# Interpreting Air Cleaner Performance Data

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The global COVID-19 pandemic has prompted widespread demand for air cleaning technologies aimed at reducing risks of airborne pathogen transmission inside buildings. The commercial landscape for air cleaning devices is complex, ranging from conventional technologies such as high-efficiency fibrous-media filters and ultraviolet germicidal irradiation (UVGI) to a wide variety of electronic air cleaning technologies such as plasma generators, hydroxyl radical generators, ionizers, photocatalytic oxidizers and others.

This article demonstrates some frequently prevalent issues in electronic air cleaner performance testing and reporting and proposes a path forward to meet research needs and improve test methods that could reduce the current uncertainty about the performance of electronic air cleaning technologies. It also provides tools to support practitioners and consumers in their decision-making regarding air cleaning technologies.

The ASHRAE Epidemic Task Force (ETF) has published extensive guidance for those who must make decisions on ventilation, air cleaning and more, often in the context of the limited resources available to building owners and managers. Along with increased ventilation, the ETF has advised that cleaning indoor air using particle filtration at MERV 13 or higher can improve air quality and reduce risks from COVID-19 by removal of viral aerosols and by diluting their concentration.

To date, the ETF has published limited specific guidance on the risk reduction potential of electronic air cleaning technologies, and the "ASHRAE Position Document on Filtration and Air Cleaning"[1] cites a lack of definitive conclusions on the efficacy of many electronic air cleaners. This is consistent with the fact that no ASHRAE or other industry standard currently exists to validate the marketing materials of many of these technologies. And, ETF's "Core Recommendation for Reducing Airborne Infectious Aerosol Exposure,"[2]

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which states in Section 2.3, "Only use air cleaners for which evidence of effectiveness and safety is clear," has prompted the authors of this article to look more closely at commonly available test reports on the effectiveness of air cleaners in general, and the risk reduction potential for COVID-19 and other microorganism in particular.

## Key Definitions

A wide variety of air cleaning technologies are used in commercially available stand-alone/portable and central HVAC system applications to capture, inactivate, and/or react with a variety of **particulate**, **chemical** and/or **microbiological** contaminants in indoor environments. In any such device, one or more air cleaning technologies may be used to accomplish its goals. Commercially available technologies vary widely in the types of pollutants they address, their mechanism of action and potential side effects of their use.[1,3]

Some air cleaning technologies operate in a primarily **"subtractive"** manner, meaning their mechanism of action generally relies on removing or inactivating targeted contaminants from indoor air when they come in contact with the technology. For example, fibrous media filters require that air pass through them to capture airborne particles (including airborne microbes). Similarly, activated carbon and other sorbent media require air to pass through them to capture airborne gases. One key influencing parameter for subtractive technologies is the **airflow rate** through an air cleaning device, which governs how much air is getting to the air cleaner or filter.

Other technologies, chiefly those broadly characterized as "electronic" air cleaning technologies, operate primarily in an **"additive"** manner, meaning their mechanism of action relies on adding constituents to the air to remove particles, inactivate microorganisms and/or react with contaminants. The effectiveness of both additive and subtractive technologies can be measured, but a key difference among these two categories is that additive technologies actively contribute constituents—often chemically reactive compounds—to a space. The addition of reactive constituents to a space can initiate indoor chemical reactions, which in turn raises the potential for unintended consequences such as forming chemical by-products.[4–6]

A key influencing parameter for additive technologies is **dose,** i.e., how much of the added constituents (e.g., ions, oxidants, or others) is required, and for how long, to be effective? Many further questions remain regarding additive air cleaning. For example: How does the dose added in lab tests compare to how much is added to the space in actual buildings? To what extent is the added dose spatially heterogeneous throughout a space? How does aging of the device affect both the production and type of added constituents? To what extent are added constituents variable across air cleaners of the same type? These parameters will greatly influence air cleaner performance and by-product formation.

This distinction between additive and subtractive technologies is not always a rigid, clear line. For example, in-duct ultraviolet germicidal irradiation (UVGI) systems require airflow to pass through them and also require a sufficient dose of UV to inactivate microorganisms. Nevertheless, the additive versus subtractive distinction is a useful framework for thinking about many air cleaning technologies.

