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Evaluation of a Gas-Phase Hydrogen Peroxide Generating Device

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ABSTRACT

The novel Coronavirus disease (COVID-19) pandemic has driven innovation of new air cleaning technologies with renewed interest in determining effectiveness of both new and existing air cleaning technologies. A standardized test method for the evaluation of reactive air-cleaning technologies for both volatile organic compounds (VOCs) and microbiological agents does not exist at present. Since air movement in a building is very dynamic and situational, the lack of standardized test methods often leads to contradictory results or sub-optimal evaluation of a device's performance in a laboratory setting.

In this paper, an air cleaning device that generates gas-phase hydrogen peroxide (H_2O_2) is evaluated for general effectiveness against bacteriophage MS2 (*Emesvirus zinderi*). The authors also describe the testing methodology used and discuss variables that could impact the reproducibility and repeatability of the results. In addition, various by-products were measured that could be generated by the device, specifically ozone, ions, and formaldehyde. The results of the study demonstrate that the gas-phase H_2O_2 generator is effective in reducing both airborne MS2 and MS2 on surfaces. Possible implications are discussed.

1. INTRODUCTION

The COVID-19 pandemic has spurred a growing body of research around indoor environmental quality (IEQ) factors, with added focus on indoor air quality (IAQ) due to the role it plays in mitigating the risk of transmission of certain airborne diseases. Indoor environmental quality is an occupant's perceived indoor experience of the built environment that includes aspects of thermal comfort, lighting, acoustics and IAQ. Standards to measure, maintain and optimize IEQ for energy consumption, thermal comfort, lighting, and acoustics are well defined, but standards for measuring IAQ are still under development at the time of this publication. IAQ contaminants of concern fall primarily into three classes: particles, gases (including volatile organic compounds, VOCs) and microorganisms. Distinct categorization of IAQ contaminants are not mutually exclusive and similar technology approaches can be used for mitigation. For example, both microorganisms and dust are particles whose total concentration can be reduced by particle removal technologies. IAQ standards to measure and optimize the quality of indoor air have been slow to develop in part because IAQ contaminants of concern are both difficult to control and measure within the built environment. One objective of this paper is to describe a testing methodology that could be used as input to develop a test standard to evaluate the performance of IAQ technologies against microorganisms like MS2.

There are generally four traditional approaches to removing or reducing various IAQ contaminants. The first two approaches, dilution and exhaust, are usually used in combination to remove contaminants and reduce exposure to IAQ contaminants including particles, VOCs, and microorganisms. Increasing outdoor air ventilation to bring in more fresh air that has lower concentrations of IAQ contaminants will dilute or reduce the concentration of the contaminants in the occupied space. Increasing the supply of fresh air will also increase the exhaust airflow in order to maintain an

adequate building pressure. Increasing exhaust airflow increases the rate at which the IAQ contaminants are removed from the occupied space. Dilution and exhaust are effective methodologies and are primary approaches in managing a building's IAQ through the HVAC systems. Of course, there are many building designs or environmental variables that have an impact on the IAQ contaminant removal or reduction effectiveness through the dilute and exhaust methodology; these will not be discussed here.

The third approach is to reduce the concentration of IAQ contaminants of concern through control of indoor humidity. HVACR systems are used to control humidity to improve indoor comfort. Generally, managing indoor humidity can support the mitigation of the growth of airborne and surface bound microorganisms like bacteria and fungi. ASHRAE® recommends 40%-60% relative humidity (RH) to maximize human comfort and to reduce microbial growth. Humidity can also have an impact on particle size and number of water-based aerosols of microorganisms after emission by a host source.

The fourth and last approach is passively cleaning the air through various means. One common approach is to capture the IAQ contaminant through filtration so it cannot reach occupants. Air is circulated through a filter and the contaminant can be captured through various mechanisms, but primarily through impingement or adsorption onto a filtration media. ASHRAE developed Standard 52.2 -2019, Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size, to determine the Minimum Efficiency Reporting Value (MERV) for air filters. This method is limited to media filters since it measures the pressure drop as particle loading of the filter increases. Devices, like electrostatic precipitators, which do not have increasing pressure drop with particle loading, cannot be given a MERV rating. Using a filter with a higher MERV rating is an effective tool in removing particles but may cause increased pressure drop in installations with little flexibility in filter choice. Increased pressure drop will increase energy consumption, but this increase in energy use can be more effective in reducing indoor contaminants than that associated with increased outdoor air ventilation or use of in-room air cleaners (Pistochini, 2021).

