, so it is a good idea to be sure that any test or in situ data that are reported are based on the filters that will be installed.

In a laboratory study of five on-the-market gas-phase ATUs, Owen et al. (2014a and b) ran ASHRAE Method 145.2 tests on HVAC ATUs with sorbent amounts ranging from under an ounce to 48 pounds. **Table 2** gives descriptions of the devices. These ATUs were chosen with the expectation that they would show a variety of results from low to high removal efficiency across different test VOCs. The VOC challenge gases in this study (toluene, hexane, and formaldehyde) were tested separately as required by the method. Also as required by the test method, the initial efficiency portion of the tests was performed at a gas concentration of 400 parts per billion (ppb) for 1 hour. The capacity portion of the test has the challenge level at 50 ppm for toluene and 25 ppm for hexane and exposure for up to 4 hours. Formaldehyde was tested for only the initial efficiency portion at 100 ppb.

The test results show that the different ATUs have significantly different performance when compared to each other and for different compounds. For most ATUs, the efficiency was stable over the initial efficiency test period; however, the efficiency dropped for some. The reported initial efficiency percentage is the average over the hour of the test. For the capacity test, the efficiency is reported at intervals over the course of the test, which runs for 4 hours or to less than 5% efficiency, whichever comes first. The capacity is the calculated amount of the challenge gas that the ATU captures during this test; it is not adjusted by any desorption seen after the challenge gas is turned off.

Table 3 summarizes the gas phase data for all five filters. The initial efficiencies are graphed in **Figure 3**. To show how the efficiency can change with loading, **Figure 4** plots the toluene efficiency curves over the capacity tests (ATU A did not remove toluene). Note that the capacity tests were performed at a very high concentration relative to normal room air and are intended to rank the relative performance of the equipment, not to measure how long a filter will function in an actual installation (i.e., not to estimate filter lifetime).

Table 2. Air Treatment Units Tested by Owen et al. (2014a, b)

Air Treatment Unit ID	A	B	C	D	E
Size, in.	20 x 25 x <1	20 x 25 x 1	24 x 24 x 4	24 x 24 x 12	24 x 24 x 12
Application	residential	residential	commercial	commercial	commercial
Airflow rate, cfm	1,024	1,024	2,000	2,000	2,000
Type of air treatment unit	flat panel	pleated panel	pleated panel	rigid v-cell	rigid cell, deep pleat
Media type	activated carbon	activated carbon	50/50 blend of (impregnated) activated carbon and permanganate-impregnated alumina	loose fill media blend of activated carbon and potassium permanganate, 48 lbs./air treatment unit	activated carbon, coconut shell, small granule (20x50 mesh), impregnated for removal of formaldehyde. ~12.8 lbs./air treatment unit

Table 3. Summary of Gas-phase Data from Owen et al. (2014a, b)

Challenge Gas	Measured Value	Air Treatment Unit				
		A	B	C	D	E
	Initial weight of filter (carbon plus housing), g	266	463	2,043	27,264	17,234
	Pressure drop at rated airflow, in. H_2O	0.18	0.27	0.48	0.39	0.35
Toluene	Initial efficiency, %	0	30	35	61	91
	Capacity test, lowest efficiency, %	0	4	3	37	24
	Capacity, g	4.4	47.3	56	773.8	417.2
Hexane	Initial efficiency, %	6	27	34	70	95
	Capacity test, lowest efficiency, %	0	0	0	2	15
	Capacity, g	2.1	17.0	13.3	285.6	406.7
Formaldehyde	Initial efficiency, %	2	3	35	41	NA

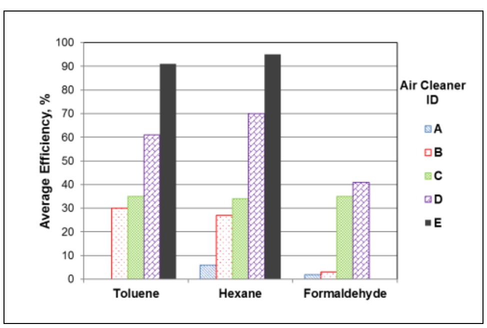

Figure 3. Initial efficiency test averages for the indoor gases (Owen et al., 2014a, b)

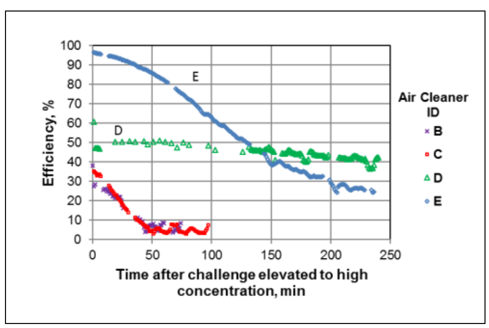

Figure 4. Toluene capacity test efficiency curves (Owen et al., 2014a, b)

4.2 *Controlled (Unoccupied) Building-scale Demonstrations of Air Treatment Units*

An extensive series of well-controlled, factorial studies of ATU performance have been conducted by the National Institute of Standards and Technology (NIST) and reported by Howard-Reed et al. (2005, 2007, 2008a, 2008b) and Persily et al. (2003). There are several features of these studies that make them somewhat different from common ATU VI applications:

- The contaminant tested was decane introduced at a constant controlled rate from a permeation oven directly into the indoor environment. Decane is very nonpolar and should adsorb quite well to GAC.
- The studied structure was apparently a research structure not actually occupied by residents, which would tend to limit the number of indoor sources of VOCs. However, ambient air VOCs would be expected to be present.
- The studied structure was a double-wide manufactured home with an unusual crawlspace—one divided vertically by an "insulated plastic belly" which contained the HVAC ductwork (Persily et al., 2003). However, the house was otherwise fairly typical for modern U.S. residential construction, consisting of three bedrooms, two bathrooms, a utility room, and a continuous living/dining/kitchen/family room.
- The test durations were relatively short—typically 1 to 3 days. The ATU devices tested had modest masses of sorbent, such as a duct ATU with 0.75 kg of activated carbon or a portable ATU with 500 g of carbon, potassium permanganate, and zeolite (Howard-Reed et al., 2007, 2008b).

Nevertheless, important insights and findings were generated from this series of tests that should be applicable to residential-scale implementations of ATUs for VI:

- The 140 m^2 structure (1,506 $feet^2$) was operated either as a single ventilation zone, using the forced-air HVAC system to provide recirculation, or as multiple zones by turning off the HVAC system and closing bedroom doors. This had a dramatic influence on contaminant distribution in tests of a single portable ATU:
  - When the source and ATU were in the same isolated bedroom, with the HVAC off, concentrations in other rooms of the house were "almost unaffected" by the contaminant release and remained low (Howard-Reed et al., 2007).
  - When the source and ATU were in the same bedroom with the door closed but with air distributed throughout the house by the HVAC, the ATU in the closed bedroom had the most effect on the bedroom concentration but also had some beneficial effects on VOC concentrations in other rooms.
  - When the source and the ATU were in different rooms, with the HVAC off, "the tests showed limited ability of the portable ATU…to remove decane from the entire house" regardless of whether the doors were open or closed (Howard-Reed et al., 2007, 2008a).
- The average "direct removal efficiency" (outlet concentration divided by the inlet concentration) for the portable ATU tested was 54%. The duct-mounted device had an average removal efficiency of 42%.
- New media was used in each test. When the HVAC system was operated to mix the air in the 140 m^2 structure, the reduction in VOC concentration in the whole structure was approximately the same (within 15% for the portable systems) as would have been

mathematically predicted based on measurements at the outlet of the ATU for both the portable and duct-mounted systems (Howard-Reed et al., 2007, 2008a). The authors interpret this result to mean that "a single zone was achieved in the test house and that the ATU was operating without significant short-circuiting" (Howard-Reed et al., 2007). Thus, the mathematical approaches that were used by Howard-Reed to predict changes in indoor air concentrations based on the single pass removal efficiency of the ATU were validated.

- Although the authors define ATU effectiveness as "the fractional reduction in pollutant concentration that results from application of a control device" (Howard-Reed et al., 2007), they do not report their results in these practical units. However, effectiveness can be estimated from the figures presented. In test 48 with the portable ATU in use, HVAC on, and the ATU in a bedroom with the door closed, the decane concentration was reduced from 0.86 to 0.31 mg/m^3 in that bedroom, which would be an effectiveness of 64%. A similar effectiveness (58%) can be estimated from the kitchen/family room dataset. These effects were observed over approximately 1 day of operation after the ATU was turned on. The reported air exchange rate for that test was 0.21 per hour. The portable ATU flow rate was 340 m^3/hour and the volume of the house was reported as 340 m^3. Thus, the ATU was operating at 4.8 times the natural air exchange rate of the structure.
- When the house was operated as multiple zones, with the contaminant injected into a different room/zone than the portable ATU, ATU effectiveness dropped to between 14 and 23% of the optimal predicted benefit (Howard-Reed et al., 2007).

Howard-Reed et al. (2008a) summarize their results stating, "When a building does not have a uniform concentration of contaminants, an in-duct ATU may not be as effective at reducing the whole-building mass. Likewise, a portable will also not be as effective at removing total mass when operated in rooms different from the contaminant source, but it can also effectively exceed predicted performance when the source and ATU are in the same room isolated from the remainder of the house." One practical conclusion of this study for VI sites is that it is advantageous to locate an ATU in the lowest level of a building, close to the presumed VOC entry points, or both.

Howard-Reed et al. (2008b) tested a small (37 m^2; 398 ft^2) unfurnished single-room house with wood-frame construction and an attic. Decane was directly injected into indoor air from a permeation oven. The in-duct system tested in this house contained 0.6 kg of activated carbon, alumina, and potassium permanganate in a filter housing. The portable ATU contained 2.7 kg of charcoal, potassium permanganate, and zeolite. The portable ATU operated on its highest airflow setting and delivered an average flow rate of 350 m^3/hour (206 cfm) versus a manufacturer reported air flow rate of 510 m^3/hour (300 cfm). The average direct measurement of ATU efficiency based on inlet and outlet concentrations was 38% for the duct-mounted unit and 43% for the portable ATU. Efficiencies calculated based on measurements in the center of the room and either transient or steady state mass balance were somewhat less. The effectiveness defined as "the fractional reduction in pollutant concentration that results from application of a control device" was always greater than 80%. Both ATUs were used for repeated short-term challenge tests (8 for the duct mounted unit and 16 for the portable unit) and showed decreasing decane removal efficiency as the total mass of decane treated increased (without changing the sorbent).

4.3 Practical (Occupied) Field Applications to VI Cases

A review of publicly available literature was completed for sites where ATUs have been used to reduce indoor air VOC concentrations in occupied buildings. The documents reviewed are listed in **Table 4**. A full summary of the parameters of the treated space (e.g., volume, potential indoor sources, HVAC operational parameters) was not consistently available. These case studies include ATU deployments in commercial, industrial, and residential buildings. In some cases, multiple buildings were included in the deployments. In these cases, one or two representative buildings are discussed below.

4.3.1 Naval Weapons Industrial Reserve Plant, Bethpage New York (TetraTech, 2010)

Site 1 of the Former Drum Marshalling Area was impacted by historic releases of chlorinated solvents to soil and groundwater. Site impacts were remediated by an air sparging/soil vapor extraction (AS/SVE) system between 1998 and 2002. Soil gas testing conducted in 2008 indicated elevated concentrations of VOCs along the eastern boundary of Site 1, affecting the adjacent residential neighborhood. Soil gas, indoor air, outdoor air, and subslab soil vapor samples were collected from January through April 2009 at 18 residences. As an interim measure, ATUs were placed in homes. Following additional sampling, subslab depressurization (SSD) systems were installed in a subset of the homes.

The available reports did not provide information on the size of each of the residences, the flow rate of the ATUs, or ATU run time. For this discussion, we assume that the residences were constructed similarly and that most contain basements. Available analytical data included indoor air concentration prior to installation of the ATUs, indoor air concentration after ATU installation, subslab soil vapor concentrations, and indoor ATU post-SSD system installation (where applicable). A summary of key parameters is provided in **Table 5**.

In Homes 1, 4, 6, 7, 10, 12, 13, and 14, the ATUs reduced indoor air concentrations of TCE to levels below the New York State health screening levels when initial concentrations were above the indoor air screening levels (**Table 5**). Similar reductions in indoor air concentrations for PCE (82–87%) and 1,1,1-trichloroethane (33–72%) were also found at the site (see referenced report in **Table 4** for full information). However, the ATUs did not appear to adequately reduce indoor air concentrations in Homes 2 and 3 and SSD systems were subsequently installed at those locations. SSD systems were also installed in Homes 4, 6, 13, and 14 as a precautionary measure. Across all cases, an average TCE concentration reduction of approximately 80% was observed in the post-ATU installation samples.

Assuming that the ATUs were operating in similar home volumes and at similar flow rates, there appears to be a correlation between elevated subslab and indoor concentrations (i.e., orders of magnitude above screening levels) and the ability of the ATU to reduce concentrations and maintain acceptable indoor air concentrations (refer to the basements of Homes 2 and 3). In the two cases with subslab concentrations greater than 10,000 $\mu g/m^3$, although reductions in indoor concentrations of 67–81% were achieved in indoor air, those reductions were insufficient to reach the New York State screening level. This is consistent with the mathematical design approaches outlined in Section 5.3.2, which show that the needed ATU capacity/number of ATU devices required increases sharply with increasing baseline subslab and indoor air concentrations.

A complete dataset was not available for review, and, thus, the data are not conclusive. For example, the run time for each system is not provided. Some residences may not have operated specific units during the entire time between samples. However, the apparent correlation between subslab soil vapor concentration and ATU effectiveness should be given further consideration as it is discussed based on the theory in Section 5.

Table 4. Field Applications of Activated Carbon VOC Air Treatment Units (ATUs) at VI Sites

Site	City, State (Regulatory Authority)	Buildings with ATUs	Duration of ATU Operation	Report Name	Report Date	Report Author	Report Link	Report Notes
Bethpage Naval Weapons Industrial Reserve Plant	Bethpage, NY (NY DOH)	2 residences with granular activated carbon ATUs.	8 months	Final Quarterly Data Summary Report for Soil Vapor Intrusion Monitoring (May–August 2010) NWIRP Bethpage, NY	11/1/2010	TetraTech	http://www.navfac.navy.mil/niris/MID_ATLANTIC/BETHPA.GE_NWIRP/N90845_001199.pdf	Addresses only one residence (#3). Has a description of ATU/SSD history.
Gardena Marketplace	Gardena, CA (CA DTSC)	3 residences with granular activated carbon ATUs	4 months	Supplemental Vapor Intrusion Assessment Summary Report #2, Former Honeywell Gardena Site, 1711-1735 West Artesia Boulevard, Gardena, CA	3/25/2016	CH2M	http://www.envirostor.dtsc.ca.gov/regulators/deliverable_documents/6357958734/Gardena%20Marketplace_Supp_VI%20Assessment_Report_No%202_32516.pdf	Documents concentrations before installation of air treatment units at 3 residential locations
				Second Quarter 2016 Vapor Intrusion Monitoring Event Report, Honeywell Gardena Site, West Artesia Boulevard, Gardena, California	7/29/2016	CH2M	Not yet posted. But will appear here http://www.envirostor.dtsc.ca.gov/public/profile_report.asp?global_id=19360536	Documents concentrations after installation of air treatment units at 3 residential locations
		9 commercial bldgs. with granular activated carbon ATUs	2.5 years	First Quarter 2016 Vapor Intrusion Monitoring Event Report, Honeywell Gardena Site, 1711-1735 West Artesia Boulevard Gardena CA	4/29/2016	CH2M	http://www.envirostor.dtsc.ca.gov/public/deliverable_documents/6771593987/Gardena%20Marketplace_1Q16_VI_Monitoring_Report_42916.pdf	HVAC manipulation and crack sealing was also used for mitigation
CRREL	Hanover, NH (NH DES)	1 industrial research facility	not specified	The Value of an Iterative Approach to VI Evaluation and Mitigation: Lessons Learned at the CRREL Facility in Hanover, NH		Geosyntec		Not available online (2016 conference presentation)
Bruscoe Property	Belmont, CA (SFRWQCB)	1 commercial bldg. with AirPura c600 ATU.	8 months	Vapor Intrusion Summary Report, Former Brusco Property	10/31/2013	CH2M	http://geotracker.waterboards.ca.gov/esi/uploads/geo_report/3363481044/T10000002681.PDF	Pre-cleaner investigation
				Completion Report - Interim Remedial Measure and SVE Construction	10/10/2014	CH2M	http://geotracker.waterboards.ca.gov/esi/uploads/geo_report/2903016567/T10000002681.PDF	

(continued)

Table 4. Field Applications of Activated Carbon VOC Air Treatment Units (ATUs) at VI Sites (continued)