Fortunately, performance metrics exist that can be used to evaluate the efficacy of air cleaners regardless of underlying mechanism of action.[3] By "efficacy," we broadly mean the ability of an air cleaner to produce a desired or intended result, regardless of the actual performance metric being used. In subsequent sections, we discuss three commonly used performance metrics, their relevance to additive and/or subtractive air cleaners. We also provide tools for interpreting test reports.

## Applicable Test Standards

While fibrous media filters are routinely tested for their ability to remove particles,[7,8] many electronic air cleaning technologies are not routinely evaluated by any federal agency or industry standards for their efficacy or their potential for unintended consequences, including the generation of chemical by-products.[3]

Instead, the efficacy of electronic air cleaning technologies is frequently demonstrated in tests conducted by commercial laboratories, with reports commonly provided by device manufacturers or distributors. However, as we will demonstrate here, these tests and reports commonly have limitations that make them difficult to interpret and even harder to translate to real-life performance.

Moreover, to date, these test reports do not adequately characterize emissions of primary or secondary products formed during operation of the device and/or chemistry initiated in the indoor space. The peer-reviewed literature on the potential for chemical by-product formation from electronic air cleaners (other than ozone generation) remains limited in scope, and publicly available test methods do not yet adequately address by-product formation.[9,10] The most widely used test standards for by-product formation focus only on ozone: UL 867 and UL 2998. UL 2998 is the more stringent "zero ozone emissions" standard (allowing up to 5 ppb in a standard 27 $m^3$ to 31 $m^3$ [954 $ft^3$ to 1,095 $ft^3$] test chamber), while UL 867 is the less stringent standard (allowing up to 50 ppb in a standard test chamber).

However, no standard test methods exist for evaluating the potential for formation of other types of by-products such as nitrogen oxides ($NO_x$), volatile organic compounds (VOCs), including aldehydes or other chemical compounds due to air cleaner operation. Thus, while this article focuses primarily on characterizations of *efficacy* rather than by-product formation, readers should understand that concerns for by-products resulting from additive oxidizing air cleaning technologies should not be limited to ozone.

## Three Commonly Used Performance Metrics

- The single-pass **efficiency** of an air cleaning device is a fractional measure of its ability to reduce the concentration of pollutants in the air that passes through the device once (*Equation 1*). The fractional efficiency (dimensionless) of a device is typically measured in a laboratory test duct but can also be extracted from well-designed chamber or even field tests.[11,12]

$$\text{Efficiency} = 1 - \frac{C_{\text{downstream}}}{C_{\text{upstream}}} \quad (1)$$

where $C_{\text{upstream}}$ and $C_{\text{downstream}}$ are the contaminant concentrations immediately upstream and downstream of a filter or air cleaner, respectively (#/$m^3$ or equivalent). Efficiency is a straightforward metric for subtractive technologies but perhaps less useful for additive or mixed technologies that rely on the addition of constituents to a space. Efficiency is usually expressed as a percentage, in which case the above is multiplied by 100. Efficiency can also be calculated for multiple pass units by comparing loss rates between air cleaner on and off conditions and accounting for the volume of the test space and the flow rate through the device.

- The **effectiveness** (dimensionless) of an air cleaning device or system is a measure of its ability to remove pollutants from the spaces it serves in real-world situations (*Equation 2*).[13] It is simply a comparison of pollutant concentrations in a space with and without an air cleaning technology operating, assuming other parameters like source rates, ventilation rates and other loss rate mechanisms are held constant. Effectiveness can also be assessed by comparing pollutant loss rates in a space measured during air cleaner on and off conditions. This performance metric can be applied to any air cleaning intervention, regardless of underlying mechanism of action.