Another approach to cleaning is to break down or inactivate the IAQ contaminant in the air and/or on surfaces. For example, application-specific ultraviolet germicidal irradiation (UVGI) systems are now a widely accepted technology for controlling microorganisms and may be installed in the HVAC duct system or inside an HVAC unit to irradiate a surface like a coil or drain pan. Another approach that has been used as far back as the 1920s is to bring UVGI into the room (occupied spaces) and either treat a portion of the room's air as it circulates (e.g., upper room UVGI) or treat surfaces directly (typically unoccupied spaces). A wide range of additional air cleaning technologies have also been developed and are currently available on the market and the need for standard methods of testing these devices and verifying performance has become a clear priority. ASHRAE Standard 185.1 is available for single pass in duct inactivation and ASHRAE Standard 185.2 for irradiance of coils and duct surface inactivation, but standards are not available for in-room inactivation. A safety standard exists for the generation of secondary contaminates such as ozone for air cleaning devices. ASHRAE Standards 62.1-2019, Ventilation for Acceptable Indoor Air Quality, requires that air-cleaning devices comply with UL 2998 which limits ozone to 5 parts per billion (ppb) or less (UL 2998, ED3). Current test standards for in-duct devices only allow single-pass testing (ASHRAE 2017, ASHRAE 2016). For in-room air cleaners, AHAM AC-1 (2013), which defines the Clean Air Delivery Rate (CADR), measures reduction of particles but does not address gas-phase contaminants or duct-mounted devices. Still, the chamber decay methodology of AHAM AC-1 allows longer exposure and multiple passes through the air cleaner. Thus, this method serves as the basis of the chamber work discussed here. Methodologies similar to AHAM AC-1 are also recommended in the NRCC version of the chamber test (NRCC 2011).

The COVID-19 pandemic has accelerated the development and testing, and development of various IAQ technologies by the HVAC industry that could facilitate the removal and inactivation of airborne pathogens such as the SARS-CoV-2 virus in various applications. As a result, Trane Technologies accelerated the development and refinement of a set of HVAC-focused testing methodologies for measuring the safety, applicability, and efficacy of various air cleaning technologies and incorporated various facets from existing standards.

One technology that showed promising efficacy towards airborne pathogens is a gas-phase hydrogen peroxide (H_2O_2) generator, which utilizes titanium dioxide photocatalysts to convert atmospheric water into gas-phase H_2O_2 through a photocatalytic oxidation (PCO) process. The new technology releases H_2O_2 into room air at very low levels (<25 ppb) to inactivate microorganisms. H_2O_2 is used commonly to clean surfaces by direct surface application as a liquid formulation or by aerosolization of vapor-phase H_2O_2 into the air to clean entire rooms (e.g., disinfecting hospital

rooms). Like other technologies, there is a balance between effectiveness and safe use of the chemistry. The direct products of the PCO process are hydroxyl radicals ($^{\cdot}OH$) and superoxide ($O_2^{\cdot-}$) which can lead to the formation of H_2O_2. Hydroxyl radicals are extremely reactive/unstable and have sub-microsecond lifetimes. As a result, these radicals are not sufficiently long-lived enough to leave the device and inactivate microorganisms in the occupied space. The technology combines unstable hydroxyl radicals generated through the PCO process into more stable H_2O_2 molecules that can then diffuse throughout the space and remotely inactivate microorganisms over time. H_2O_2 is highly hydroscopic and will likely associate with water vapor in the air as it is generated by the device.