Site	City, State (Regulatory Authority)	Buildings with ATUs	Duration of ATU Operation	Report Name	Report Date	Report Author	Report Link	Report Notes
Early Ave.	Torrance, CA (LARWQCB)	7 commercial bldgs. With AirPura C600 air purifiers.	2 years	First Quarter 2014 Supplemental Vapor Intrusion Evaluation Summary Report	4/30/2014	CH2M	http://geotracker.waterboards.ca.gov/esi/uploads/geo_report/5185718595/SL2041M1512.PDF	HVAC manipulation and crack sealing was also used for mitigation
				Interim Mitigation Measures and Indoor Air Quality Assessment at Suite K of Torrance Business Center Property	5/15/2014	CH2M	http://geotracker.waterboards.ca.gov/esi/uploads/geo_report/4345945239/SL2041M1512.PDF	HVAC manipulation and crack sealing was also used for mitigation
Brighton	Brighton, MA (Mass DEP)	unclear	unclear	Post Temporary Solution Status and Remedial Monitoring Reports October 2014 through March 2015	7/1/2015	CH2M	http://public.dep.state.ma.us/fileviewer/Default.aspx?formdataid=0&documentid=309887	
Omega Chemical Corporation Superfund Site	Whittier, CA	Total of 16 air treatment units in 2 commercial buildings	17 months at one location	Short Term Mitigation Air Sampling Report for April 2012 Omega Chemical Superfund Site	6/6/2012	CDM		Other actions in both buildings included HVAC adjustment and crack sealing
				Administrative Settlement Agreement and Order on Consent for Removal Action	10/2/2009	US EPA Region IX CERCLA Docket No. 09-2010-02	https://yosemite.epa.gov/r9/sfund/r9sfdocw.nsf/3dc283e6c5d6056f88257426007417a2/6f77e358ecc151a288257a55007f2b0b/$FILE/AOC%20indoor%20air%20final_110909.pdf	
28th Street Elementary School	Los Angeles, CA	10 class-rooms located in 7 bungalows with granular activated carbon ATUs	About 7 years in some bungalows	Quarterly Indoor Air Sampling and Analysis Report 3rd Quarter 2009	1/5/2010	Geosyntec	http://www.envirostor.dtsc.ca.gov/public/deliverable_documents/7116742789/28th%20St%203rd%20Qtr%20IA%20Report-complete.pdf	Carbon filtration installed after initial HVAC modification and crawlspace ventilation was partially successful. Annual carbon change out.
				2015 Annual Indoor Air Sampling/ Analysis Report	3/1/2016	Geosyntec	http://www.envirostor.dtsc.ca.gov/public/deliverable_documents/4021716058/28th%20St%202015_Annual_IA%20Report.pdf	

Table 5. Summary of Bethpage Data[1]

Home #	Subslab Soil Vapor TCE Concentration (µg/m³)	Indoor Air TCE Concentration Prior to Air Treatment Unit Installation (µg/m³)	Sample Location	Indoor Air TCE Concentration Post- Air Treatment Unit Installation (µg/m³)	Percent Reduction	Indoor Air TCE Concentration ~4 Months Post- Air Treatment Unit Installation (µg/m³)	SSD System Installed Prior to 4-Month Event?
1	160	2.2	Living Space	0.44	80	0.93	N
2	16,000	100	Living Space	3.1	97	9.2	Y
	16,000	140	Basement	46	67	61	Y
3	13,000	110	Living Space	2.8	97	16	Y
	13,000	180	Basement	34	81	79	Y
4	1,400	6.1	Living Space	1.1	82	NS	Y
	1,400	6.8	Basement	1.2	82	3	Y
6	740	6.6	Living Space	1.2	82	NS	Y
	740	43	Basement	2.1	95	13	Y
7	170	0.40	Living Space	NS	NS	NS	N
	170	0.75	Basement	0.2 J	73	0.4 J	N
10	300	ND	Living Space	NS	NS	NS	N
	300	2.9	Basement	1.5	48	2.1	N
12	94	ND	Living Space	NS	NS	NS	N
	94	0.55	Basement	0.21 J	62	0.22 J	N
13	230	ND	Living Space	NS	NS	NS	Y
	230	1.5	Basement	0.50	67	1.9	Y
14	290	0.73	Living Space	NS	NS	NS	Y
	290	1.9	Basement	ND	NS	NS	Y

[1] Only select data shown; refer to the administrative record for the full data set.

Gray shading indicates exceedance of a New York State Department of Health Screening Level (5 µg/m³ for indoor air and 250 µg/m³ for subslab).

NS = Not Sampled; ND = Not Detected; J = estimated

4.3.2 Gardena Marketplace, Gardena, California (CH2M 2014b, 2016a, 2016b)

This site is a commercial development consisting of a grocery store and a strip mall over contaminated soil and groundwater. ATUs were installed as an interim VI mitigation measure to reduce indoor-air concentrations of PCE and TCE. Information for each affected space is as follows:

- Space Number 1
  - Commercial strip mall space with independent HVAC unit.
  - Single story, approximately 1,700 ft².
  - Premitigation subslab concentrations: PCE = 130,000 µg/m³; TCE = 4,600 µg/m³.
  - Temporary mitigation measures included (1) HVAC adjustment to increase outdoor air ventilation and change from intermittent to continuous operation and (2) installation of one portable ATU with a flow rate of approximately 500 cfm.
  - Indoor PCE decreased from 4.9 µg/m³ to 1.4 µg/m³ (71% reduction). Indoor TCE decreased from 0.36 µg/m³ to 0.11 µg/m³ (69% reduction).

- ◦ Reductions sustained for at least 1 year prior to startup of a SVE pilot test, which further reduced indoor-air concentrations. Final PCE and TCE concentrations prior to SVE startup were 1.8 and 0.13 μg/m^3, respectively with concentration ranges varying from 1.1–1.8 μg/m^3 and nondetect–0.17 μg/m^3, respectively.
- Space Number 2
  - Commercial strip mall space with independent HVAC unit.
  - Single story, approximately 1,700 ft^2.
  - Premitigation subslab concentrations: PCE = 55,000 μg/m^3; TCE = 2,700 μg/m^3.
  - Temporary mitigation measures included (1) HVAC adjustment to increase outdoor air ventilation and change from intermittent to continuous operation, (2) sealing of slab cracks and utility line entry points through the slab, and (3) installation of two portable ATUs each with a flow rate of approximately 500 cfm.
  - Indoor PCE decreased from 87 μg/m^3 to 0.73 μg/m^3 (99% reduction). Indoor TCE decreased from 7 μg/m^3 to 0.079 μg/m^3 (99% reduction).
  - Reductions sustained for at least 1 year prior to startup of a SVE pilot test, which further reduced indoor-air concentrations. Final PCE and TCE concentrations prior to SVE startup were 0.25 μg/m^3 and 0.083 μg/m^3, respectively with concentration ranges varying from 0.25–1.2 μg/m^3 and nondetect–0.15 μg/m^3, respectively.

4.3.3 U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, NH (Calicchio and Malinowski, 2016; Clausen and Shoop, 2015; Folkes and Tripp, 2016)

This site is a large, multistory research building with industrial operation overlies multiple soil and groundwater VOC sources. ATUs were installed to reduce indoor air concentrations of TCE. Information for the site is as follows:

- 200 ATUs with an approximate maximum flow rate of 300 cfm (per unit) were distributed throughout the building.
- Subslab concentrations: TCE = 12,000–3,000,000 μg/m^3.
- Pretreatment indoor air concentrations: TCE = 2–84 μg/m^3.
- No other concurrent mitigation measures reported with treatment unit deployment.
- Indoor air TCE was reduced 25–75%.

4.3.4 Nonantum West Street Area, Newton, MA (Newton Environmental Health,[3] 2016; Mass DEP,[4] 2016)

This site, a former auto-salvage parts facility, is underlain by TCE contaminated groundwater. To screen the area for the existence and elimination of imminent hazard (IH) conditions, 39 groundwater monitoring wells were installed and sampled; and 157 indoor air grab samples from 57 residences were initially analyzed. For residences with TCE concentrations above the IH limits, air cleaning/purifying units were installed. Site information and results were as follows:

- ATUs contained 12.5 pounds of activated carbon plus a layer of zeolite (for moisture removal) and potassium iodide (KI) to enhance chemisorption of certain organic compounds.
- Flow rate was 125 cfm (per unit).

[3] http://www.newtonma.gov/gov/health_n_human_services/enviro/environmental_health_information.asp

[4] http://public.dep.state.ma.us/fileviewer/Default.aspx?formdataid=0&documentid=368843

- Indoor air concentrations of TCE were <1–180 μg/m^3.
- TCE concentrations were reduced by 50–75% within 1 week of operation when initial TCE concentrations were 60–120 μg/m^3.
- TCE concentrations were reduced by 50–75% within 2 weeks of operation when initial TCE concentrations were 6–20 μg/m^3.

4.3.5 Field Study Summary

Comparison of these field studies highlights some of the challenges in using this type of information to assess ATU performance:

- It may not be possible to distinguish the effect of VOC ATUs from other concurrent measures such as sealing and HVAC modifications. Because ATUs are generally employed in situations perceived as urgent, the natural inclination of the project team is to implement multiple measures to best ensure reductions in indoor air concentrations.
- Building size (especially volume) and ATU operating flow rate are not adequately reported to allow calculating a normalized air exchange rate through the ATUs. It is possible that a more extensive information-gathering effort could develop this information for the sites in question.
- Building-specific indoor/outdoor air exchange rates through natural ventilation and HVAC operation are not available. This makes it more difficult to accurately estimate the VOC mass flux into the building at a specific time. However, data are sometimes available on VOC mass accumulated in an ATU carbon bed over a long operational period, which could be used to estimate VOC mass flux into the structure. Air exchange rates could potentially be established through field measurements as the implementations are ongoing.
- Multiple ATUs may be needed to achieve mitigation goals within given timeframes.

Without the normalized parameters mentioned above, it is difficult to draw generalized conclusions about ATU performance from the available case studies. However, the case studies suggest that ATUs can be part of a multimeasure effort to reduce indoor VOC concentrations.

5. SELECTING AN AIR TREATMENT UNIT, DESIGNING AND IMPLEMENTING AN AIR TREATMENT UNIT APPLICATION

This section provides detailed information on designing and implementing a successful ATU installation for reducing indoor air VOC concentrations in a variety of buildings, including important factors for selecting an ATU and how to design, install, and operate an ATU system.

5.1 *Chemical and Physical Characteristics of the Air Stream to be Treated*

Air in buildings, even within a single HVAC zone, is not uniform. The contaminants of concern and background VOCs can both vary in concentration spatially and temporally. Humidity and temperature also vary across time in the same room, by location in a building, and across climate zones. Outdoor air conditions can also affect VOC ATU performance because outdoor air can influence indoor air VOC concentrations.

5.1.1 Humidity

The relative humidity (RH) level is important in choosing and maintaining an ATU because the humidity can change the performance of some types of ATUs (see Section 3). In general, indoor air in controlled spaces is likely to be in the 30–65% RH range in the breathing space. For GAC, higher humidity (>80% RH) will reduce sorbent effectiveness (ASHRAE, 2015).

While the effects of humidity will vary among GACs and contaminants, Owen (1996) showed much better VOC removal efficiency below 65% RH than above 80% RH for 4x8 mesh coconut shell carbon. Keener and Zhou (1990) reported on the influence of humidity for one type of pelletized carbon over a range of 54–92% RH for toluene, carbon tetrachloride, ethylbenzene, methylene chloride, and ethyl alcohol at VOC concentrations of 300–900 ppm. They found a decrease by as much as 65% in VOC capacity over this RH range with great variability across the compounds. They also report a decrease in toluene capacity of 75% when humidity rises from 5% to 92% based, apparently, on calculated values. However, because these concentrations are so much higher than those found in indoor air, it is difficult to know whether the relationship can be easily extrapolated to low concentration VOCs.

For reactive ATUs such as photocatalytic systems, the presence of humidity may change the reaction rate, reaction products, or both depending on the specifics of technology and the other contaminants in the air. It may also change the reaction byproducts. Alberici et al. (1998) showed that for TCE and the test devices, increasing the RH from 20% to 80% decreased the destruction from nearly 100% to 70%. Similarly, Lee et al. (2016) saw a decrease in air cleaning efficiency with increasing RH, ranging from 20% to 55% for benzene, toluene, and xylene. In contrast, Jo and Park (2004) showed no variability in VOC destruction due to RH. Mo et al. (2013) showed water vapor has a significant effect not only on the photocatalytic decomposition rate of toluene, but also its byproducts due to the competitive adsorption among water vapor, toluene, and its breakdown byproducts. If photocatalytic devices are employed at field scale, the designer should understand the device-specific humidity effects that could apply.

In summary, increases in humidity are well-known to drive sorbed contaminants off GAC. This effect is seen most often at very high humidity (>80% RH) and would result in the ATU temporarily emitting more VOCs than are present in the inlet air. This desorption, while highly undesirable for short-term indoor air quality, actually allows the carbon to sorb additional contaminants once the humidity is lower again, which means that the ATU should return to functionality after a temporary humidity increase. However, for best use of carbon-based ATUs, humidity control, at least to prevent surges of high humidity, is useful. This control could take the form of a separate dehumidifier or operation of an air conditioning system.

5.1.2 Temperature

Most occupied buildings in the United States are conditioned to keep the air temperature at comfortable levels, usually in the low to mid 70s (°F). However, some residences either do not have air conditioning or allow the temperature to decrease into the 50s or low 60s in the winter to reduce heating costs. Temperatures in the summer can rise into the 90s or higher in unconditioned structures in some parts of the United States. With lower temperatures, RH increases, and vice versa for higher temperatures.

High temperatures, given a constant RH, will decrease sorption capacity and efficiency (ASHRAE, 2015). This decrease may be similar across carbon types and devices such that relative ranking of sorbents or ATUs may be the same.

5.1.3 Particles

Indoor air contains particles. The concentration and sizes of the particles will depend on the sources in the structure and the filtration system, if any, in use. Sources of indoor particulates include ambient air infiltration, cooking, combustion heating systems, cigarette smoking, and some hobbies.[5] While sorbent

[5] https://www.epa.gov/indoor-air-quality-iaq/indoor-particulate-matter#indoor_pm

beds will not catch many particles, those that are caught can hinder the performance by blocking active sorption sites or increasing pressure drop by obstructing air flow. It is common to include a particulate filter upstream of carbon bed type ATUs. Some units, especially room units, come with standard particle filters upstream of the carbon beds. Sorbent beds also shed particles with use, which can constitute at least a nuisance. To avoid having these particles emitted into the air, a particle filter may also be used downstream of the sorbent bed. In either case, the particle filters that are present in a VOC ATU should be checked regularly and changed according to the manufacturer's recommendations.

Air filters that include sorbents within or attached to fibrous media are intended to provide particle filtration and gas-phase filtration in one unit. Note that when particles are captured and lead to a pressure drop increase, the entire filter must be replaced. However, for many existing buildings, this type of filter will fit into the existing HVAC filter housing and can provide a simple and quick-to-install adaptation to including VOC filtration in an existing building. If a sorbent-containing media is introduced, it should continue to provide adequate particle filtration (ASHRAE, 2009). The expected particle loading on the filter based on the indoor air particulate load would then be an additional control on the frequency with which such a dual-purpose filter would need to be replaced.

5.1.4 Target Organics

Target VOC compounds for VI situations are most frequently chlorinated hydrocarbons, such as PCE and TCE, that enter the residence or commercial building in soil gas, primarily advectively (U.S. EPA, 2012). Thus, differential pressure across the building envelope will strongly influence the mass flux into the structure as the contaminants can enter with airflow. The differential pressure across the building envelope is in turn affected by the differential temperature between the building interior and exterior as well as wind loads (U.S. EPA, 2012). These factors influence the air exchange rate of the structure (U.S. EPA, 2011b). These two effects can offset to some extent, so the percentage increase in indoor concentration due to increased entry rate can be lower than the percentage increase in the mass flux.

However, even in the absence of a differential pressure driving force, contaminants can enter diffusively following concentration gradients (U.S. EPA, 2012). Due to this method of entry, it is possible that air treatment could increase the mass flux of entry as the ATU lowers the indoor concentration.

5.1.5 Nontarget Organics and Other Air Contaminants

As with the target organics, other organics (both anthropogenic contaminants and naturally occurring VOCs) will enter the building at variable mass flux rates, dependent in general on whether the area around the building is urban, suburban, or rural, as well as how well the building is weatherized. Inorganic constituents such as ozone, SO_2, and NO_2 that can also interact with sorbents are present in all urban atmospheres. Differential pressure, concentration gradients, and outdoor environmental conditions will influence the rate of entry of these contaminants into the building. Opening of windows, mostly in homes, may result in increased air exchange and allow outdoor contaminants to more easily enter the building. Increasing outdoor inlet air to HVACs (for example, when outdoor temperatures yield heating/cooling energy savings) will cause outdoor air pollutants to enter the building. Some outdoor contaminants (e.g., ozone) will enter the building and can react with other compounds including those that enter through VI, potentially forming different contaminants.