$$\text{Effectiveness} = 1 - \frac{C_{\text{on}}}{C_{\text{off}}} \quad (2)$$

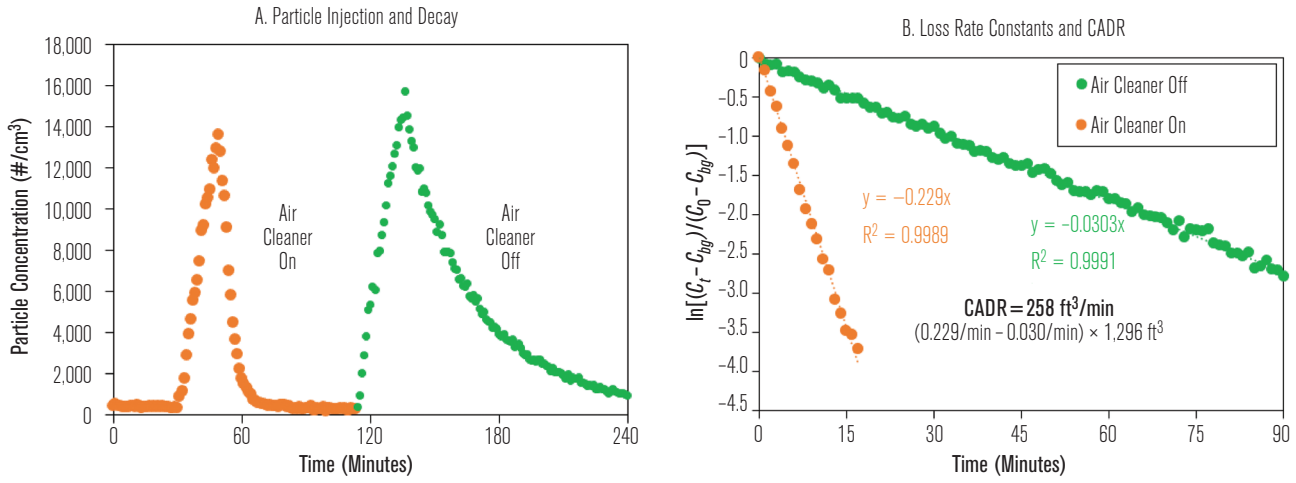
where $C_{\text{on}}$ and $C_{\text{off}}$ are the contaminant concentrations in a space with the air cleaner on and off, respectively (#/$m^3$ or equivalent).

- The **clean air delivery rate (CADR)**—sometimes also referred to as the **effective cleaning rate (ECR)**—of an air cleaner is an important measure of the amount of contaminant-free air delivered by an air cleaner.[14] The terms CADR and ECR are used interchangeably in the peer-reviewed literature, although the Association of Home Appliance Manufacturers (AHAM) specifically uses CADR to characterize its standard metric for an air cleaner's efficacy. Our use of the term CADR herein does not imply endorsement of AHAM or its CADR standard, but rather reflects the term as used generally in the scientific literature and in practice.

A higher CADR relative to the size of the room will increase the effectiveness of an air cleaner. The CADR is pollutant-specific and can be measured/calculated for specific gases, specific particle sizes and/or specific microorganisms, pathogens or surrogate pathogens. Current test standards such as ANSI/AHAM AC-1 only rate CADRs for the removal of particles.[15]

The CADR of any air cleaning device—whether it is installed as an in-duct device or a stand-alone/portable unit—is readily measured in a controlled chamber[14–18] or even a well-controlled field environment.[19,20] The general test procedure to measure CADR relies on elevating concentrations of a contaminant of interest and measuring its subsequent first-order loss rate constant

FIGURE 1 Example particle injection and decay test conducted to measure loss rate constants and CADR of a portable HEPA air cleaner operating in a 1,296 ft³ (36.7 m³) chamber.




with and without an air cleaner operating. The CADR (in units of m³/h or cfm) is calculated as the difference between the two loss rate constants times the volume of the chamber (*Equation 3*). The CADR can also be calculated by multiplying the flow rate through an air cleaner by its efficiency, but it is not necessary to measure flow rates in *Equation 3*.

$$\text{CADR} = V\left(L_{\text{on}} - L_{\text{off}}\right) \tag{3}$$

where $L_{\text{on}}$ and $L_{\text{off}}$ are the first-order contaminant loss rates measured in a space with an air cleaner on and off, respectively ($h^{-1}$ or $min^{-1}$), and $V$ is the volume of the space in which an air cleaner is tested ($m^3$ or $ft^3$). To estimate loss rate constants ($L_{\text{on}}$ and $L_{\text{off}}$), we take the natural logarithm of the contaminant concentration in the chamber at each time step ($C_t$) minus the steady-state background concentration in the chamber ($C_{bg}$) divided by the concentration at the initial time step ($C_0$) minus $C_{bg}$ (*Equation 4*).

$$-\ln\left(\frac{C_t - C_{bg}}{C_0 - C_{bg}}\right) = Lt \tag{4}$$

This is a simple first-order exponential decay model, assuming the chamber is well-mixed. We then fit a straight-line regression through these calculated data points versus time to estimate first-order loss rate constants.