Photocatalytic oxidation (PCO) has been studied for several decades and its application towards the cleaning of air streams remains a maturing technology (Jacoby, 1996; Tsang, 2019, Noguchi, 1998; Kormann, 1988; Schneider, 2014; Perry, 2011). The most widely used photocatalytic material in PCOs is titanium dioxide (TiO_2) which has a bandgap of 3.2 eV (corresponding to 388 nm). Bandgap excitation produces both a potent oxidizing agent, i.e., a conduction band hole, and a potent reducing agent, i.e., a conduction band electron, both of which lead to the formation of reactive oxygen species such as hydroxyl radicals ($^{\cdot}OH$), superoxide ($O_2^{\cdot-}$), hydroperoxide radical ($^{\cdot}OOH$), and hydrogen peroxide (H_2O_2) (Howe, 1987; Nosaka, 2017). A review of the literature shows that the following elementary mechanistic steps are the likely key contributors toward the production of reactive oxygen species (ROS) that can cause the subsequent degradation/oxidation of organic species such as microorganism like MS2: (1) oxidation of surface-bound water molecules to produce hydroxyl radicals, (2) reduction of oxygen by conduction band electrons to produce superoxide followed by formation of hydrogen peroxide, and (3) production of hydrogen peroxide from two adjacent surface-bound hydroxyl radicals (Howe, 1987; Nosaka, 2017; Schneider, 2014). Competing with ROS creation is the recombination of the conduction band electrons with valence band holes. This process diminishes the overall yield of ROS that can be created by absorbed photons. The quantum yield for producing ROS by TiO_2 and is reported to fall in the range 1-5% (Nosaka, 2017).

The ROS that are formed on the surface of TiO_2 during photocatalysis are often depicted as remaining on the surface until they naturally decay or are utilized in the surface-based oxidation of incoming or nearby organic species such as nearby microorganisms. However, several literature examples exist that have experimentally demonstrated that these oxidizing agents can enter the gas-phase and be detected down-stream from the photocatalytic structure and utilized in the oxidation of nearby organic species that are located a certain distance away from the photocatalysts (Murakami, 2006; Tatsuma, 2001). These experiments were performed under zero to low air flow conditions. The maximum diffusion length of photocatalytically-produced OH radicals generated by TiO_2 that reach the gas-phase has been determined to be approximately 2 mm under specific experimental setup and conditions (Murakami, 2006). This short diffusion length is consistent with the sub-microsecond lifetimes often reported for airborne OH radicals (Stone, 2012; Nosaka, 2017). Superoxide has been observed to form photocatalytically on TiO_2 surfaces and has been assigned as an intermediate in hydrogen peroxide and hydroperoxide radical formation (Howe, 1987; Ishibashi, 1998). Hydroperoxide radicals, like OH radicals, are short-lived species with sub-second lifetimes. In contrast, the lifetime of gas-phase H_2O_2 is significantly longer (minutes to 0.5 hour) and is highly dependent on environmental conditions such as temperature and humidity (Steris, 2006). Importantly, hydrogen peroxide, hydroperoxide radicals, and OH radicals are all known to exist and form within the Earth's atmosphere with well-documented lifetimes (Zheng, 2003; Das, 1994; Stone 2012). Taken together, it is theoretically possible that H_2O_2, OH radicals, and hydroperoxide radicals can enter an air stream that passes through an operating photocatalytic TiO_2 structure. From an indoor air space standpoint, only H_2O_2 will survive long enough to be detected at distances greater than about 1 cm from the photocatalyst. Over time, the H_2O_2 that has entered the room will either react with organic species within the indoor space or decay naturally into the benign products, water and oxygen.

The gas-phase H_2O_2 generating device comprises a TiO_2-based photocatalytic structure through which airstreams can flow (Figure 1). The photocatalyst becomes activated by light given off by a nearby UV-A bulb which excites electrons across the bandgap of TiO_2. Both in room and in duct device designs are available on the market, the latter of which can be placed wherever it is needed in the duct (e.g., either far away from or adjacent to the diffuser that allows air to re-enter a room). A series of evaluations were conducted to gain further insights into the performance and behavior of gas-phase H_2O_2 generators.