However, for many buildings, most indoor air organic contamination comes from indoor sources. These sources include off-gassing from furniture, carpets or equipment, cooking, pesticides, paint, cosmetics, personal care products, personal hygiene products, smoking, air fresheners, and others. The nontarget compounds compete for sorption sites and may deactivate photocatalytic technologies (Hay et al., 2010). The best method for lowering concentrations of nontarget organics is source removal or reduction (ASHRAE 2009; U.S. EPA 2011a, 2012). Reducing these compounds will help any ATU function more effectively. It is important to realize that an ATU will treat the air, to the extent possible, for both the target compounds and the nontarget compounds. Depending on the sorption properties of the target compounds and the nontarget compounds, the ATU may take up the intended compounds better or worse than the unintended compounds.

Although the authors were not able to find systematic tabulated information about the relative strength of carbon adsorption for various VOCs in indoor air applications, the literature on gas phase carbon efficiency for air pollution control devices could be a useful alternative in evaluating interactions between VOCs. Example sources of tabulated information include U.S. EPA (1998) and Shephard (2001).

Sorption for a given compound will change depending on the other compounds in the same atmosphere. In a test of HVAC-insertable carbon beds (a 24x24x24" housing filled with 100-pounds of carbon in 1" deep trays in a zigzag format inserted into the test rig's HVAC duct section), VanOsdell et al. (1996) tested a five-VOC mixture (**Figure 5**). The test concentrations were 0.2 ppm per VOC for a total of 1 ppm VOC. The efficiency curves in the figure are shown as trend lines based on the observed data. The graph shows differences among the compounds in how well the carbon bed removed them from the air (toluene is the most strongly sorbed, followed by PCE). This test was run long enough that the less well-sorbed compounds (isobutanol and MEK) were pushed through the bed when the more strongly sorbing compounds displaced them from active sorption sites. This result can be shown since the

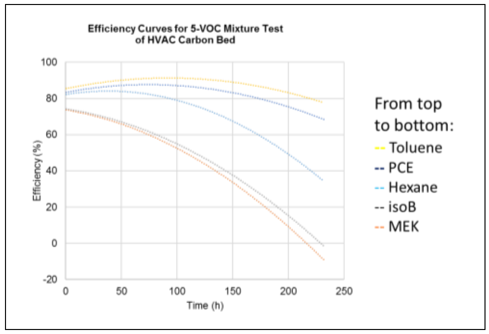

Figure 5. Efficiency curves for a five-compound VOC test mixture from VanOsdell et al. (1996)

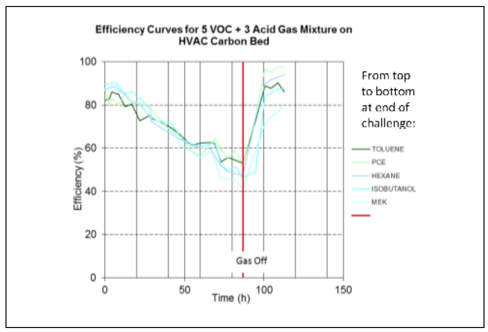

Figure 6. Efficiency curves for a five-compound VOC test mixture with three additional inorganic gases from VanOsdell et al. (1996)

outlet concentrations were above the inlet concentration (where efficiency is thus less than 0%) after the 200-hour mark.

A separate test with the same five-VOC mixture, same RH, and same airflow rate but with acid gases (ozone, SO_2, and NO_2 at National Ambient Air Quality Standard maximum levels) added to the challenge gas mixture is shown in **Figure 6** (also reported in VanOsdell et al., 1996). This second test was run for just over 100 hours.

Comparing **Figures 5 and 6** shows that the presence of the acid gases caused the VOC compounds to break through the active charcoal bed much quicker (VanOsdell et al., 1996). There is also less apparent separation in efficiency between strongly and weakly adsorbing VOCs. In the later stages of the test, all the challenge gases were turned off, as shown by the red line, such that only clean air passed through the carbon bed. The efficiencies then had an increase due to a calculation artifact in which the data were still presented in this period, relative to the upstream concentration during the challenge on portion. Thus, the graph shows that all the challenge gases continued to be present in the treated air after they were no longer present in the influent, showing desorption. PCE desorbed the least of the five VOCs.

5.2 *Building Characteristics*

Characteristics of the building requiring treatment play a large roll in selection, deployment, and monitoring of an ATU for a particular space. Some of these characteristics include:

- Occupancy
- Size of the space requiring treatment
- Operation of HVAC systems and the target air exchange rate
- Existing air circulation patterns
- ATU power requirements
- Security requirements
- Space requirements.

Each of the listed characteristics influences the necessary air exchange rate and is discussed further in the following subsections. Determining these characteristics will generally require a combination of:

- Review of plans and building energy audits/ HVAC balancing reports
- Discussions with building managers who have knowledge of HVAC systems operation, tenant activities, and other factors that can affect indoor VOC levels
- A field survey, using standard forms generally found in VI guidance documents and is often called an “Indoor Air Sampling Questionnaire” or “Building Evaluation Form.”

5.2.1 Type of Occupancy

The use of the treated space should be considered during selection and sizing of the ATU. Specific considerations are as follows:

- **Target indoor air concentrations**: Target indoor air concentrations should be based on the occupancy of the space (commercial vs. residential) and specific exposure durations. If very low target air concentrations are required, a higher level of ATU efficiency will be needed for the same level of contaminant flux.
- **Products in use:** Products in use within the treated space can have significant impact on recommended air exchange rates (fresh air supply requirements) and carbon use in air cleaning applications. For example, if the space being treated has frequent use of products that emit VOCs, the presence of these VOCs, rather than target compound concentrations may drive the rate of carbon consumption and breakthrough times. Note that these products include intentionally used items such as deodorant and bug spray and always-present items such as furniture and carpet. Particular attention should be paid to any situation where a liquid source of VOCs may be in equilibrium with indoor air because they can provide a large source as the ATU removes VOCs from indoor air. Possible examples of such sources include a loosely covered jar of paint thinner, a gasoline can with the air vent open, or air fresheners designed to continuously emit a fragrance. When a volatilizing substance is at equilibrium with the overlying air, and the concentration in the overlying air is reduced, the rate of volatilization increases (Le Chatelier’s Principle; Oxtoby et al., 1990).
- **Noise tolerance:** The noise tolerance of the occupants should be considered when selecting the specific ATU and number of

units required. Most ATUs are well tolerated by occupants, with noise as the primary complaint. In a residential or office setting, units are often too noisy to be operated at the highest level (Lawrence Berkley National Laboratory, 2016). The background (ambient) noise level of the space should be considered; for example, bedrooms would typically have a low acceptable noise level.

5.2.2 Size of Treated Space—Volume Requiring Treatment and Space Needed for Portable Unit

The volume of air to be treated within the target space is a critical element for ATU selection. The volume of the space is used—along with the estimated number of air exchanges per hour—to select the size, operating speed, and number of units needed. This selection process requires an understanding of not just square footage, but also ceiling height and the degree of interconnectedness of airflow between rooms and floors. As discussed in the following sections, this will also require an understanding of the zones in the building in which air is mixed (either naturally through air currents or by a forced air system).

Once the required volume of air treatment has been determined, an evaluation is conducted to determine the number of air cleaning units required. Residential portable units are typically small (Attachment A) and can often be placed in an unobtrusive location; however, free flow of air in and out of the unit and good mixing of the room air should be ensured. If a larger treatment volume is needed, several units may be required to meet the target air exchange rate and multiple small units may become difficult to locate.

5.2.3 HVAC Systems and Air Exchange Rate

Existing HVAC system operating parameters (e.g., flow rate, on-off cycling) and connectivity between the treated space and the remainder of the building need to be considered during ATU selection. HVAC systems often recirculate some portion of the air within the building as well as provide some fresh outdoor air (Althouse et al., 1988). Most residences only recirculate air through the HVAC system and rely on air infiltration through the building envelope to provide outdoor air exchanges. The portion of outdoor air introduced through the HVAC system is typically higher and more variable in commercial buildings. In these buildings, the percentage of outdoor air provided by the HVAC system may be varied by occupancy or temperature (Althouse et al., 1988). Thus, the rate of air exchange within the target space (both designed and actual) as well as the source and portions of recirculated air and outdoor makeup air should be considered in selecting the ATU to be used.

The volume of outdoor air (makeup air) required for proper space conditioning is determined by the size and use of the space (e.g., number of occupants, background indoor air sources, whether smoking is allowed). In general, a minimum exchange rate of four air changes per hour is recommended; however, as noted the recommended exchanges vary dependent upon the use of the target space.[6]

When calculating the volume of treated space, connectivity to other portions of the building through the HVAC system should be considered. Additional contaminant mass could be delivered to the target space through the HVAC system and additional air changes could be necessary. Additional mass could be in the form of products used within the building or from subsurface contamination extending beyond the initially considered space. Mass contributions from other portions of the building connected by the HVAC must be considered as part of carbon consumption rates.

[6] http://www.engineeringtoolbox.com/air-change-rate-room-d_867.html

5.2.4 Power Requirements

Power requirements depend on the size and type of ATU selected. In general, smaller residential type air purifying units require a 100–120-volt power supply, while larger units may require 230 volts. If an in-duct ATU is added to the HVAC system, the filter may add significant pressure drop, which can increase fan energy requirements in HVAC systems and increase operating costs. If an in-line system is used, the potential pressure drop should be considered and the HVAC system evaluated to determine if modifications are needed to maintain designed operational parameters while overcoming the added pressure drop.

In-duct air cleaning systems will reduce the air flow delivered in most residential forced air HVAC systems. The effect on airflow and energy use in a commercial system will depend on whether the system has a constant volume or variable air volume design. Air handlers are often set to run at a specific pressure drop, so adding an ATU is likely to cause the airflow to go down. Slower airflow will cause the air to be cooled more (or heated more) but less efficiently. But with less airflow, the system will need to run longer to meet space temperature conditioning requirements, increasing energy use (Jung, 1987; Nassif, 2012).

Power consumption can be estimated using the following equation:

$$E(kWh) = \frac{q\ x\ \Delta P\ x\ t}{n\ x\ 1000}$$

Where:

E = energy consumption (kWh)

q = airflow volume (m^3/s)

ΔP = average resistance of the filter (Pascals)

t = operating hours (h)

n = fan efficiency

Depending on how the HVAC system is operated (constant temperature or constant flow), energy increases may result from increased run times to meet temperature requirements rather than the pressure drop across the filter.

5.2.5 Security Requirements

Unit security is a consideration with the primary objective of preventing occupants or trespassers from removing, tampering with, or turning off air cleaning units. These concerns are dependent upon the specific conditions of the ATU deployment and of lower concern for HVAC ATUs.

5.3 Design Process—Standalone Units

The design process incorporates the building characteristics listed above. The design process discussed in this subsection refers specifically to standalone units (which can be either wall-mounted or portable). Some different design considerations apply for duct-mounted units as outlined in Section 5.4. Frequently, ATU sizing and selection must be done rapidly; therefore, in many cases a detailed evaluation of the HVAC system and cataloging of potential mass contributions, either from subsurface sources or indoor sources, is not feasible.

Two approaches can be used to develop ATU specifications for a particular scenario:

1. If more specific information is available, conduct a mass-balance evaluation to appropriately size the ATU.
2. Size the ATU based on a simpler equation that uses a multiple of the baseline air exchanges per hour for the target space to derive a target treatment rate for the ATU.

Temporal variability and other uncertainties should be used for either design approach, and follow-up sampling is recommended to confirm the effectiveness of either approach.

Commented [YN1]: Alt text for equation:
Energy consumption (E) in kilowatt hours equals the product of airflow volume (q) in cubic meters per second times the average resistance of the filter (delta P) in Pascals times the operating hours (t) divided by the product of fan efficiency (n) times 1000.

5.3.1 Predesign/Selection Data Collection

For the mass-balance method, the following information is needed (specific or estimated):

- Current indoor air concentration
- Treatment space volume
- Contaminant infiltration rate from the subsurface
- Contaminant concentration in the subsurface (which would typically be estimated from subslab concentrations)
- Outdoor air exchange rate (some information available in U.S. EPA, 2011b)
- Outdoor contaminant concentrations
- Flow rate of indoor sources of contaminants
- Concentration of indoor air sources of contaminants
- Exchange rate of air recirculated from an adjacent HVAC zone to the treated zone
- Concentration of contaminants in the air being exchanged between adjacent zones.

For the air exchange method, the following information is needed:

- Treatment space volume (also consider volume of total HVAC zone)
- Treatment space use (to select needed air exchanges and determine available space)
- Flow rates for potential ATUs.

Carbon consumption estimates can be developed more accurately if mass balance information is available to estimate loading. Otherwise, general assumptions can be made using current indoor air concentrations, which under residential or office scenarios would be expected to remain relatively stable (within an order of magnitude). In an industrial scenario where large volumes of VOC-containing products are frequently used, more variability would be expected.

5.3.2 Sizing/Number/Capacity Calculations

The equations in the following subsections have been derived using multiple simplifying assumptions to provide relatively simple equations for selecting a design starting point. In real systems, every input to the equations will vary over time and these variations can be difficult to predict.

Concentration reductions within the target space using ATUs would generally be expected to follow an asymptotic curve in the period immediately after initial activation, but before efficiency drops, as illustrated by **Figure 7**.

However, variations in indoor product use, flux across the slab due to barometric pressure changes/ temporal changes in subslab concentrations, changes in operation of HVAC units, and other factors will impact both the effectiveness of treatment and carbon saturation times.

As such, the equations presented below provide a starting point for selecting ATUs. Follow-up monitoring is required to confirm that the correct number and size of ATUs has been installed for the specific scenario as well as to monitor media breakthrough times.

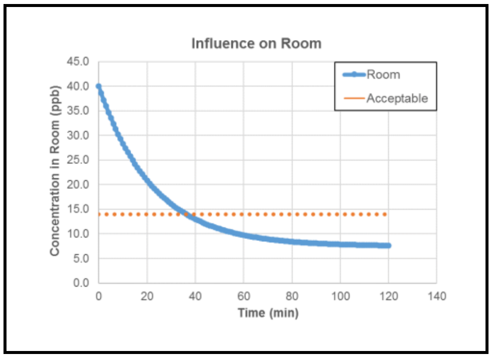

Figure 7. Air treatment unit influence on indoor air concentrations (idealized example after initial startup)

Mass Balance Sizing Method

The overall mass balance can be generalized as follows:

$$\begin{aligned} &\mathit{Mass\ entering\ the\ space} \\ &\qquad = \mathit{mass\ adsorbed} \\ &\qquad + \mathit{mass\ exiting\ the\ space} \end{aligned}$$

Contaminant mass enters a space from several primary locations:

- Outdoor air.
- Air recirculated from other zones within the building.
- Soil gas entry points.
- VOC-containing products in use within the target space or other VOC generating processes, such as cooking (Huang et al., 2011) or combustion appliances.
- The flow rates of outdoor air exchange and recirculated air depend on HVAC operation and are based on the use of the space and the number of people generally occupying the space. Information on typical background concentrations of many VOCs of concern in VI is available from U.S. EPA (2011a). Data on indoor air concentrations of a longer list of VOCs are summarized in Appendix C of the New York State VI guidance (New York State Department of Health, 2006).
- Mass generally enters a space from the subsurface through specific entry points (e.g., cracks, utility lines entry points) and to a lesser extent as diffusive flux across a slab. This term can be estimated using subsurface concentrations and a default soil gas entry rate (Qs) or by direct measurements of mass flux. Methods for mass flux estimation from VI are discussed in Dawson and Wertz (2016) and Guo et al. (2015).
- Product use within a space may contribute significant mass to the space dependent upon use and may be more difficult to estimate. However, if the air exchange rate is known and a long-term integrated VOC sample is acquired for a full list of VOCs, an estimate may be obtained.

It should be recognized that concentrations and flow rates change temporally. However, in the following equations, pseudo-steady state conditions are assumed as a simple way to make initial estimates. This approach uses a constant removal rate for the air cleaner based on the value it would have at the initial room concentration, $Q_f n_f C_i$. This estimate allows us to avoid the complicated equations that describe the actual non-steady state situation, while providing an acceptable estimate for an initial assessment.