The above performance metrics are interrelated. For example, a subtractive air cleaner with a high-efficiency filter and high airflow rate will have a high CADR, resulting in a high realized effectiveness in the space. However, it is the CADR specifically that allows for a quantitative comparison of pollutant loss rates with and without an air cleaner operating in a space, which also allows for extrapolating performance from lab tests to field conditions and incorporating into mass balances for equipment sizing (e.g., CADR per room size).[21,22]

*Figure 1* shows an example of a "smoke"-sized (0.09 µm–1 µm) particle injection and decay test conducted with and without a portable HEPA air cleaner operating in a 1,296 ft³ (36.7 m³) chamber. The resulting first-order loss rate constants during air cleaner on and off conditions were 0.229 per minute and 0.030 per minute, respectively, resulting in a CADR of 258 cfm (438 m³/h).

Next, we explore how electronic air cleaner test reports often show their efficacy data and will attempt to translate them to these more conventional performance metrics of loss rate constants and equivalent CADR.

## Issues in Electronic Air Cleaner Performance Testing and Reporting

Common generic examples of efficacy statements in test reports include statements such as:

- Air Cleaner Technology A uses reactive molecules to destroy pathogens. Independent testing demonstrates

a net 4 log reduction in pathogen surrogate after 30 minutes.

- Air Cleaner Technology B reduces viable SARS-CoV-2 by over 99% in 60 minutes.

They often sound impressive. For example: "Pathogen killing with over 99% efficacy in less than an hour," or "Multiple orders of magnitude of pathogen reduction in 30 minutes," or "Reactive species that kill COVID-19 in the indoor environment." Such statements are frequently made based on results from test reports from commercial laboratories.

To understand these test reports and translate their results to real-world situations, several important factors must be considered. These may include but are not limited to:

- Lack of standardized performance metrics, which limits the ability to compare devices and translate to operation in real occupied spaces;
- Testing in small sealed chambers that can overestimate performance in actual buildings;
- Testing that does not account for control conditions (such as natural decay rates);
- Testing conducted at elevated (or sometimes unreported) concentrations of additive/reactive constituents that might not reflect real-world use;
- Lack of chemical by-product testing or demonstration of complete oxidation;
- Omission of test parameters, such as chamber volume or mixing conditions;
- Variation in parameters between control and test conditions.

Here we illustrate some of these factors using generic examples of performance data from test reports, again focusing primarily on efficacy given the nascent stage of by-product testing that exists.

## Hypothetical Example 1: Concentration Decrease in a Medium-Size Chamber

Manufacturer A has provided a third-party test report in which their air cleaning technology was tested for its ability to inactivate aerosolized *E. coli* in a medium-sized 500 ft$^3$ (14.2 m$^3$) chamber. The report highlights 98% reduction in *E. coli* viability after 60 minutes. The test report provides the following *E. coli* concentration data (in CFU/m$^3$) for both control (air cleaner off) and test (air cleaner on) conditions in the first three columns of *Table 1*.

TABLE 1 Hypothetical air cleaner test results (on a concentration basis) and subsequent loss rate calculations for an *E. coli* inactivation test conducted in a medium-sized 500 ft$^3$ (14.2 m$^3$) chamber.

| TIME (MIN) | TEST REPORT DATA | | LOSS RATE CALCULATIONS | |
|---|---|---|---|---|
| | CONCENTRATION (CFU/m$^3$) | | $\ln(C/C_0)$ | |
| | CONTROL | TEST | CONTROL | TEST |
| 0 | 5,000 | 5,000 | 0 | 0 |
| 15 | 4,200 | 2,700 | –0.174 | –0.616 |
| 30 | 3,300 | 1,200 | –0.416 | –1.427 |
| 45 | 2,700 | 400 | –0.616 | –2.526 |
| 60 | 2,000 | 100 | –0.916 | –3.912 |