This paper presents initial results of the performance of the gas-phase H_2O_2 generating technology against the MS2 virus. Emphasis is made on the HVAC-focused testing methodologies that were developed for measuring the safety, applicability, and efficacy of gas-phase H_2O_2 generators that are placed within a room (in-room) or placed within the

HVAC ductwork (in-duct). In addition, data is presented that demonstrates the inactivation of both surface-bound and airborne/aerosolized MS2 viruses.

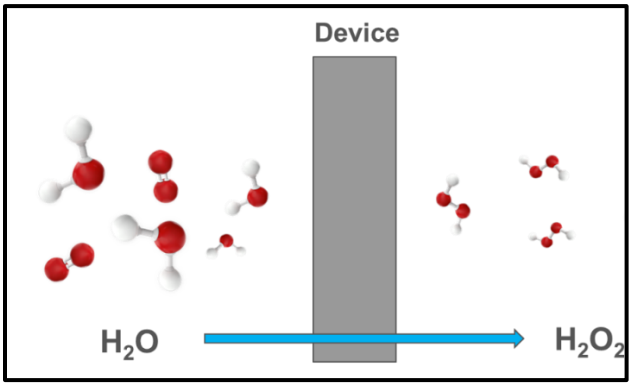

Figure 1. Schematic of the gas-phase H_2O_2 generator showing the utilization of atmospheric water and conversion into H_2O_2 via the photocatalytic oxidation process.

2. EXPERIMENTAL

As COVID-19 focused the industry's attention on air cleaners and the need for air cleaning, Trane Technologies began a project to test several air cleaning devices that were not yet covered by test standards. We worked with LMS Technologies Inc. to determine which methodologies and procedures made sense within the framework of accepted test standards and the needs of air cleaners that are not yet covered by test standards. It should be noted that these air cleaning technologies were not manufactured by Trane Technologies.

2.1 Test Chamber Overview

Many air cleaners require a longer period of time to operate and clean the air within a space; as a result, these air cleaners are not adequately covered by current standard test methods. Because of this, a test chamber similar to the AHAM AC-1 standard for testing in-room air cleaners for particle removal was a good starting point. However, some of these air cleaners are duct-mounted, so a simple chamber is not sufficient, and a combination chamber with a removable side duct apparatus was chosen as the basis for these tests. A removable side duct allowed the same chamber to be used for both in-room and duct-mounted devices. The two test chambers used for these experiments were 1007 ft^3 and 4096 ft^3 in volume, with both having an optional side duct with approximately 80 ft^3 of volume with an available 24"x24" device mounting section for mounting HVAC-mounted devices. Figure 2 provides an overview of the test chambers. Flexible 12-inch HVAC tubing was used to connect the side/by-pass duct with the chamber; for the 4096 ft^3 chamber, an additional ~30 ft of tubing was needed.

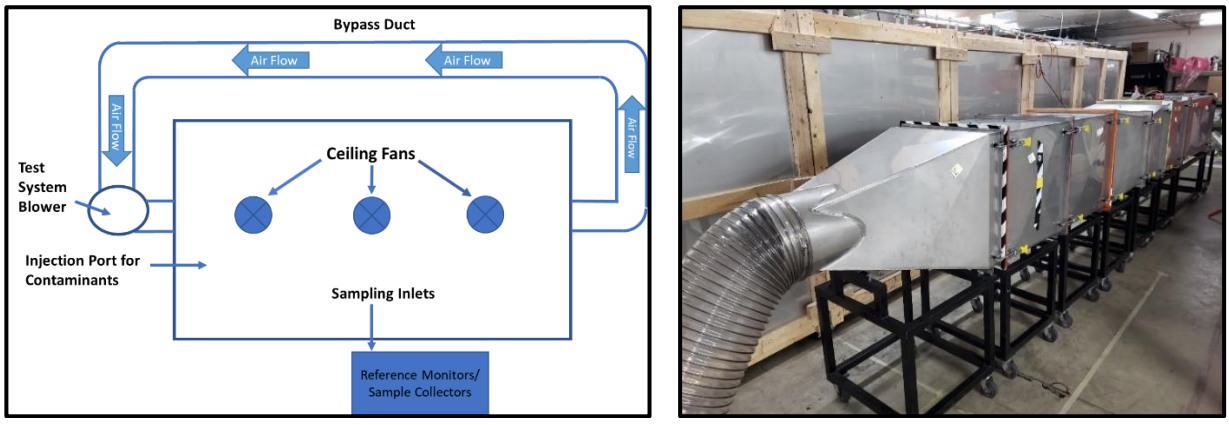

Figure 2. ***Left.*** Environmental test chamber schematic depicting placement of various sensors, injection location, and sampling. ***Right.*** Image of the chamber with the bypass recirculating duct.