Figure 8 is a representative depiction of the mass balance inputs used in the following equation:

$$\begin{aligned} &Q_o C_o + Q_{r1} C_{r1} + Q_s C_s + Q_p C_p \\ &\qquad = Q_f n_f C_i + Q_{r2} C_{r2} + Q_e C_e \end{aligned}$$

Where:

Q_o = outdoor air flow rate
C_o = outdoor air concentration
Q_{r1} = air flow rate from target space to adjacent space
C_{r1} = air concentration in air moving from target space to adjacent space
Q_{r2} = air flow rate from adjacent space to target space
C_{r2} = air concentration in air moving from adjacent space to target space
Q_s = subsurface soil gas infiltration rate
C_s = subsurface soil gas concentration
Q_p = product flow rate
C_p = product concentration
Q_f = air filter flow rate
n_f = air filter efficiency
C_i = starting indoor air concentration
Q_e = flow rate of air exiting target space through the building envelope
C_e = concentration of air exiting target space (i.e., after filtration).

Commented [YN2]: Alt text for equation:

This equation is related to the model depicted in Figure 8. Outdoor air flow rate times the outdoor air concentration plus the air flow rate from the target space to the adjacent space times the air concentration in air moving from the target space to the adjacent space plus the subsurface soil gas infiltration rate times the subsurface soil gas concentration plus the product flow rate times the product concentration equals the air filter flow rate times the air filter efficiency times the starting indoor air concentration plus air flow rate from adjacent space to target space times air flow rate from adjacent space to target space plus flow rate of air exiting target space through the building envelope times concentration of air exiting target space (i.e., after filtration).

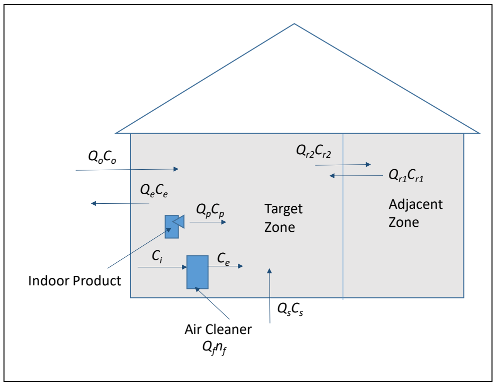

Figure 8. Representative depiction of mass balance inputs

In most office and residential scenarios, where only one HVAC zone is present, then the terms involving Q_{r1}, and Q_{r2} are eliminated as zero.

If the number of air exchanges is known or estimated, the flow rate of outdoor air (Q_0) into the space can be estimated using the following:

$$Q_o = \frac{V\ x\ ACH}{60}$$

Where:

V = volume (ft^3)

ACH = air changes per hour.

The term (C_i) is the starting indoor concentration, with C_e being the target indoor concentration after treatment. Using a simplifying assumption that there are no indoor sources and that the flow rates in and out of the structure are essentially equal ($Q_o = Q_e$) because the flow through the slab is much smaller than the flow through the exterior walls, the equation becomes:

$$Q_f n_f C_i = \frac{V\ x\ ACH}{60}(C_o - C_e) + Q_s C_s$$

Or rearranging to:

$$Q_f n_f = \frac{\frac{V\ x\ ACH}{60}(C_o - C_e) + Q_s C_s}{C_i}$$

This equation can then give a starting point for selecting an ATU and is similar to that previously derived in Howard-Reed et al. (2007). A hypothetical example is provided in **Table 6 and Figures 9–11.** For each scenario, all parameters are the same except for the starting indoor air concentration and the subslab concentration. Starting indoor air concentrations were determined by allowing the indoor concentration to reach steady state with the ATU off (Q_f=0). Scenario 3 shows the required ATU flow rate under the same conditions as Scenario 2. A spreadsheet was set up to calculate indoor air concentrations over time using a mass balance and assuming no indoor air sources, one HVAC zone, and perfect mixing within that zone. The inputs for each scenario are provided in **Table 6.** The results of each analysis are provided as **Figures 9–11**. an indoor source without a subslab source). However, it should be used with caution and it is suggested to add uncertainty factors to address potential indoor sources and to address temporal changes.

As noted in Section 4.2, the subslab soil vapor concentration, and by association the mass flux from the subsurface (Q_sC_s), is shown in this formulation.

In Scenario 1, the mass balance indicates that an air filter with a flow rate of 50 cfm and an efficiency of 80% (0.80 in fractional terms) will reduce the indoor air concentration of the target space to below the target level. However, if the subslab concentration is increased only moderately from 200 ppb to 1,000 ppb (Scenario 2), the starting equilibrium indoor concentration and same ATU will barely reduce the indoor air concentration as shown in **Figure 10**. However, if the ATU flow rate increases to 350 cfm, the target concentration can be achieved despite the stronger subslab and initial indoor concentration (Scenario 3; **Figure 11**). This exercise demonstrates the importance of subsurface contributions when sizing ATUs for specific conditions. This is supported by analysis of the data collected at Bethpage, discussed in Section 4.2.

Commented [YN3]: Alt text for equation:

Flow rate of outdoor air (Q_0) equals the volume (V) in cubic feet times the air changes per hour (ACH) divided by 60

Table 6. Summary of Scenario Input Parameters

Parameter	Scenario 1 (base case)	Scenario 2 (stronger source)	Scenario 3 (stronger source, larger air treatment unit flow rate)
Initial Indoor Air Concentration (C_i)	21 ppb	52 ppb	52 ppb
Target Space Air Volume (V)	1,000 ft^3	1,000 ft^3	1,000 ft^3
Subsurface Infiltration Rate (Q_s)	4 cfm	4 cfm	4 cfm
Subsurface Concentration (C_s)	200 ppb	1,000 ppb	1,000 ppb
Outdoor Air Concentration (C_o)	0 ppb	0 ppb	0 ppb
Air Changes per Hour (ACH)	2	2	2
Air Treatment Unit Flow Rate (Q_f)	50 cfm	50 cfm	350 cfm
Air Treatment Unit Efficiency (n_f)	0.80 (80%)	0.80 (80%)	0.80 (80%)
Target Indoor Air Concentration (C_e)	14 ppb	14 ppb	14 ppb

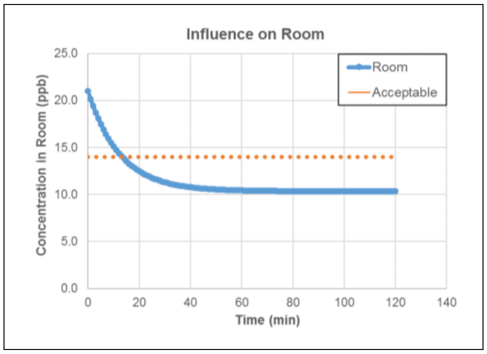

Figure 9. Results of Scenario 1 after air treatment unit startup (base case)

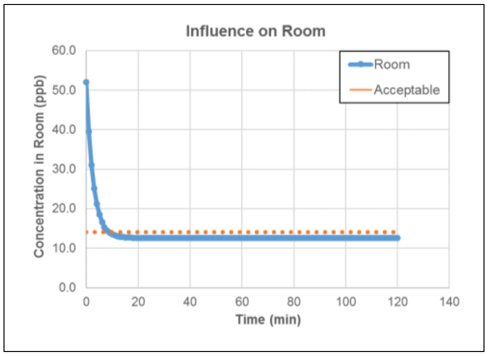

Figure 11. Results of Scenario 3 after startup, stronger source, larger air treatment unit flow rate.

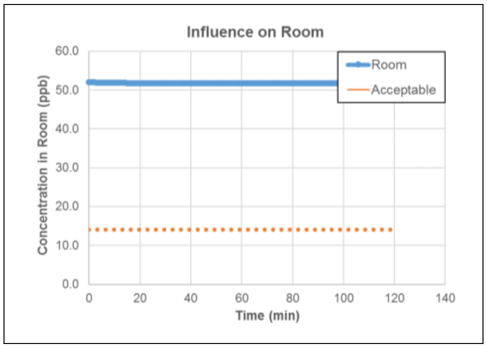

Figure 10. Results of Scenario 2 after air treatment unit startup (stronger source)

Air Exchange Sizing Method

For the air exchange method, a target air exchange for the ATU or ATUs is set (ACHt) and the size and number of ATUs needed can be calculated as follows:

$$\#\ of\ ATUs = \frac{V\ x\ ACHt}{60} \div (ATU\ flow\ rate \times n_f)$$

In this case, the ACHt is the target for given space for the ATUs (i.e., the ATU or units will produce the desired number of air changes per hour). In general, a total target ATU flow rate (produced from one or multiple units) of approximately 4 to 5 times the flow rate of outdoor air (Q_o) (the baseline fresh air exchange rate) will be sufficient to address contributions from a subslab source with low-to-moderate VOC concentrations. The ratio of ATU flow rate to the flow rate of outdoor air required will increase for high subslab source strength. Additionally, if indoor sources are known to be present, the ratio should be increased.

This calculation estimates the number of ATUs required for a specified flow rate. It is important to consider the noise level produced by each ATU when selecting the flow rate for calculation. For example, the maximum flow rate of a given ATU may be 300 cfm; however, operation of the treatment unit at this rate may produce noise levels that are not tolerable to occupants. Therefore, in this case, a lower operation rate should be assumed.

5.3.3 Air Treatment Unit Efficiency Calculations

Air treatment unit efficiency is defined based on the difference between the inlet concentration and the outlet concentration based on the following equation:

$$n_f = \frac{(C_i - C_e)}{C_i}$$

Where:

n_f = air treatment unit efficiency (fractional)
C_i = air treatment unit inlet concentration
C_e = air treatment unit outlet concentration

It should be expected that as the carbon becomes saturated, ATU efficiencies will decrease.

5.3.4 Sourcing/Procurement/Contracting

The source of a particular ATU depends on the type of unit selected. Residential-sized standalone units are widely available commercially and are relatively low cost (typically < $1,000). Larger units can be rented or purchased from specialty suppliers. When deciding whether to rent or purchase a specific ATU, the life-cycle cost as well as client/homeowner preferences should be considered. The decision between renting and purchasing will also be influenced by the anticipated time of operation before a more long-term mitigation or remediation system is installed and becomes effective.

A list of potential vendors is included with the equipment information in Attachment A.

5.3.5 Permitting/Inspection Requirements

In general, permits are not required for portable ATU systems that are plugged in and not hard-wired to a power source. However, if a powered in-duct system or hardwired system is selected, check local jurisdictions for specific requirements. Potential permitting inspections could include a building permit, HVAC inspection, and electrical permit or inspection.

5.4 *Design Process—Differences for Duct-Mounted Systems*

Similar mass balance concepts to those discussed in Section 5.3 for standalone systems could be applied to duct-mounted systems. However, in most retrofitted duct-mounted applications, the airflow of the duct is not a variable that the designer has full control over. As discussed above, it will be influenced by the existing air handler and its control algorithm. So similar mathematical approaches may allow estimation of the resulting indoor air concentration, but there may be limitations on the ability to achieve a target level of treatment.

Commented [YN4]: Alt text for equation:

The number of air treatment units (ATUs) equals the volume (V) in cubic feet times the target air exchange for the ATUs (ACHt)) divided by 60. That result is divided by the product of the ATU flow rate times the fractional air treatment unit efficiency (n_f)

Commented [YN5]: Alt text for equation:

Fractional air treatment unit efficiency (n_f) equals the result of air treatment unit inlet concentration (C_i) minus air treatment unit outlet concentration (C_e) divided by air treatment unit inlet concentration.

For in-duct HVAC applications, if a system can accommodate a thick filter or supplemental filter (for example, a box filter or V-bank filter, which are commonly 12" deep and are found in many commercial buildings), a deep filter is recommended as the deeper depth should provide more sorbent media and is recommended for higher efficiency and longer life. Major manufacturers generally recommend speaking to a technical salesperson for assistance in selecting the right sorbent for your site. Manufacturers' technical representatives should know the test data for their products and the influence of variables such as temperature, humidity, source variability, and HVAC design on filtration performance. A buyer should use the information in this document as a reality check for the selection advice given by such a manufacturer's representative and should contact multiple manufacturers.

For HVAC system installations, ATU sizing considerations are mainly based on estimated carbon consumption rates; in other words, they are based on concentrations of VOCs in indoor and outdoor air. For an HVAC application that can only accommodate a thin filter (i.e., 1" to 2"), calculations are likely to show that the sorbent will be rapidly consumed. However, this may still be a good option for locations with low-level sources, only slightly out of specification concentrations, and a willingness to change a filter every 1 to 3 months (as is usual for a residential particle filter or a commercial building particles-only prefilter). This may also be a good quick improvement while waiting for a better ATU to arrive.

5.5 *Air Treatment Unit Deployment*

The complexity of deploying ATUs to a site varies depending on the scale of indoor air problems being addressed. When the plan calls for a few, small portable units, deployment consists of placing the units within the space and starting them following the manufacturer's directions. The complexity increases as more or larger units are required. Examples include:

- The electrical demands increase as more units are used within a space. It may be necessary to consult an electrician or electrical engineer to assess whether sufficient power is safely available given the demands of the ATUs and existing electrical equipment. Attention should be paid to which circuits the ATUs are using, the rated capacity of those circuits, and what equipment is already connected to those circuits. Note that it is common for motorized electrical devices to require more current at startup than in routine operation.
- Larger portable units may not be suitable for placement directly into the space being treated because of noise generation or space requirements, so temporary ducting may be required.
- Larger, built-in systems are the most complex and may require the involvement of engineers and tradespeople from mechanical, electrical, and other disciplines. Deployment of such systems could involve significant construction work, which will likely require building permits, and could require temporary suspension of normal operations within the space being treated.
- Adding an in-duct supplemental filter or changing the HVAC filter may be simple, but the energy costs must be considered.

The positioning of ATUs within a space requires consideration of three key factors:

- Minimizing disruption of normal use of the space. The equipment and power cords should be placed where they will not cause tripping hazards or otherwise disrupt people's movements. Particular attention is warranted when mobility-impaired people are or could be present; consultation with an adaptive-design specialist may be necessary.

- To minimize occupants' discomfort due to noise, the units should be placed as far as practical from locations where occupants spend large amounts of time. In occupational settings, this could include being away from desks or other workstations. In a residential setting, this could include avoiding proximity to dining tables, kitchen work areas, sofas, chairs, and beds.
- As discussed previously, the results from the testing conducted by Howard-Reed et al. (2007, 2008a) imply that it is beneficial to locate the unit in the same room that soil gas is entering. It is also necessary to place the unit so it has free air circulation, and the treated air is rapidly mixed with the bulk of the air in the targeted zone.

Startup of small portable units can be as simple as turning the fan on to the desired speed setting and confirming that air if flowing through the unit. Startup of larger and built-in units will be more complex, especially if the air is to be ducted into existing ductwork or if a supplemental filter is to be introduced into the existing ductwork that markedly changes the flow. In that case, startup will likely involve rebalancing of airflow, requiring the expertise of a knowledgeable mechanical engineer or technician (National Environmental Balancing Bureau, 2005).

5.5.1 Verification Testing and Performance Monitoring

Verification and ongoing performance testing is a requirement following ATU deployment and startup. Although the ATU mitigation may have been specified with a conservatively high airflow rate, no system can be assumed to be operating as intended without collecting and analyzing indoor air VOC samples. Also, as the system operates and the sorbent gets loaded with VOCs, the potential for VOC breakthrough and desorption increases. Therefore, some type of ongoing performance monitoring is required.

The sampling and analytical methods for verification and operational monitoring typically consist of time-weighted samples collected in the breathing zone, that is, 3 to 5 feet above the floor within the space of interest. The sampling location should be selected to be well away from the air cleaning device. Sample durations can vary from hours to days. Some current sampling strategies may include the following:

- Collecting 8-hour indoor air samples in occupational settings using U.S. EPA Method TO-15
- Collecting 24-hour air indoor air samples in residential settings using U.S. EPA Method TO-15
- Collecting 7-day or longer indoor air samples using passive-diffusion samplers and U.S. EPA Method TO-17.

Selection of a sample duration and methods is a project-specific decision. Initial verification samples typically match the duration and methods used to collect the investigation samples that led to the need for mitigation. The strategy may be changed as the goal changes to long-term monitoring.

Initial verification samples are collected after an equilibration period of 24 to 48 hours following ATU startup. If the initial verification samples show indoor air VOC concentrations below applicable thresholds, such as project action levels, then the monitoring program transitions to operational monitoring. If the VOC concentration exceed thresholds, then modification to the system may be required followed by additional verification sampling.

The frequency of operational indoor air monitoring is a function of two main factors: the anticipated time for VOC breakthrough and the presence of other indoor air contaminants that may influence ATU performance. An example of the latter, as discussed in Section 5.1, is nontarget VOCs present in indoor air, which may consume sorption capacity and reduce the lifetime of the sorbent. Another example is airborne particles. Most ATUs include some type of prefilter to remove particulates prior to the sorbent material. Often high-efficiency particle air (HEPA) filters or other fine-particulate filtration media is used. Such filter media may become clogged resulting in decreased airflow and air-cleaning efficiency over time. Due to these factors, it is prudent to include a margin of safety when selecting a sampling frequency. For example, if breakthrough is calculated to take 1 year, then quarterly monitoring could provide sufficient resolution to see breakthrough in advance of the expected time. The monitoring frequency could be reduced once the breakthrough period is understood through two or more cycles of sorption media change out with site-specific data collection.