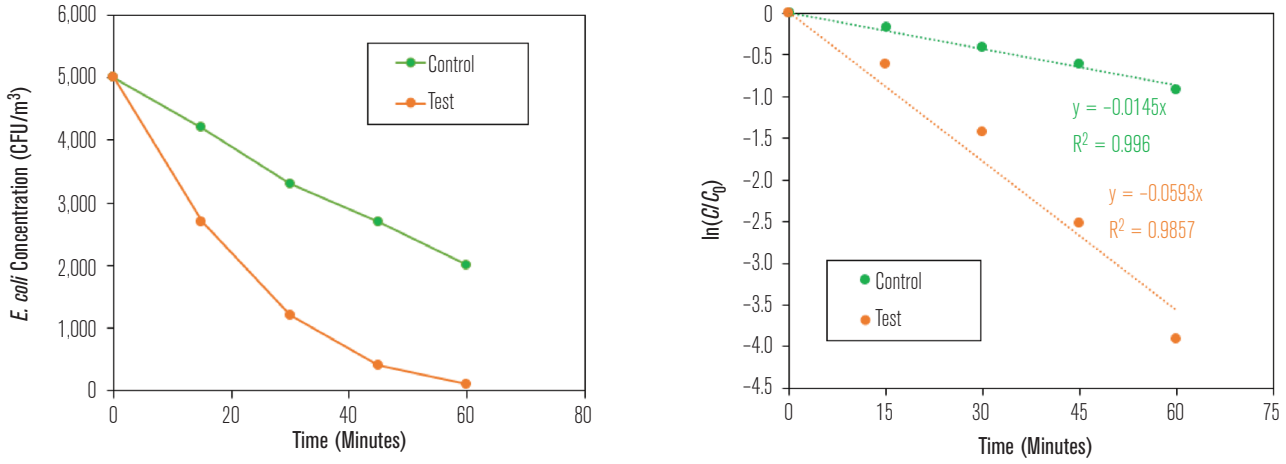
After 60 minutes of testing with this air cleaner operating, the concentration of *E. coli* is only 100 CFU/m$^3$ compared to an initial concentration of 5,000 CFU/m$^3$—a reduction of 98% from the initial concentration, which is about 95% lower than the control condition concentration at that same point in time. We can use these data to calculate first-order loss rate constants during both the control and test conditions, as shown in the last two columns of *Table 1*. To do so, we take the natural logarithm of the concentration at each time step ($C$) divided by the concentration at the initial time step ($C_0$), which is again a simple first-order exponential decay model assuming $C_{bg}$ from *Equation 4* is set to 0 and that the test chamber is reasonably well-mixed. We fit a straight-line regression through these calculated data points versus time to estimate first-order loss rate constants, as shown in *Figure 2*. If the chamber is not well-mixed, then the effective volume of treated air could be even smaller than the chamber volume, and the effective loss rates and resulting CADR could be lower than shown here.

The resulting loss rate constants are approximately 0.0145 per minute during the control condition (which represents the natural decay rate in the chamber) and approximately 0.0593 per minute with the air cleaner operating. The difference in loss rate constants in this setup is thus approximately 0.045 per minute. Using *Equation 3*, we can calculate an equivalent CADR by multiplying this loss rate difference by the volume of the chamber (500 ft$^3$ or 14.2 m$^3$), which yields an estimated CADR of approximately 22 cfm (37 m$^3$/h) (*Equation 5*).

$$\text{CADR} = 500\,\text{ft}^3 \times 0.045\,\frac{1}{\text{min}} = 22\,\frac{\text{ft}^3}{\text{min}} \qquad (5)$$

In this case, an equivalent CADR of 22 cfm (37 m$^3$/h) is not a particularly effective air cleaner compared to the

FIGURE 2 Hypothetical air cleaner test results and example first-order loss rate constant estimates for an *E. coli* inactivation test conducted in a medium-sized 500 ft³ (14.2 m³) chamber and with results reported on a concentration basis.




example in *Figure 1*, despite the report of 98% reduction after 60 minutes.

To put this in perspective, let's calculate the expected percentage reduction over time if the mid-range portable air cleaner with a HEPA filter (from *Figure 1*) was tested in the same chamber as the hypothetical scenario in *Figure 2*. We will take the CADR determined for particles in the "smoke" size range (0.09 µm–1 µm) of 258 cfm (438 m³/h) previously determined. The first-order loss rate, ignoring background deposition losses, can be calculated as the CADR divided by the volume of the chamber (*Equation 6*).

$$\frac{\text{CADR}}{V} = \frac{258\,\frac{\text{ft}^3}{\text{min}}}{500\,\text{ft}^3} = 0.516\,\frac{1}{\text{min}} = 31\,\frac{1}{\text{h}} \qquad (6)$$

We would expect to see a 99.9999999999999% reduction in particle concentrations after 60 minutes using *Equation 7*. That is several more decimal places—and orders of magnitude—of removal efficacy than the example in *Figure 2*.

$$\frac{C(t)}{C(t=0)} = e^{-\frac{\text{CADR}}{V}t} = e^{-0.56\frac{1}{\text{min}}\times 60\,\text{min}} \qquad (7)$$
$$= 3.6\times10^{-14} \approx 99.9999999999999\%\ \text{reduction}$$

The core issue is that percentage reduction values do not tell a complete story, and only after incorporating the chamber volume and calculating comparative loss rates between on and off conditions can one obtain a quantitative metric such as CADR that can also be used to extrapolate to other operating conditions and compare to other commercially available air cleaning technologies.

TABLE 2 Hypothetical air cleaner test results (on a log10-reduction) and subsequent loss rate calculations for a SARS-CoV-2 inactivation test conducted in a small 5 ft³ (0.14 m³) chamber

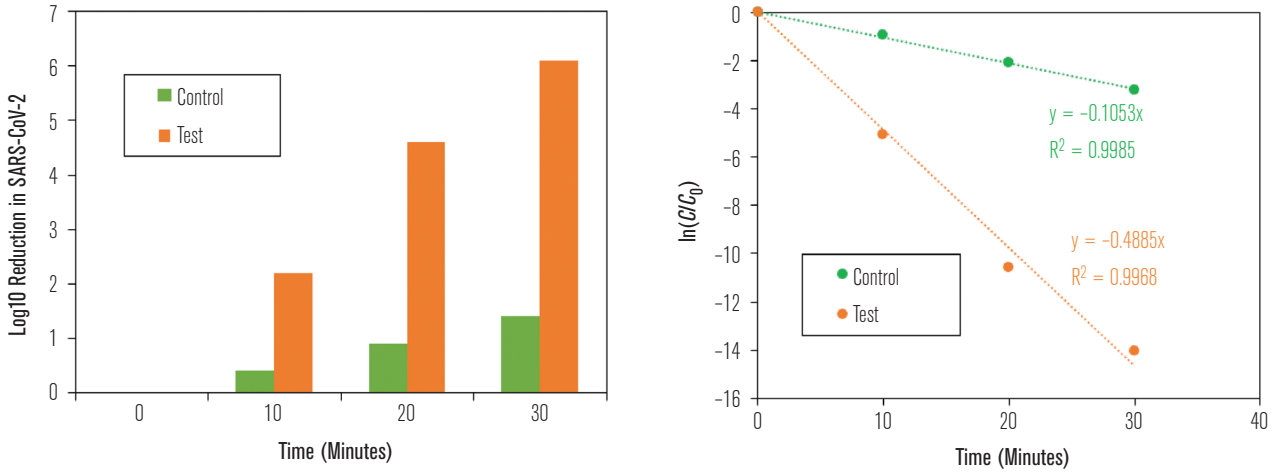
| TIME (MIN) | TEST REPORT DATA | | LOSS RATE CALCULATIONS | | | |
|---|---|---|---|---|---|---|
| | LOG REDUCTION | | $C/C_0$ | | $\ln(C/C_0)$ | |
| | CONTROL | TEST | CONTROL | TEST | CONTROL | TEST |
| 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| 10 | 0.4 | 2.2 | 0.398 | 0.0063 | –0.921 | –5.066 |
| 20 | 0.9 | 4.6 | 0.126 | $2.51\times10^{-5}$ | –2.072 | –10.592 |
| 30 | 1.4 | 6.1 | 0.040 | $7.94\times10^{-7}$ | –3.224 | –14.046 |

## Hypothetical Example 2: Log-Reduction in a Small Chamber

Manufacturer B has provided a third-party test report in which their air cleaning technology was tested in a small 5 ft³ (0.14 m³) chamber for its ability to inactivate aerosolized SARS-CoV-2. The marketing materials based on this report highlight 99.9999% reduction in SARS-CoV-2 viability after 30 minutes of exposure. The test report provides the following SARS-CoV-2 concentration reduction data (in units of log10 reduction) over time for both control (air cleaner off) and test (air cleaner on) conditions in the first three columns of *Table 2*.