5.5.2 Operation and Maintenance

ATU equipment requires ongoing routine maintenance. The user manuals will provide detailed information for a specific unit. General operations and maintenance procedures include:

- Inspections to verify that the equipment is in place and running at the intended air flow. While this may seem like a simple procedure, experience has shown that it may be the most critical inspection criterion. Building occupants may turn off, move, or unplug portable ATUs for various reasons including noise (Lawrence Berkley National Lab, 2016), access of areas for cleaning, or lack of understanding of the equipment's purpose. With more permanent, built-in systems, data loggers and telemetry may be incorporated to verify system uptime.
- Checking the seating of the filters. Many portable units have filters that are loosely mounted. It is important that they be in the correct place so that the air does not inadvertently bypass the filter.
- Replacing prefilters at the frequency recommended by the manufacturer or more frequently if airflow is reduced due to high concentrations of particulates.
- Replacing the VOC filtration media. The operational air monitoring data will provide information on trends of the target analytes. Media change out can be specified for when the monitoring data shows concentrations of target analytes at some fraction, say 50% or 75%, of the site-specific action level. This will minimize the potential for breakthrough prior to the subsequent monitoring event.
- Cleaning. Keeping the exterior of the ATU clean will improve its aesthetic appeal.

Because VOC filtration media will accumulate VOC mass, it is possible that spent media could meet state or federal criteria for characterization as hazardous waste. Testing, such as EPA's Toxicity Characteristic Leachate Procedure (TCLP), may be necessary to support waste characterization. A waste management specialist should be consulted to evaluate this possibility and develop waste characterization and management plan. Prefilter media will typically be managed as non-hazardous waste and disposed of as municipal solid waste.

The need for ATUs may end for reasons such as the following:

- A longer-term mitigation system has been installed. For example, a subslab depressurization system may be installed when VI is the cause of indoor air contamination.
- Environmental remediation has diminished the source of VOCs to the point where mitigation is no longer required.

When portable equipment is used, demobilization may be as simple as removing the equipment from the building and managing spent media appropriately. Removal of a built-in system may be as significant an effort as the original installation. Building owners or operators may prefer to leave the equipment in place to improve indoor air quality issues unrelated to environmental contamination. In such cases, ownership and responsibility for operations and maintenance will typically be transferred to the owner or operator.

5.6 *Communication and Instructions for Occupants During Air Treatment Unit Deployment and Operation*

Communication with building owners, operators, and occupants is key to successful deployment and operation of ATUs. For environmental clean-up projects, this will likely take place as part of a larger property access and stakeholder-communication effort. Some examples of needed communication regarding ATUs include the following:

- Informing stakeholders that use of ATUs may be implemented if results from planned indoor air VOC samples exceed applicable thresholds. This is particularly important if the need for a rapid response is a possibility (rapid responses were performed in many of the applications discussed previously in Section 4.3). In such cases, it may be most efficient to include the potential deployment of ATUs into the agreement used to gain access to the property for sampling. Including pictures and other information about the units may ease communication with stakeholders.
- If portable ATUs are being deployed, outreach to building occupants, maintenance staff, and others with access to the units is important. As noted in Section 5.5, people turning the units off, unplugging them, or removing them is a common problem. Regular inspections can help minimize such events, but educated occupants are the first line of defense. Direct, face-to-face education, wall signs, and other methods can be used to educate occupants about the purpose of the ATUs and the importance of their continuous operation to maintaining indoor air quality.
- If deployment of built-in or in-duct ATUs is a possibility, it will be important to identify decision makers early in the process. In commercial settings in particular, the decision-making authority may be complex and could involve owners, property managers, and the businesses leasing the property. Workers' unions may also require notification in commercial and industrial setting.
- Establishing a clear line of communication for occupants to report problems with the ATUs during operations is important. This can take the form of stickers or wall notices placed on or near the units. It may also be beneficial to place property tags on the equipment that clearly identify the equipment owner with contact phone numbers. Portable ATUs have gone missing during deployment and property tags could aid in recovering the equipment.

Identifying these and other communications needs and establishing a communications plan early in the project planning process will facilitate a more successful project.

6. MONITORING AND VERIFYING AIR TREATMENT UNIT PERFORMANCE

Since the performance of VOC ATUs can decline over time for various reasons, including saturation of the sorbent media, increases in VOC sources, and changes in building flow regimes, a monitoring program is needed to verify that performance objectives are met. Performance objectives for a VOC ATU installation can be specified in several ways, but the primary ones are:

- Maintenance of indoor air concentrations below pre-specified standards
- ATU efficiency (concentration out over concentration in)
- ATU placement and continued operation

- Reduction of indoor air concentration while a longer-term mitigation solution is being installed.

As detailed in Section 5.5.1, the desired performance objectives can be monitored in several ways including:

- Regular VOC monitoring by measuring indoor air VOC concentrations (to check for exceedances of the specified standards), or VOC concentrations at the ATU inlet and outlet (to check on VOC removal efficiency).
- Scheduled check-ins (visits and calls) before and after installation to ensure that the system is and remains correctly installed and operated. For example, for residential installations, it may be prudent to contact the homeowner within a few days of installation to ensure that the ATU is still operational (e.g., is it plugged in? Is air coming out of the discharge?) and has not caused issues such as excessive noise. Check-in visits can also inspect the premises to help identify changes in HVAC operations or building modifications that could adversely affect treatment unit operation and performance.
- Contacts for the building occupants in case of problems with the units.

When developing a monitoring plan, performance objectives should also be expressed in terms of data quality objectives (DQOs) that specify the type, amount, and quality of indoor air quality data that needs to be collected to verify performance at the specific location of interest, including how samples will be collected and analyzed. For example, DQOs for a commercial building might specify 8-hour summa canister (Method TO-15) samples for short-term VOC concentration checks while DQOs for a residential setting may specify 24-hour samples to accommodate the longer exposure period.

An ATU monitoring plan should be consistent with the indoor air sampling plan that was used to identify the indoor air problem and select VOC ATUs as part of the solution, with the original indoor air sampling establishing the baseline that will be compared to the ATU monitoring results. This monitoring plan can include sampling frequency and locations (for comparability), although ATU placement will influence sampling locations (for example inlet and outlet samples for efficiency measurements).

In addition, the monitoring plan should specify an end date for sampling, based on site-specific estimates or measurements of when VOC concentrations may fall below concentrations of concern. This may involve different sampling frequencies during treatment system operation, such as specifying 2-week or 1-month passive samplers (U.S. EPA, 2015) for longer operations with TO-15 samples at the beginning and end of operation, or when concentration increases are identified from passive samplers or field VOC sensor measurements. Although they do not provide compound-specific data, field VOC sensors (e.g., photo- or flame-ionization detectors) may also be useful in identifying VOC sources associated with VOC increases identified during routine VOC monitoring.

Finally, specifications of sampling and analysis techniques should be appropriate for the problem and consistent with what is being used by the regional or state regulatory authorities.

7. CURRENT CHALLENGES, LIMITATIONS, AND RESEARCH AND DEVELOPMENT NEEDS

As shown in the examples and data presented in Section 4.3, there has been considerable variability in the effectiveness of the practical applications of ATUs to vapor intrusion. Most field applications have been to rapid action cases and have relied on rules of thumb rather than computational engineering design approaches.

The best field-scale, measurement-based testing program results found reported in Section 4.2 were for decane, not the chlorinated or aromatic hydrocarbons that drive the vast majority of U.S. vapor intrusion sites. That test program employed a constant indoor source of the test VOC, and; thus, did not test the complex set of geologic and meteorological factors that control VI behavior in buildings (U.S. EPA, 2012).

As exemplified by the publications of the California Air Resources Board (2016), not all currently marketed ATUs can be recommended for use. Some of the devices are ineffective or produce excessive ozone. There have not been adequate field demonstrations of photocatalytic ATUs in complex real indoor atmospheres with trace VOCs, such as are found at VI sites, to fully evaluate whether any observed destruction of target VOCs outweighs the formation of undesirable reaction byproducts in some designs. Therefore, the use of sorbent-based VOC ATUs in current applications is preferred and suggest that the photocatalytic devices merit additional testing.

7.1 *Technology Development and Chamber Verification Needs*

7.1.1 Future Technology Development

Although carbon filtration for VI contamination removal is most effective at this point, there are many technologies that could eventually be developed to successfully remove VOCs from indoor air. Specifically treated sorbents designed for chlorinated hydrocarbons could be developed. Systems using currently available sorbents could be designed to allow periodic stripping of sorbed compounds to increase lifetime and yield better prediction of performance. Reactive ATU technologies are still relatively new and newer designs could lead to units with predictable byproducts or extremely short half-life intermediates that are not problematic.

7.1.2 Potential Duct-Testing Programs

Duct-testing apparatuses can be used to directly test replacement filters and similar devices that are directly installed in existing HVAC systems. These apparatuses can also be used to test the filter or sorbent components of portable or wall-mounted ATUs (dismounted from the portable equipment).

Single-pass efficiency and capacity information is extremely useful in ranking devices for performance. Testing of units based on the ASHRAE 145.2 test should be done. Simply testing more commercially available units with a VI-relevant chlorinated hydrocarbon would increase our knowledge of how these units work relative to each other. These data used in modeling would allow improved calculations of the likely effectiveness of the devices.

Another useful approach using duct testing would be to use a mixture of VOCs typically found in VI situations, considering both soil gas and indoor air background VOCs. This testing could be conducted at typical concentrations observed in the field, but as low as needed to include regulatory limits. Testing could also be conducted at standard and high humidity, to include conditions common to basements and crawlspaces, low income communities where air conditioning may not be universal, and high humidity spaces such as bathrooms and kitchens. Although this approach would not give exact information for every situation, it could provide very different answers than provided by the single-compound, typical condition testing. A measurement-based pilot study of representative units could determine whether all units should be tested this way.

7.1.3 Potential Chamber-Testing Programs

Chamber testing is used for portable and wall-mounted units. Chamber testing specifically allows multiple passes of air through the ATUs. HVAC units should be scaled to the size of the room. Chamber testing is needed, especially for small devices with low airflow that cannot be tested using the duct-testing method.

A chamber test could start with a single injection of a contaminant or set of contaminants, continuous injection, pulsed injection, or even injection with changing characteristics over time, which could be helpful in emulating VI situations. Chamber testing using high sensitivity analysis could detect byproduct compounds that might not be seen in duct testing as they may be concentrated over time in the chamber. Conditions such as humidity and various concentrations of mixed VOCs and inorganic gases can be tested.

For the future development of reactive devices, chamber testing allows for the multiple passes and time for reactions to occur and be completed. Testing can then determine both reaction intermediaries that might be unacceptable and capability to actually destroy contaminants.

7.2 *Field-Scale Testing, Verification, and Tech Transfer Recommendations*

7.2.1 Quantitative Reviews of Existing Field Applications

Existing applications are generally managed only to meet the human health protection, regulatory compliance, and economic needs of a situation. Therefore, data that may be helpful in designing future applications of the devices are generally not systematically gathered, reported, or analyzed. However, more analysis using the mathematical approaches outlined in this paper (and in Howard-Reed et al., 2008a, b) is possible. Information on building volumes while not frequently reported could be easily gathered. Records of operational runtime as well as concentrations found on sorbent beds prior to disposal are other valuable information that may be gathered. Comparison of existing subslab concentration data to indoor air performance would be valuable. Applications funded by government potentially responsible parties or EPA Regions, and data already in the public record, may be amenable to additional systematic analysis.

Buildings with ongoing applications could be approached to allow the measurement of key parameters such as air exchange rates and indoor humidity. Indoor source surveys might also be undertaken with field instruments, such as the HAPSITE gas chromatograph/mass spectrometer system, to understand performance differences between buildings. In government-funded or controlled cases, collection of additional indoor air quality data to provide more time resolution or source strength information may be feasible.

Such applications have the benefit of realism with varying weather conditions and VOC-generating indoor activities. However, with that realism also comes more potentially confounding variables to analyze. Additionally, systems in occupied buildings cannot be run to breakthrough or other failure modes.

7.2.2 Field-Scale Demonstrations

Studies in normally constructed, but currently unoccupied structures, have been informative to the VI field. Tests of ATU performance in such structures have been previously performed by Howard-Reed for indoor sources. Ideally a building that has concentrations of VOCs from vapor intrusion that might require rapid response in an occupied building could be selected. Such a structure could be carefully instrumented to observe air exchange rate, soil gas entry rate (i.e., with radon tracer), time-resolved VOC concentrations, humidity, and other factors. Tests could be done initially without indoor sources. Later, indoor sources (i.e., air fresheners, loosely capped solvent containers, shower water) could be introduced in a controlled manner. Testing could be conducted with and without air conditioning or dehumidification.

Multiple ATUs or multiple flow settings could be tested to validate the mathematical design approaches presented in this EIP. Additional spreadsheet scenarios, such as those presented in Table 6, could be developed as a technology transfer/training tool. The ability of such a simple spreadsheet model to provide useful design guidance could be explored by comparison to results of more complex models. More complex models, such as the NIST multizone indoor air quality model CONTAM[7] or a three-dimensional or transient VI model, could provide the ability to explore the sensitivity of ATU performance to variations in environmental conditions.

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ATTACHMENT A
AVAILABLE VOC AIR CLEANER EQUIPMENT

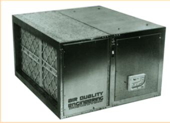
Image	Brand Name	Model	Installation Type	Manufacturer	Manufacture Country	Website
	Aerus	Sanctuairy by Aerus In-Duct Whole House Air Purifier	Built in. Ducted	Aerus		http://www.aerushome.com/Site/Air
	Air Oasis	Large commercial models	Portable. Not ducted	Air Oasis	USA	http://www.airoasis.com/shop/air-oasis-5000pro
	Air Quality Engineering	M66 R&L	Built in. Ductable or not ducted.	Air Quality Engineering		http://www.air-quality-eng.com/
	Air Quality Engineering	M73	Portable. Not ducted	Air Quality Engineering		http://www.air-quality-eng.com/
	Airgle	AG950 PurePal Multigas Air Purifier	Portable. Not ducted	Airgle	China	http://www.airgle.com/
	AirPura	C600 DLX Air Purifier	Portable. Not ducted	Airpura Industries	Canada	http://airpura.com/index.html

Image	Brand Name	Model	Installation Type	Manufacturer	Manufacture Country	Website
	Airpura	R600 All Purpose	Portable. Not ducted	Airpura Industries	Canada	http://www.airpura.com/
	Alen	Breathesmart-HEPA-FreshPlus	Portable. Not ducted	Alen		https://www.alencorp.com/collections/air-purifiers-for-chemicals-and-cooking-odors/products/breathesmart-air-purifier-w-hepa-freshplus-filter?variant=890004515
	Amaircare	3000 HEPA Air Purifier	Portable. Not ducted	Amaircare	Canada	http://amaircare.com/
	Amaircare	7500 Airwash Cart	Portable. Ductable or freestanding.	Amaircare	Canada	http://amaircare.com/
	Amaircare	Air Wash 10000	Built in. Ducted	Amaircare	Canada	http://www.airpurifiersandcleaners.com/amaircare-10000-hvac-air-cleaner

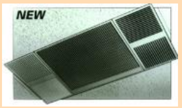
Image	Brand Name	Model	Installation Type	Manufacturer	Manufacture Country	Website
	Austin Air	Healthmate Plus	Portable. Not ducted	Austin Air	USA	http://austinair.com/
	Blue Air	Pro XL	Portable. Not ducted	Blue Air		https://www.blueair.com/us
	Coway	AP-1512HH Mighty Air Purifier	Portable. Not ducted	Coway	Korea	http://retail.coway-usa.com/
	Dyson	Pure Cool Link Tower	Portable. Not ducted	Dyson	Malaysia	http://www.dyson.com/
	EverClear	Delux CM-11	Built in. Not ducted.	Air Quality Engineering		http://www.air-quality-eng.com/