After 30 minutes of testing with this air cleaner operating, the concentration of viable SARS-CoV-2 is reduced by 6 orders of magnitude down to ~$8\times10^{-7}$ of the initial concentration, or over 99.9999% lower than

FIGURE 3 Hypothetical air cleaner test results and example first-order loss rate constant estimates for a SARS-CoV-2 inactivation test conducted in a small 5 ft$^3$ (0.14 m$^3$) chamber and with results reported on a log-reduction basis.




the initial concentration. ($C/C_0$ values are calculated as $1/(10^{\text{log10-reduction}})$). Again, we can use these data to calculate first-order loss rate constants during both the control and test conditions, as shown in the final four columns of *Table 2*. We again take the natural logarithm of the ratio of the concentration at each time step divided by the concentration at the initial time step, and then fit a straight-line regression through these calculated $\ln(C/C_0)$ data points versus time to estimate first-order loss rate constants, as shown in *Figure 3*.

The resulting loss rate constants are approximately 0.1053 per minute (6.3 per hour) during the control condition, which again represents the natural decay rate in the chamber, and approximately 0.4885 per minute (29.3 per hour) with the air cleaner operating. The difference in loss rate constants in this setup is thus approximately 0.38 per minute (or 23 per hour). However, we can again calculate an equivalent CADR by multiplying this loss rate difference by the volume of the chamber (using *Equation 3*), which, in this case, is only 5 ft$^3$ (0.14 m$^3$). This yields an equivalent CADR of approximately 2 cfm (i.e., 5 ft$^3$ × 0.38/min = 2 cfm or 3.4 m$^3$/h). An equivalent CADR calculated from these data is very low, despite the impressive sounding 99.9999% reduction after 30 minutes.

In addition to further demonstrating how percentage reduction values do not tell a full story, this example also demonstrates how operating air cleaners in increasingly small volumes can further influence reported results. In addition to influencing results, small chamber volumes are problematic because they result in operating conditions that are highly unlikely to represent performance in the field; for example, if an ionizer or other reactive constituent generator is operated in a very small chamber, it is certainly plausible that the resulting concentration of those generated constituents is much higher than would be present in an actual building.

## Tools to Support Practitioners and Consumers

The aforementioned examples show how air cleaner performance data, often reported by manufacturers and test labs in the form of a fractional or log removal versus time, can be converted into an equivalent CADR for comparison among different technologies and products. Next, we build on these examples to provide some tools that can assist in making sense of air cleaner performance data and test results.

Especially in promotional materials, manufacturers commonly provide performance data in the form of a single value of net log removal or net percentage removal at a given time. In this case, the resultant CADR can be quickly estimated using *Figure 4*, which shows the test chamber volume-normalized clean air delivery rate (CADR) as a function of log and/or percent removal achieved at a specified time. The vertical axes shown in *Figure 4* are simple rearrangements of *Equation 3*, normalizing CADR by test chamber volume (CADR/*V*), which allows for "compacting" results for many possible test chamber volumes into a single figure.

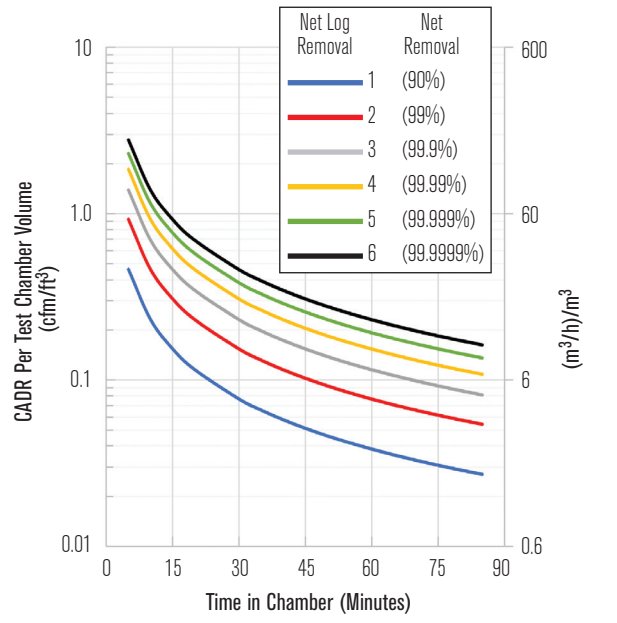
Note that while *Figure 4* allows for scaling test chamber results to a CADR based on volume, factors exist that are not incorporated into *Figure 4* that may impact the realized CADR in the environment where the air cleaner is used. For example, in the case of electronic air cleaners, the concentration of added reactive constituents should scale with realized loss rates for target air pollutant(s). The concentration of added constituents can differ between testing and actual use due to device settings, types of surfaces present, surface area to volume ratios and the background air matrix (i.e., constituents in air other than the target pollutant or pollutants), among other reasons. For any air cleaner, imperfect mixing in the space (e.g., short-circuiting) may also reduce the realized effectiveness of an air cleaner.

As an example of how to use this figure, consider a manufacturer test report of "99.9% removal of a pathogen in 60 minutes." By identifying the appropriate curve (gray line) and time (60 minutes), one can determine the volume-normalized CADR (i.e., CADR/*V* on the vertical axis of *Figure 4*) for these conditions to be ~0.1 cfm/ft$^3$ or (6 m$^3$/h)/m$^3$. Thus, if the test were conducted in a 100 ft$^3$ (2.8 m$^3$) chamber, the resulting CADR from that test would be approximately 10 cfm (17 m$^3$/h). If the test were conducted in a 10 ft$^3$ (0.28 m$^3$) chamber, the resulting CADR from that test would be only ~1 cfm (~1.7 m$^3$/h).

For comparison, AHAM recommends that portable air cleaners have a CADR of ~⅔ of the floor area of the space being served. By this rule of thumb, an air cleaner with ~10 cfm (~17 m$^3$/h) would be suitable for a 15 ft$^2$ (1.4 m$^2$) room, or perhaps a small closet. As with prior examples, this shows that an impressive sounding performance statement must be carefully scrutinized in terms of test conditions and expected impact in a real indoor environment. Use of *Figure 4* also demonstrates that the volume of the test chamber scales proportionally with the CADR. In other words, a high value of percent removal does not inherently mean the device has a high CADR even if achieved in a short duration test.

The examples shown in *Figures 2* and *3* demonstrate that loss rates from chamber tests can be determined by plotting the natural logarithm of the reduction in the target compound achieved as a function of time. For these more complex analyses involving regression across values of removal measured over time, we developed a spreadsheet application to make calculations, visualize data and perform regressions to determine loss rates,

FIGURE 4 The test chamber volume-normalized clean air delivery rate (CADR) as a function of removal achieved in a specified time. For a given removal and time to achieve that removal, the resulting CADR of the air cleaner is determined by multiplying the associated value on the vertical axis. Left axis: cfm/ft$^3$, right axis: (m$^3$/h)/m$^3$ by the test chamber volume (ft$^3$ or m$^3$).




CADRs and equivalent clean air changes per hour provided to a space. This spreadsheet application provides instructions, including rationale for and comparisons to generally accepted air cleaning thresholds. This spreadsheet tool can be accessed at: https://www.pdx.edu/healthy-buildings/ace-it.

## Charting a Path Forward for Research Needs and Improving Test Methods and Standards

Given these persistent issues and others, we provide the following suggestions for future research needs and improving test methods and standards for evaluating the efficacy and impacts on indoor air of current and emerging air cleaning technologies:

**1. Fundamental studies that elucidate underlying mechanisms of action of air cleaning technologies.** Statements from manufacturers and distributors often confuse and conflate terms, such as interchanging "ions" and "radicals," which limits the ability to evaluate the expected primary (i.e., air cleaning) and secondary (i.e., by-product formation or other unintended consequences) effects of the device operation.

**2. Controlled chamber studies that enable robust calculation of loss rates of target air pollutants and generation rates of by-products.** Ideally, chamber studies will occur following established test protocols at conditions representative of the real-world use of the device (e.g., installation in a duct vs. the room, with airflows consistent with that reported by the manufacturer, and appropriate mixtures of VOCs and other contaminants). A clear need exists for new controlled chamber test methods for electronic or additive air cleaners that include metrics of efficacy for target pollutants as well as quantification of emitted species (ions, radicals), dose-response relationships and formation of by-products. We must also recognize that these studies can be costly and require sophisticated analytical instrumentation and protocols to yield meaningful insights.

**3. Field studies in real environments.** Ideally, field studies will be conducted in environments where scientists and engineers are able to manipulate the space served by the device, while monitoring target compounds, by-products and constituents responsible for the air-cleaning mechanism (e.g., ion concentrations). Performance metrics from both field and chamber studies should also consider other factors that may affect the use of an air cleaning technology such as energy use or noise.

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