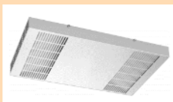
Image	Brand Name	Model	Installation Type	Manufacturer	Manufacture Country	Website
	Fresh-Aire UV	APCO	Built in. Ducted	APCO	USA	http://www.freshaireuv.com/apco.html
	Hammacher Schlemmer	Air Purifier				-
	Honeywell	F111C1073W-3S		Air Pure Systems		https://www.cleanairfacility.com/asp_pages/catalog.asp?PCA=10
	Honeywell	F114C1008 commercial ceiling mount	Built in. Not ducted.	Honeywell		http://www.honeywellstore.com/
	Honeywell	F115A1064 commercial ceiling mount	Built in. Not ducted.	Honeywell		http://www.honeywellstore.com/
	Honeywell	F116A1120-3S Commercial Ductable	Built in. Ductable or not ducted.	Honeywell		http://www.honeywellstore.com/
	Honeywell	F120A1023 Ducted	Built in. Not ducted.	Honeywell		http://www.honeywellstore.com/

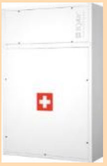
Image	Brand Name	Model	Installation Type	Manufacturer	Manufacture Country	Website
	IAP	M-25DDCC	Built in. Not ducted.	Industrial Air Purification	USA	http://industrialairpurification.com/
	IQAir	Clean Zone 5200	Portable. Ductable or not ducted.	IQAir	Switzerland	http://www.iqair.com/
	IQAir	Clean Zone SL	Portable. Not ducted	IQAir	Switzerland	http://www.iqair.com/
	IQAir	GC/X VOC Air Purifier	Portable. Not ducted	IQAir	Switzerland	http://www.iqair.com/gcx-series-air-purifiers/tech-specs
	IQAir	GCX Multigas	Portable. Not ducted	IQAir	Switzerland	http://www.iqair.com/gcx-series-air-purifiers/tech-specs
	MaxFlo	MAXFLO D-25	Built in. Not ducted.	Diversified Air Systems	USA	http://maxfloair.com/Home.aspx
	MaxFlo	MAXFLO D-30	Built in. Not ducted.	Diversified Air Systems	USA	http://maxfloair.com/Home.aspx

Image	Brand Name	Model	Installation Type	Manufacturer	Manufacture Country	Website
	NQ Clarifier	Air Purifier	Portable. Not ducted	NQ clarifier	USA	http://www.nqinc.com/
	RabbitAir	BIOGS 2.0 - 625A	Portable. Not ducted	RabbitAir		https://www.rabbitair.com/?utm_source=bing&utm_medium=cpc&utm_campaign=Search%20%7C%20US%20%7C%20ALPHA%20%7C%20Brand&utm_term=RabbitAir&utm_content=Rabbit%20Air
	Sentry Air Systems	SS-700-FH	Built in. Not ducted.	Sentry Air Systems	USA	http://www.sentryair.com/index.htm
	Sun Pure	SP-20C	Portable. Not ducted	Field Controls		http://www.fieldcontrols.com/sun-pure
	Temp Air	C2000	Portable. Ductable or not ducted.	Temp air	Rental	http://temp-air.com/

Image	Brand Name	Model	Installation Type	Manufacturer	Manufacture Country	Website
	Trion	Air Boss ATS	Built in. Ducted.	Trion	USA	https://www.trioniaq.com/index.aspx
	Winix	U450	Portable. Not ducted	Winix	USA	https://winixamerica.com/

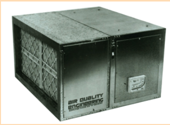
Image	Brand Name	Model	Power		Noise		
			Voltage	Current (amperes)	Decibels (Maximum)	Decibels (Minimum)	Noise Measurement Notes
	Aerus	Sanctuairy by Aerus In-Duct Whole House Air Purifier	100-240V	0.4			
	Air Oasis	Large commercial models	24 VDC				No noise measurements recorded
	Air Quality Engineering	M66 R&L	110-480	12-4.4	73-70		70 at 15 ft. 73 at 9 ft., no minimum measurement
	Air Quality Engineering	M73	208-480 V				No noise measurements
	Airgle	AG950 PurePal Multigas Air Purifier	110V		32		
	AirPura	C600 DLX Air Purifier	115-220V		62	28	Measured at 6 ft. distance

Image	Brand Name	Model	Power		Noise		
			Voltage	Current (amperes)	Decibels (Maximum)	Decibels (Minimum)	Noise Measurement Notes
	Airpura	R600 All Purpose	115V or 220V	40 - 120 watts	62.3	28.1	At distance of 6 ft.
	Alen	Breathesmart-HEPA-FreshPlus	120 V		56	41.5	
	Amaircare	3000 HEPA Air Purifier	115V		57	33	
	Amaircare	7500 Airwash Cart	120V		96	82	

Image	Brand Name	Model	Power		Noise		
			Voltage	Current (amperes)	Decibels (Maximum)	Decibels (Minimum)	Noise Measurement Notes
	Amaircare	Air Wash 10000	115 V		75	75	Only one noise measurement listed
	Austin Air	Healthmate Plus	120V		65	<50	Unspecified minimum noise measurement
	Blue Air	Pro XL	33-256W		58	32	
	Coway	AP-1512HH Mighty Air Purifier			53.8	24.4	

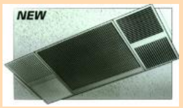
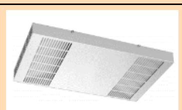
Image	Brand Name	Model	Power		Noise		
			Voltage	Current (amperes)	Decibels (Maximum)	Decibels (Minimum)	Noise Measurement Notes
	Dyson	Pure Cool Link Tower					
	EverClear	Delux CM-11	115	4.3			No noise measurements
	Fresh-Aire UV	APCO	18-32 VAC	0.68			No noise measurements recorded
	Hammacher Schlemmer	Air Purifier					
	Honeywell	F111C1073W-3S	120	7.5	61	53	@ 3.3 feet
	Honeywell	F114C1008 commercial ceiling mount	220-240 V	1.7	59	55	Measured at 3.3 ft.
	Honeywell	F115A1064 commercial ceiling mount	220-240 V	3.6	56	52	Measured at 3.3 ft.

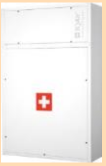
Image	Brand Name	Model	Power		Noise		
			Voltage	Current (amperes)	Decibels (Maximum)	Decibels (Minimum)	Noise Measurement Notes
	Honeywell	F116A1120-3S Commercial Ductable	120-220 VAC	14-7			No noise measurements recorded
	Honeywell	F120A1023 Ducted	120-240V	2.8-7	52	48	
	IAP	M-25DDCC	115V	10.2	62		No minimum measurement
	IQAir	Clean Zone 5200	220-240V		65	35	10 ft. measurement
	IQAir	Clean zone SL	220-240V		45		10 ft. measurement, no minimum measurement

Image	Brand Name	Model	Power		Noise		
			Voltage	Current (amperes)	Decibels (Maximum)	Decibels (Minimum)	Noise Measurement Notes
	IQAir	GC/X VOC Air Purifier	100-120V		69	35	Max sounds like dishwasher, Min sounds like a whisper
	IQAir	GCX Multigas	100-120V		69	35	Max sounds like dishwasher, Min sounds like a whisper
	MaxFlo	MAXFLO D-25	230V	11.2	63		No minimum measurement
	MaxFlo	MAXFLO D-30	115V	8.5	62		No minimum measurement
	NQ Clarifier	Air Purifier	115-230V		55		Minimum noise level not listed
	RabbitAir	BIOGS 2.0 - 625A	120V		50.4	22.8	

Image	Brand Name	Model	Power		Noise		
			Voltage	Current (amperes)	Decibels (Maximum)	Decibels (Minimum)	Noise Measurement Notes
	Sentry Air Systems	SS-700-FH	115V	4.9	71		No minimum measurement
	Sun Pure	SP-20C	120		68	48	
	Temp Air	C2000	115	15			No noise measurements
	Trion	Air Boss ATS	NA				No noise measurements
	Winix	U450	110W		56	29	Minimum noise level not listed

Image	Brand Name	Model	Flow Rate			Modes of Action	
			Flow Rate Minimum (cfm)	Flow Rate Maximum (cfm)	Listed Room Size	Filter Type Description	Adsorption
	Aerus	Sanctuairy by Aerus In-Duct Whole House Air Purifier			3000 ft. ^{2}	Uses light waves and catalytic process to remove pathogens, air pollution, dust, dander, and odors. (Photo catalysis and UV)	N
	Air Oasis	Large commercial models	60	120	5000	Bi-Polar Ionization & AHPCO (advanced hydrated photocatalytic oxidation) technology that was developed by NASA (ionization and UV	No
	Air Quality Engineering	M66 R&L	1940	3225	NA	30-35% efficient pleated filters, HEPA and electrostatic add-on modules, 45 or 90 lbs. of activated carbon	Yes
	Air Quality Engineering	M73		5500	NA	Two 24” x 24” x 4” pleated prefilter, four 24” x 24” x 2” mist impingers, two 24” x 24” x 12” Polypropylene ESF, 180 lbs. activated carbon	Yes
	Airgle	AG950 PurePal Multigas Air Purifier	268	463	max. 617 ft^2	HEPA Carbon - 15 lbs. coconut shell activated carbon with premium quality activated alumina	Yes

Image	Brand Name	Model	Flow Rate			Modes of Action	
			Flow Rate Minimum (cfm)	Flow Rate Maximum (cfm)	Listed Room Size	Filter Type Description	Adsorption
	AirPura	C600 DLX Air Purifier	560	560	2000 ft²	HEPA Prefilter Carbon - 26 lbs. of granular activated carbon	Yes
	Airpura	R600 All Purpose	440	440	up to 1650 sq. ft.	Cleanable prefilter; 2 anti-microbial filters; 18 lb. carbon filter, 2" deep; True HEPA filter (40 sq. ft. of media w/ 10 pleats per inch)	Yes
	Alen	Breathesmart-HEPA-FreshPlus	150	286	1100 ft²	HEPA air prefilter, electrostatic HEPA material, 3 lbs. activated carbon.	Yes
	Amaircare	3000 HEPA Air Purifier	50	225	about 800 ft² @ 2 exchanges per hr.	HEPA Prefilter 12 lbs. Activated Carbon; have option for Carbon/ Zeolite filter	Yes
	Amaircare	7500 Airwash Cart	1000	1000	about 3750 ft² @ 2 exchanges per hr.	HEPA Prefilter Carbon - 26 lbs. of granular activated carbon; have option for Carbon/ Zeolite filter	Yes

Image	Brand Name	Model	Flow Rate			Modes of Action	
			Flow Rate Minimum (cfm)	Flow Rate Maximum (cfm)	Listed Room Size	Filter Type Description	Adsorption
	Amaircare	Air Wash 10000	1980	1980	11250 ft2	Triple cylindrical perfect seal 3-stage cartridges (each: 13" diameter x 16" height); stage one: 1/8" foam prefilter sleeve x3; stage two: 100 sq. Ft. Pleated easy twist HEPA cartridge x3; stage three: ½" non-woven polyester filter media imbued 200% with activated carbon (164 g = 180,400 m2adsorption surface area) x3; optional stage three canister: Granulated carbon pellets encased in steel mesh canister (1550 g = 1,705,000 m^2 adsorption surface area) x3	Yes
	Austin Air	Healthmate Plus	75	400	up to 875 ft^2 @ 2 exchanges per hr.	HEPA Prefilter 15 lbs. Activated Carbon / Zeolite filter impregnated with potassium iodide	Yes
	Blue Air	Pro XL	800	950	1180	Activated carbon pellets and thermally bonded fibers containing polypropylene and polyethylene free of chemicals and binders.	Yes

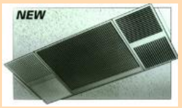
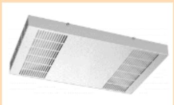
Image	Brand Name	Model	Flow Rate			Modes of Action	
			Flow Rate Minimum (cfm)	Flow Rate Maximum (cfm)	Listed Room Size	Filter Type Description	Adsorption
	Coway	AP-1512HH Mighty Air Purifier		269	up to 326 ft^2	HEPA prefilter Carbon - 26 lbs. of granular activated carbon	Yes
	Dyson	Pure Cool Link Tower	190	190	unspecified	HEPA prefilter Carbon at unspecified quantity	Yes
	EverClear	Delux CM-11	400	850	NA	95% efficient (at .3 micron) HEPA type filters, 44 lbs. of activated carbon	Yes
	Fresh-Aire UV	APCO				Combination of UV-C light and activated carbon	Yes
	Hammacher Schlemmer	Air Purifier			up to 150 ft^2	HEPA Nano confined catalytic oxidation	No
	Honeywell	F111C1073W-3S	1150	825	n/s	Model selected is for a 95% ASHRAE particulate filter. HEPA available in different model. 43 pounds of carbon, permanganate (Note: equipment catalog list zeolite also but replacement filter page includes only charcoal/permanganate).	Yes

Image	Brand Name	Model	Flow Rate			Modes of Action	
			Flow Rate Minimum (cfm)	Flow Rate Maximum (cfm)	Listed Room Size	Filter Type Description	Adsorption
	Honeywell	F114C1008 commercial ceiling mount	180	325	400	95% DOP (Di-octyl phthalate) Efficient Filter at 0.3 Micron, 8+ lbs. CPZ Filter	Yes
	Honeywell	F115A1064 commercial ceiling mount		600	750	99.97% HEPA Filter, 16+ lbs. CPZ Filter	Yes
	Honeywell	F116A1120-3S Commercial Ductable	1400	1675	not listed	First stage is a prefilter rated 30-40% ASHRAE dust spot efficiency, second stage is a set of 40 plus pounds of CPZ filters (charcoal, permanganate, potassium, and zeolite), The third stage includes a set of CPZ filters	Yes
	Honeywell	F120A1023 Ducted	900	1050	1200	95% DOP Efficient Filter at 0.3 Micron, 22+ lbs. CPZ Filters for gas, odor, and volatile organic compounds (VOC) control	Yes
	IAP	M-25DDCC	300	2500	NA	Pleated prefilter, 95% bag filter, 36 lb. charcoal canister filter	Yes
	IQAir	Clean Zone 5200		600		HEPA filter, activated carbon	Yes

Image	Brand Name	Model	Flow Rate			Modes of Action	
			Flow Rate Minimum (cfm)	Flow Rate Maximum (cfm)	Listed Room Size	Filter Type Description	Adsorption
	IQAir	Clean zone SL		600		HEPA filter, activated carbon	Yes
	IQAir	GC/X VOC Air Purifier	50	370	up to 1385 ft² @ 2 ex-changes per hr.	HEPA prefilter Carbon - 17 lbs. of granular activated carbon	Yes
	IQAir	GCX Multigas	40	300	up to 1125 ft² @ 2 ex-changes per hr.	HEPA prefilter Carbon - 12 lbs. of granular activated carbon & alumina pellets impregnated with potassium permanganate	Yes
	MaxFlo	MAXFLO D-25		2500	NA	4" Pleated prefilter, 95% 36" pocket filter, 2" charcoal filter	Yes
	MaxFlo	MAXFLO D-30	1600	3000	NA	4" pleated prefilter, 22" 95% pocket filter, 2" charcoal filter	Yes
	NQ Clarifier	Air Purifier	350	350	up to 1310 ft² @ 2 ex-changes per hr.	HEPA Carbon - 15 lbs. of granular activated carbon with patented oxidizing media UV	Yes

Image	Brand Name	Model	Flow Rate			Modes of Action	
			Flow Rate Minimum (cfm)	Flow Rate Maximum (cfm)	Listed Room Size	Filter Type Description	Adsorption
	RabbitAir	BIOGS 2.0 - 625A	42	167	up to 625 ft^2	HEPA Prefilter Carbon - <1 lb. of granular activated carbon in filter	Yes
	Sentry Air Systems	SS-700-FH	600		NA	MERV pre-and post-filter, 16 lbs. activated carbon	Yes
	Sun Pure	SP-20C	265	265	2,000 sq. feet max.	.3 micron HEPA / 5.0 micron prefilter Photo-catalytic purification with metal oxides, activated charcoal	Yes
	Temp Air	C2000	1600	2000	NA	HEPA, activated carbon	Yes
	Trion	Air Boss ATS	1285	10385	NA	HEPA, activated carbon	Yes

Image	Brand Name	Model	Flow Rate			Modes of Action	
			Flow Rate Minimum (cfm)	Flow Rate Maximum (cfm)	Listed Room Size	Filter Type Description	Adsorption
	Winix	U450	78	300	up to 450 ft^2	HEPA Prefilter Activated carbon filter	Yes

Image	Brand Name	Model	Modes of Action					
			Pounds of Carbon	Oxidation	Negative Ionization	Photo-Catalytic Purification	Other (describe)	Modes of Action Notes
	Aerus	Sanctuairy by Aerus In-Duct Whole House Air Purifier				Yes		
	Air Oasis	Large commercial models			Yes		UV	
	Air Quality Engineering	M66 R&L	90		Yes		electrostatic purification	40 or 90 lbs. carbon
	Air Quality Engineering	M73	180				impingers, ESF	
	Airgle	AG950 PurePal Multigas Air Purifier	15	Yes			activated alumina	
	AirPura	C600 DLX Air Purifier	26					

Image	Brand Name	Model	Modes of Action					
			Pounds of Carbon	Oxidation	Negative Ionization	Photo-Catalytic Purification	Other (describe)	Modes of Action Notes
	Airpura	R600 All Purpose	18	No	No	No		Activated coconut shell carbon
	Alen	Breathesmart-HEPA-FreshPlus	3		Yes			
	Amaircare	3000 HEPA Air Purifier	12					
	Amaircare	7500 Airwash Cart	26					
	Amaircare	Air Wash 10000	3.78				HEPA	

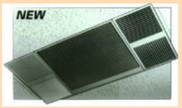
Image	Brand Name	Model	Modes of Action					
			Pounds of Carbon	Oxidation	Negative Ionization	Photo-Catalytic Purification	Other (describe)	Modes of Action Notes
	Austin Air	Healthmate Plus	15	Yes				
	Blue Air	Pro XL			Yes			
	Coway	AP-1512HH Mighty Air Purifier	26		Yes			
	Dyson	Pure Cool Link Tower						
	EverClear	Delux CM-11	44				HEPA	

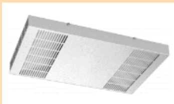
Image	Brand Name	Model	Modes of Action					
			Pounds of Carbon	Oxidation	Negative Ionization	Photo-Catalytic Purification	Other (describe)	Modes of Action Notes
	Fresh-Aire UV	APCO					UV	
	Hammacher Schlemmer	Air Purifier		Yes				
	Honeywell	F111C1073W-3S	43	Yes				
	Honeywell	F114C1008 commercial ceiling mount	8					8+ lbs. of CPZ
	Honeywell	F115A1064 commercial ceiling mount	16					16+ lbs. of CPZ
	Honeywell	F116A1120-3S Commercial Ductable	40	Yes				40 lbs. of CPZ (carbon, permanganate, potassium, zeolite)
	Honeywell	F120A1023 Ducted	22					22+ lbs. of CPZ

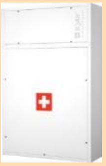
Image	Brand Name	Model	Modes of Action					
			Pounds of Carbon	Oxidation	Negative Ionization	Photo-Catalytic Purification	Other (describe)	Modes of Action Notes
	IAP	M-25DDCC	36				bag filter	
	IQAir	Clean Zone 5200						
	IQAir	Clean zone SL						
	IQAir	GC/X VOC Air Purifier	17	No				
	IQAir	GCX Multigas	12	Yes				
	MaxFlo	MAXFLO D-25						2" charcoal filter

Image	Brand Name	Model	Modes of Action					
			Pounds of Carbon	Oxidation	Negative Ionization	Photo-Catalytic Purification	Other (describe)	Modes of Action Notes
	MaxFlo	MAXFLO D-30						2" charcoal filter
	NQ Clarifier	Air Purifier	15	Yes			UV	
	RabbitAir	BIOGS 2.0 - 625A	<1	No				
	Sentry Air Systems	SS-700-FH	16					
	Sun Pure	SP-20C				Yes		
	Temp Air	C2000					HEPA	

Image	Brand Name	Model	Modes of Action					
			Pounds of Carbon	Oxidation	Negative Ionization	Photo-Catalytic Purification	Other (describe)	Modes of Action Notes
	Trion	Air Boss ATS					HEPA	
	Winix	U450		No				

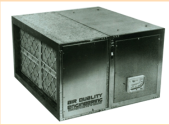
Image	Brand Name	Model	Listed filter life span	Cost ($US)					
				Equipment Price	Cost Notes	Equipment Price Source	Replacement Particulate Filter Price	Replacement VOC Filter Price	Replacement Filter Cost Information Source
	Aerus	Sanctuairy by Aerus In-Duct Whole House Air Purifier		$1,700		http://www.allergybuyersclub.com/sanctuairy-by-aerus-in-duct-whole-house-air-purifiers.html			
	Air Oasis	Large commercial models	not specified	not specified	Must contact supplier for price of unit			$150	http://www.airoasis.com/product-category/commercial/commercial-replacement-parts
	Air Quality Engineering	M66 R&L	Na		Prices not listed, contact manu-facturer for details				
	Air Quality Engineering	M73	NA		Prices not listed, contact manu-facturer for details				
	Airgle	AG950 PurePal Multigas Air Purifier	12-16 months 12-16 months	$1,800	Approx. cost for replacement filter	http://www.airgle.com/PurePalCleanRoom/		$200	

Image	Brand Name	Model	Listed filter life span	Cost ($US)					
				Equipment Price	Cost Notes	Equipment Price Source	Replacement Particulate Filter Price	Replacement VOC Filter Price	Replacement Filter Cost Information Source
	AirPura	C600 DLX Air Purifier	1 year 2 years	$849.98		http://www.allergybuyersclub.com/airpura-r600-air-purifiers.html?itemId=3012	$ 59.98	$ 249.98	http://www.allergybuyersclub.com/airpura-r600-air-purifiers.html?itemId=3012
	Airpura	R600 All Purpose	2 years	$749.98	On sale $649.98	http://www.allergybuyersclub.com/airpura-r600-air-purifiers.html?itemId=3012	$ 169.98	$ 199.98	http://www.allergybuyersclub.com/airpura-r600-air-purifiers.html?itemId=3012
	Alen	Breathe-smart-HEPA-FreshPlus	8-9 months	$658		https://www.alencorp.com/collections/air-purifiers-for-chemicals-and-cooking-odors/products/breathesmart-air-purifier-w-hepa-freshplus-filter?variant=890004515		$ 119	https://www.alencorp.com/collections/alen-breathesmart-fit50-hepa-freshplus-replacement-filters/products/alen-breathesmart-fit50-hepa-freshplus-filter
	Amaircare	3000 HEPA Air Purifier	2-5 years 1 year	$799	1yr	Phone	$ 219	$ 199	Phone

Image	Brand Name	Model	Listed filter life span	Cost ($US)					
				Equipment Price	Cost Notes	Equipment Price Source	Replacement Particulate Filter Price	Replacement VOC Filter Price	Replacement Filter Cost Information Source
	AirPura	C600 DLX Air Purifier	1 year 2 years	$849.98		http://www.allergybuyersclub.com/airpura-r600-air-purifiers.html?itemId=3012	$59.98	$249.98	http://www.allergybuyersclub.com/airpura-r600-air-purifiers.html?itemId=3012
	Amaircare	7500 Airwash Cart	2-5 years 6-12 months	$3,699	3-5 yrs., contains 2 HEPA filters	Phone	$ 219	$199	Phone
	Amaircare	Air Wash 10000	Prefilter: 1 yr.; HEPA: 3-5 yrs.; Carbon: 6 months	$4,000	Replace-ment filter costs not found	http://www.airpurifiersandcleaners.com/amaircare-10000-hvac-air-cleaner			
	Austin Air	Healthmate Plus	3-5 years	$649	Did not specify cost of HEPA prefilter	http://austinair.com/healthmate-2/		$325	http://austinair.com/healthmate-2/

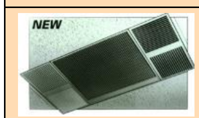
Image	Brand Name	Model	Listed filter life span	Cost ($US)					
				Equipment Price	Cost Notes	Equipment Price Source	Replacement Particulate Filter Price	Replacement VOC Filter Price	Replacement Filter Cost Information Source
	Blue Air	Pro XL	6 months	$2,500		https://www.blueair.com/us/air-purifiers/pro-xl		$360	https://www.blueair.com/us/%E2%80%8B%E2%80%8Bair-purifier-filters/pro-xl-smokestop
	Coway	AP-1512HH Mighty Air Purifier	1 year 6 months	$300	no replacement filter costs found	http://www.allergybuyersclub.com/coway-mighty-air-purifiers.html			
	Dyson	Pure Cool Link Tower	Too new to tell but claim sensor will let you know	$500					
	EverClear	Delux CM-11	NA		Prices not listed, contact manufacturer for details				
	Fresh-Aire UV	APCO	Lifetime		Prices not listed				

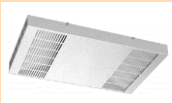
Image	Brand Name	Model	Listed filter life span	Cost ($US)					
				Equipment Price	Cost Notes	Equipment Price Source	Replacement Particulate Filter Price	Replacement VOC Filter Price	Replacement Filter Cost Information Source
	Hammacher Schlemmer	Air Purifier	3 years	$149					
	Honeywell	F111C1073 W-3S	N/S	$2,690	Particulate filter price includes prefilter cost. VOC replace-ment filter cost is for 2 (required) filters.	https://www.cleanairfacility.com/asp_pages/catalog.asp?PCA=10	$260	$610	https://www.cleanairfacility.com/asp_pages/catalog.asp?PCA=34
	Honeywell	F114C1008 commercial ceiling mount	<30 months	$1,500	Price of VOC filters not listed	http://www.honeywellstore.com/store/products/honeywell-f114c1008-commercial-ceiling-mount-media-air-cleaner.htm	$35		http://www.honeywellstore.com/store/catalog.asp?item=8917
	Honeywell	F115A1064 commercial ceiling mount		$1,860	Price of VOC filters not listed	http://www.honeywellstore.com/store/products/honeywell-f115a1064-media-air-cleaner-with-hepa-filter-and-prefilter.htm	$35		http://www.honeywellstore.com/store/catalog.asp?item=8918

Image	Brand Name	Model	Listed filter life span	Cost ($US)					
				Equipment Price	Cost Notes	Equipment Price Source	Replacement Particulate Filter Price	Replacement VOC Filter Price	Replacement Filter Cost Information Source
	Honeywell	F116A1120-3S Commercial Ductable	Unspecified	$3,300	Price of VOC filters not listed	http://www.honeywellstore.com/products/honeywell-f116a1120-ductable-or-stand-alone-three-stage-media-air-cleaner.htm	$ 200		http://www.honeywellstore.com/store/products/honeywell-32000196-media-filter-for-model-f116-95-ashrae.htm
	Honeywell	F120A1023 Ducted	unspecified	$2,650	Price of VOC filters not listed	http://www.honeywellstore.com/store/products/honeywell-f120a1023-ducted-stand-alone-media-air-cleaner.htm	$69		http://www.honeywellstore.com/store/products/prefilter-for-commercial-air-cleaner-for-f120a-12-pack-32003983-001.htm
	IAP	M-25DDCC	not listed	$3,192	Filter prices not listed	http://industrialairpurification.com/ambient-air-cleaners/m-25-ambient-air-cleaners-2500cfm.html			
	IQAir	Clean Zone 5200	NA		Would not provide with price				

Image	Brand Name	Model	Listed filter life span	Cost ($US)					
				Equipment Price	Cost Notes	Equipment Price Source	Replacement Particulate Filter Price	Replacement VOC Filter Price	Replacement Filter Cost Information Source
	IQAir	Clean zone SL	NA		Would not provide with price				
	IQAir	GC/X VOC Air Purifier	18 mos. 2-4 yrs.	$2,199		http://www.iqair.com/gcx-series-air-purifiers/buy	139/HEPA prefilter 169/postfilter sleeves (4 count)	495/GCX cartridge (4count)	http://www.iqair.com/commercial/support/replacementfilters
	IQAir	GCX Multigas	1 yr. 2.5 yrs.	$2,199		http://www.iqair.com/gcx-series-air-purifiers/buy	139/HEPA prefilter 169/postfilter sleeves (4 count)	495/GCX cartridge (4count)	http://www.iqair.com/commercial/support/replacementfilters
	MaxFlo	MAXFLO D-25	NA		Prices not listed, contact manu-facturer for details	http://maxfloair.com/Products/AirCleaners.aspx			
	MaxFlo	MAXFLO D-30	NA		Prices not listed, contact manu-facturer for details	http://maxfloair.com/Products/AirCleaners.aspx			

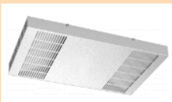
Image	Brand Name	Model	Listed filter life span	Cost ($US)					
				Equipment Price	Cost Notes	Equipment Price Source	Replacement Particulate Filter Price	Replacement VOC Filter Price	Replacement Filter Cost Information Source
	Hammacher Schlemmer	Air Purifier	3 years	$149					
	Honeywell	F111C1073 W-3S	N/S	$2,690	Particulate filter price includes prefilter cost. VOC replacement filter cost is for 2 (required) filters.	https://www.cleanairfacility.com/asp_pages/catalog.asp?PCA=10	$260	$610	https://www.cleanairfacility.com/asp_pages/catalog.asp?PCA=34
	Honeywell	F114C1008 commercial ceiling mount	<30 months	$1,500	Price of VOC filters not listed	http://www.honeywellstore.com/store/products/honeywell-f114c1008-commercial-ceiling-mount-media-air-cleaner.htm	$35		http://www.honeywellstore.com/store/catalog.asp?item=8917
	Honeywell	F115A1064 commercial ceiling mount		$1,860	Price of VOC filters not listed	http://www.honeywellstore.com/store/products/honeywell-f115a1064-media-air-cleaner-with-hepa-filter-and-prefilter.htm	$35		http://www.honeywellstore.com/store/catalog.asp?item=8918

Image	Brand Name	Model	Listed filter life span	Cost ($US)					
				Equipment Price	Cost Notes	Equipment Price Source	Replacement Particulate Filter Price	Replacement VOC Filter Price	Replacement Filter Cost Information Source
	NQ Clarifier	Air Purifier	2-3 years 1-2 years	$730					
	RabbitAir	BIOGS 2.0 - 625A	1.5-3 years	$370		https://www.rabbitair.com/products/biogs2-air-purifier		$30	https://www.rabbitair.com/products/biogs2-ac-charcoal-filter
	Sentry Air Systems	SS-700-FH	NA		Prices not listed, contact manu-facturer for details	http://www.sentryair.com/specs/ambient-air-filtration-system.htm			
	Sun Pure	SP-20C	2 years	$768		http://www.fieldcontrols.com/sun-pure-3-in-1-air-purification-system?page_id=185		$98	http://www.fieldcontrols.com/sun-pure-3-in-1-air-purification-system?page_id=185
	Temp Air	C2000	NA	Rental	This unit is a rental				

Image	Brand Name	Model	Listed filter life span	Cost ($US)					
				Equipment Price	Cost Notes	Equipment Price Source	Replacement Particulate Filter Price	Replacement VOC Filter Price	Replacement Filter Cost Information Source
	Trion	Air Boss ATS	NA		Prices not listed, contact manu-facturer for details				
	Winix	U450	12 months, wash-able at 3 months	$440	VOC filter and HEPA filter come in 1 unit			$140	https://winixamerica.com/product/filter-f-114290/

Image	Brand Name	Model	VOCs Tested For					
			VOCs tested for	Notes	TCE	PCE	1,1-DCA	Vinyl chloride
	Aerus	Sanctuairy by Aerus In-Duct Whole House Air Purifier						
	Air Oasis	Large commercial models	Unspecified VOCs	Reduces carbon-based contaminants and provides the space with fresh, clean air within minutes. Carbon-based contaminants are natural impurities like bacteria, mold, viruses, foul odors, and volatile organic compounds (VOCs).				
	Air Quality Engineering	M66 R&L	Unspecified VOCs	Fine dusts, smoke, soot, vapors, mist, VOC's				
	Air Quality Engineering	M73	Unspecified VOCs	Smoke, mist, dust and other airborne contaminants				
	Airgle	AG950 PurePal Multigas Air Purifier	Benzene, toluene, and xylene, as well as cooking gas, paint and building material vapors, and tobacco smoke.	Residential				

Image	Brand Name	Model	VOCs Tested For					
			VOCs tested for	Notes	TCE	PCE	1,1-DCA	Vinyl chloride
	AirPura	C600 DLX Air Purifier	Tobacco smoke, perfumes, vehicle emissions, off gassing from new flooring, cleaning chemical vapors, formaldehyde, benzene, toluene, ammonias, and other VOCs, nitrous dioxide, nitrous trioxide, monoethylamine, hydrogen sulfide, mercury vapors, chlorine dioxide, hydrogen bromide, sulfur dioxide, hydrogen fluoride, hydrogen chloride, methylene chloride, radioactive iodine, naphthene, pesticides, chlorine	Residential				
	Airpura	R600 All Purpose						
	Alen	Breathesmart-HEPA-FreshPlus	Unspecified VOCs	Large particles, dust, pollen, pet dander, mold spores, odors, VOCs, smoke				

Image	Brand Name	Model	VOCs Tested For					
			VOCs tested for	Notes	TCE	PCE	1,1-DCA	Vinyl chloride
	Amaircare	3000 HEPA Air Purifier	Unspecified VOCs	Residential				
	Amaircare	7500 Airwash Cart	Unspecified VOCs	Commercial use				
	Amaircare	Air Wash 10000	Unspecified VOCs	Biologicals, particulate and VOCs				
	Austin Air	Healthmate Plus	"Removes broadest spectrum of VOCs"	Residential	Y	Y	Y	

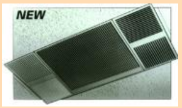
Image	Brand Name	Model	VOCs Tested For					
			VOCs tested for	Notes	TCE	PCE	1,1-DCA	Vinyl chloride
	Blue Air	Pro XL	Unspecified VOCs	Large particles, dust, pollen, pet dander, mold spores, odors, VOCs, smoke				
	Coway	AP-1512HH Mighty Air Purifier	Unspecified VOCs	Residential				
	Dyson	Pure Cool Link Tower	A layer of activated carbon granules eliminates odors and potentially harmful toxins such as paint fumes. No specified VOCs	Residential				
	EverClear	Delux CM-11	Unspecified VOCs	Odors, tobacco smoke, pollen, dust, vapors and many other irritants.				
	Fresh-Aire UV	APCO	Unspecified VOCs					Y

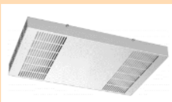
Image	Brand Name	Model	VOCs Tested For					
			VOCs tested for	Notes	TCE	PCE	1,1-DCA	Vinyl chloride
	Hammacher Schlemmer	Air Purifier	Unspecified VOCs A numeric display indicates the level of VOCs present and continues to count down as the air purifier removes them	Residential				
	Honeywell	F111C1073W-3S						
	Honeywell	F114C1008 commercial ceiling mount	Unspecified VOCs	8+ lbs. CPZ Filters for gas, odor, and volatile organic compounds (VOC) control.				
	Honeywell	F115A1064 commercial ceiling mount	Unspecified VOCs	16+ lbs. CPZ Filters for gas, odor, and volatile organic compounds (VOC) control.				
	Honeywell	F116A1120-3S Commercial Ductable	Unspecified VOCs					
	Honeywell	F120A1023 Ducted	Unspecified VOCs	22+ lbs. CPZ Filters for gas, odor, and volatile organic compounds (VOC) control.				

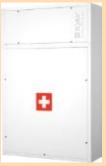
Image	Brand Name	Model	VOCs Tested For					
			VOCs tested for	Notes	TCE	PCE	1,1-DCA	Vinyl chloride
	IAP	M-25DDCC	Unspecified VOCs	Welding smoke/fumes, grinding dust, Bondo dust, diesel smoke, oil mist, printer powder, plastic dust, other smoke/dust problems				
	IQAir	Clean Zone 5200	Unspecified VOCs					
	IQAir	Clean zone SL	Unspecified VOCs					
	IQAir	GC/X VOC Air Purifier	Benzene, butane, carbon tetrachloride, chlorine, chloroform, chloropicrin, cyclohexane, 1.1 Dichloroethane, ethylene oxide, Freon 11, indole, methyl chloride, methyl chloroform, methylene chloride, nitrobenzene, phosgene, pyridine, sulfuric acid, toluene, xylene.	commercial use	Y	Y	Y	

Image	Brand Name	Model	VOCs Tested For					
			VOCs tested for	Notes	TCE	PCE	1,1-DCA	Vinyl chloride
	IQAir	GCX Multigas	Acetic acid, acetone, acrolein, acrylonitrile, 1.3 butadiene, butyric acid, carbon disulfide, chlorine dioxide, cresol, cyclohexanone, Diethylamine, dimethylamine, ethanol, ethyl acetate, ethyl acrylate, ethylamine, formic acid, hydrogen chloride, isoprene, isopropanol, methanol, methyl acrylate, methyl disulfide, methyl ethyl ketone, methyl mercaptan, methyl sulfide, methyl vinyl ketone, methylamine, nitroglycerine, ozone, phenol, Skatole, styrene, sulfur trioxide, trichloroethylene, tri hylamine, trimethylamine, vinyl chloride.	Highly recommended variety Residential use	Y	Y	Y	
	MaxFlo	MAXFLO D-25	Unspecified VOCs	Best for welding smoke, grinding dust, sanding dust, oil smoke, coolant mist, powders, odors, etc.				
	MaxFlo	MAXFLO D-30	Unspecified VOCs	Best for welding smoke, grinding dust, sanding dust, oil smoke, coolant mist, powders, odors, etc.				

Image	Brand Name	Model	VOCs Tested For					
			VOCs tested for	Notes	TCE	PCE	1,1-DCA	Vinyl chloride
	NQ Clarifier	Air Purifier	Unspecified VOCs	Commercial use				
	RabbitAir	BIOGS 2.0 - 625A	Unspecified VOCs	Residential				Y
	Sentry Air Systems	SS-700-FH	Unspecified VOCs	Solvent fume control, pharmacy pill dust, secondary clean room scrubber, shop fumes				Y
	Sun Pure	SP-20C	Carbon monoxide, pesticides, hair spray, alcohols, tobacco smoke, ammonia, paint solvents, chlorinated solvents, nitrous oxide, cleaning chemicals, ozone + smog	VOC's tested for not listed	M	M		
	Temp Air	C2000	Unspecified VOCs					

Image	Brand Name	Model	VOCs Tested For					
			VOCs tested for	Notes	TCE	PCE	1,1-DCA	Vinyl chloride
	Trion	Air Boss ATS	Unspecified VOCs	Smoke, fumes, and oil/coolant mists, nuisance odors				
	Winix	U450	Not published	Residential				

Image	Brand Name	Model	VOCs Tested For	General Notes
			Others	
	Aerus	Sanctuairy by Aerus In-Duct Whole House Air Purifier		
	Air Oasis	Large commercial models		
	Air Quality Engineering	M66 R&L		This company used to be the supplier and manufacturer for Honeywell industrial air cleaners until they decided to start making their own. There are a huge range of add-ons, configurations, and motor types for this specific model, for details see http://www.air-quality-eng.com/specs/m66-media-air-filtration-systems/ or http://www.breathepureair.com/aqe_m66.html
	Air Quality Engineering	M73		There are a huge range of add-ons, configurations, and motor types for this specific model, for details see http://www.air-quality-eng.com/specs/m73-industrial-air-filter/ or http://www.breathepureair.com/aqe_m73.html
	Airgle	AG950 PurePal Multigas Air Purifier		AG950 PurePal Multigas Air Purifier discontinued, AG900 PurePal Clean Room closest model found

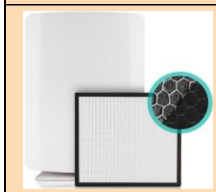
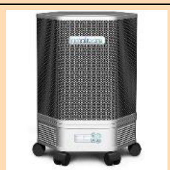
Image	Brand Name	Model	VOCs Tested For	General Notes
			Others	
	AirPura	C600 DLX Air Purifier		
	Airpura	R600 All Purpose		
	Alen	Breathesmart-HEPA-FreshPlus		
	Amaircare	3000 HEPA Air Purifier		
	Amaircare	7500 Airwash Cart		

Image	Brand Name	Model	VOCs Tested For	General Notes
			Others	
	Amaircare	Air Wash 10000		This model not listed on official Website
	Austin Air	Healthmate Plus		
	Blue Air	Pro XL		
	Coway	AP-1512HH Mighty Air Purifier		Unclear where the amount of GAC was found, as unit only weighs 15 lbs.

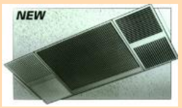
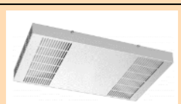
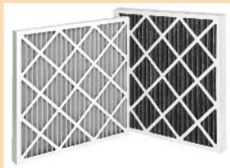
Image	Brand Name	Model	VOCs Tested For	General Notes
			Others	
	Dyson	Pure Cool Link Tower		Minimal data about what contaminants were tested, noise output and power requirement
	EverClear	Delux CM-11		There are a huge range of add-ons, configurations, and motor types for this specific model, for details see http://www.air-quality-eng.com/products/everclear-cm-11-commercial-air-cleaner/
	Fresh-Aire UV	APCO		Not much information available
	Hammacher Schlemmer	Air Purifier		
	Honeywell	F111C1073W-3S		
	Honeywell	F114C1008 commercial ceiling mount		
	Honeywell	F115A1064 commercial ceiling mount		
	Honeywell	F116A1120-3S Commercial Ductable		Essentially you can mix and match this unit with different types of filters to fit your needs, the specs listed are with two CPZ filters. Can create a positive or negative pressure gradient

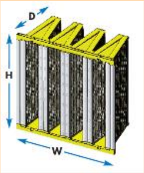
Image	Brand Name	Model	VOCs Tested For	General Notes
			Others	
	Honeywell	F120A1023 Ducted		
	IAP	M-25DDCC		
	IQAir	Clean Zone 5200		
	IQAir	Clean zone SL		
	IQAir	GC/X VOC Air Purifier		

Image	Brand Name	Model	VOCs Tested For	General Notes
			Others	
	IQAir	GCX Multigas	Acetic acid, acetone, acrolein, acrylonitrile, 1.3 butadiene, butyric acid, carbon disulfide, chlorine dioxide, cresol, cyclohexanone, Diethylamine, dimethylamine, ethanol, ethyl acetate, ethyl acrylate, ethylamine, formic acid, hydrogen chloride, isoprene, isopropanol, methanol, methyl acrylate, methyl disulfide, methyl ethyl ketone, methyl mercaptan, methyl sulfide, methyl vinyl ketone, methylamine, nitroglycerine, ozone, phenol, Skatole, styrene, sulfur trioxide, tri hylamine, trimethylamine	
	MaxFlo	MAXFLO D-25		Charcoal filter can be interchanged with HEPA filter
	MaxFlo	MAXFLO D-30		
	NQ Clarifier	Air Purifier		
	RabbitAir	BIOGS 2.0 - 625A		

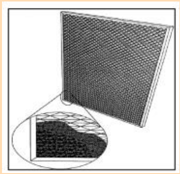
Image	Brand Name	Model	VOCs Tested For	General Notes
			Others	
	Sentry Air Systems	SS-700-FH		
	Sun Pure	SP-20C		
	Temp Air	C2000		Rental unit that uses carbon for various applications
	Trion	Air Boss ATS		
	Winix	U450		

ATTACHMENT B
AIR CLEANER EQUIPMENT

Manufacturer	Filtration Group	Filtration Group	Filtration Group
Website	www.filtrationgroup.com	www.filtrationgroup.com	www.filtrationgroup.com
Image			
Brand Name	Filtration Group	Filtration Group	Aerostar
Model	Series 750 Carbon Pleat	Series 550 Carbon Pleat	HEGA filters: Grade 653 for VOCs.
Height (in.)	24	24	24
Width (in.)	24	24	24
Depth (in.)	2	2	12
Dimension Notes	many sizes	many sizes	many sizes include 2”, 4”, 12” deep
Weight (Pounds)			depends on size
Description	Carbon pleated filters that provide particle and gas-phase filtration. Self-supportive media of 100% synthetic pre-filtration layer laminated to a chemically enhanced activated carbon filtration layer. MERV 11 for particles.	Carbon pleated filters designed for control of intermittent odors and common indoor air pollutants.	Specifications • 500 g/m^2 media loading • High Activity Carbon (85% CTC) Gas-phase units allow choice of sorbent (Series 653 is carbon), frames, and dimensions • Works on physisorption and catalysis
Listed filter life span			
Price	$125	$25	$490
Price Source	http://www.filtrationgroup.com/WFS/FGCBusiness/en_US/-/USD/HVAC/hvac-pleated-air-filters/hvac-pleated-air-filters-series-750-carbon-pleat-4/PLEAT-24x24x4-Nominal-Size-24-in-x-24-in-x-4-in--zid173444	http://www.filtrationgroup.com/WFS/FGCBusiness/en_US/-/USD/HVAC/hvac-pleated-air-filters/hvac-pleated-air-filters-series-550-carbon-pleat-1/PLEAT-24x24x1-Nominal-Size-24-in-x-24-in-x-1-in--zid15842	http://www.filtrationgroup.com/WFS/FGCBusiness/en_US/-/USD/HVAC/hvac-gas-phase-filters/hvac-gas-phase-filters-hega-3653-series/HEGA-3653-SERIES-Nominal-Size-24-in-x-24-in-x-12-in--zid17982
Price Notes	Price depends on size and quantity	Price depends on size and quantity	Price depends on size and type of frame

Manufacturer	Filtration Group	Dafco Filtration Group	AAF Intl.
Website	www.filtrationgroup.com	dafcofiltrationgroup.com	aafintl.com
Image			
Brand Name	Aerostar	Aerostar	AAF
Model	FP Gas-phase Filter	Side Access - Carbon Sorb Housing	AmAir/C family of filters
Height (in.)	24		24
Width (in.)	24		24
Depth (in.)	12		2
Dimension Notes	many sizes	from 0.5x0.5 to 2.5x5 ft. cross section, various depths	many sizes avail; 1", 2", 4" depths
Weight (Pounds)	24 for carbon; 28 for blend (media only)		
Description	removes wide range of odors and common indoor air pollutants at high air flows. Constructed of heavy-duty galvanized steel and plastic, with 3/4" honeycomb media packs. Blend of 60% CTC activated carbon and potassium permanganate on zeolite is recommended for TCE; carbon version for PCE.	This is a filter housing. Holds 2" or 4" pleated prefilters and 3/4" refillable carbon trays. Recommends 12 trays per 24" of height to achieve low-pressure drop. Standard housing depth is 36" for 2" prefilters and 38" for 4" prefilters; other depths are available upon request. Various sorbents available (carbon, PPIS, blends)	Directly interchangeable with standard air filters. Options: panels, pads, and 1", 2", and 4" pleated filters. long-lasting gas-phase and particle filters, with AAF's SAAFWeb™ technology chemical media. High chemical media density yields superior odor control. Carbon version more recommended for chlorinated hydrocarbons.
Listed filter life span			
Price			
Price Source			
Price Notes			

Manufacturer	AAF Intl.	3M	Accumulair
Website	aafintl.com	http://www.filtrete.com/3M/en_US/filtrete/products	www.accumulair.com
Image			
Brand Name	AAF	Filtrete	Accumulair
Model	VariCel RF/C	Allergen Defense Odor Reduction Filter	Carbon
Height (in.)	24	20	20
Width (in.)	24	25	25
Depth (in.)	11.5	1	6
Dimension Notes	many sizes	many sizes, intended for residences	many sizes
Weight (Pounds)	7.8	1.3	
Description	60% granular activated carbon; high-efficiency removal of multiple contaminants. The media is pleated and housed in a rigid metal frame. The frame is available in either the standard box style, no-header version, or with a single 13/16" thick header.	Lightly pleated particle and gas filter, MERV 11, activated carbon	Carbon-impregnated disposable pleated panel filter
Listed filter life span		up to 3 months	up to 3 months
Price		$10	$30
Price Source		https://www.amazon.com/dp/B006EI5V7O/ref=twister_B00O4TYSUG?_encoding=UTF8&psc=1	https://jet.com/product/detail/3fb52c1e5d6846d7b6136935c98e4994?jcmp=pla:ggl:gen_hardware_a2:heating_ventilation_air_conditioning_a2_other:na:PLA_348828540_24713608260_pla-161719582140:na:na:na:2&code=PLA15&ds_c=gen_hardware_a2&ds_cid=&ds_ag=heating_ventilation_air_conditioning_a2_other&product_id=3fb52c1e5d6846d7b6136935c98e4994&product_partition_id=161719582140&gclid=CN_ylenEj84CFQMLaQod9bsFlg&gclsrc=aw.ds
Price Notes			

Manufacturer	Cameron Great Lakes	Purafil	Clarcor
Website	http://www.cglcarbon.com/	https://www.purafil.com/	http://www.clcair.com/Brands-Products/Airguard/HVAC/Gas-Phase
Image			
Brand Name	CGL	Purafil	Airguard
Model	many	Puragrid	Vari-Klean
Height (in.)			
Width (in.)			
Depth (in.)			
Dimension Notes	many sizes	many sizes	many sizes
Weight (Pounds)			
Description	Many types from honeycombs to V-cells, to zig-zag trays and more	Different sorbent and blends available	Pleated, different sorbents available, intended for use for <500 ppb sites. Other products available
Listed filter life span			
Price			
Price Source			
Price Notes			

Manufacturer	**Clarcor**
Website	http://www.clcair.com/Brands-Products/Airguard/HVAC/Gas-Phase
Image	
Brand Name	Clarcor
Model	Carbon filter housings with refillable or replacement trays
Height (in.)	
Width (in.)	
Depth (in.)	
Dimension Notes	Various sizes
Weight (Pounds)	
Description	Different sorbents and differing weights up to 90 pounds for the AG-2000
Listed filter life span	
Price	
Price Source	
Price Notes	

United States
Environmental Protection
Agency

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Research Laboratory
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Adsorption-based Treatment Systems