The individual sections of this side duct may be exchanged with other sections to provide more space, different access, or simply different sealing options. The smaller chamber size is equivalent to a typical office or bedroom and, as such, is quite appropriate for testing small-to-medium sized in-room air cleaners. It is not, however, the size that a full HVAC-mounted device would service. For example, a 2000 cubic foot per minute (cfm) unit would result in two air exchanges in 1 minute, or 120 air exchanges per hour (ACH) for this chamber, whereas in a real-world situation the same unit might serve 20 similarly sized rooms in a building, providing a more typical 6 ACH. The size of the chamber and of the duct as well as the intended airflow rate of the air cleaner must be considered when reviewing the test data. The chamber also allowed for air cleaners and sampling devices to be positioned in different locations. The internal fan could be run continuously to guarantee good mixing during the injection of contaminants to ensure good initial mixing. Alternatively, the internal fans could not be used at all to test a zero-to-low air flow condition. Three ceiling fans and two box fans at opposite ends of the chambers were used for both chambers. A variable frequency drive (VFD) was operated to adjust the test system blower to the desired test airflow rate in the by-pass recirculating duct. The chamber was purged with high-efficiency particulate air (HEPA) filters, carbon filters, and catalyst filters until stable baseline levels were reached. UV lights were also used to decontaminate the chamber after microbial tests. The purging processes lasted 30 to 60 minutes depending on the test contaminate and chamber size. Importantly, the experiments were carried out under closed chamber conditions (i.e., essentially zero outside air). Humidity was adjusted prior to the beginning of any tests to avoid the introduction of particles during the test.

2.2 Instrumentation

Multiple measurements were made during the environmental chamber experiments during each evaluation. Ozone was measured using an ACOEM Ecotech Serinus 10 Ozone Analyzer, with a measurement range of 0-20,000 ppb and a lower detection limit (LDL) of 0.5 ppb. Background and generated formaldehyde were measured with an Aerodyne QC-TILDAS Formaldehyde Monitor with measurement range of 0-15 ppm. The potential for ions being produced by an air cleaner was monitored using an AlphaLab Air Ion Counter Model AIC2; two separate devices were used to measure positive and negative ions. Particle sizes and distributions over the size range 15-600 nanometers (nm) and concentration ranges of 1 to 10^7 particles/cm^3 were captured with a TSI Scanning Mobility Particle Sizer Spectrometer 3938. Temperature and relative humidity (RH) within the chamber were also monitored, using a TSI VelociCalc 9545, with typical ranges of 71-74ºF and 48-53%, respectively. Power consumption by the devices was also measured. When relevant, the airflow through an in-room device, due to its own fan, was determined, while for duct-mounted devices, the actual airflow rate through the duct was measured.

2.3 Generation and Sampling of MS2

MS2 bacteriophage (ATCC 15597-B1) was propagated, made into a solution, and titrated to $3x10^8$ plaque forming units per milliliter (PFU/mL) to produce the MS2 challenge. The resulting MS2 suspension from propagation was typically diluted by half with 1% saline to achieve the desired MS2 concentration for the chamber experiments. This suspension of MS2 was aerosolized into the test chamber using a TSI 9302 Single Jet Atomizer with a regulated pressure of 20 pounds per square inch (psi). For data analysis, time zero was set as the end of the injection period and injections typically lasted ~10-14 min. MS2 was sampled from the air within the chamber using impactors located in the center of the room. Three SKC QuickTake 30 high flow pumps equipped with SKC BioStage 400-hole single-stage impactors collected the bioaerosol samples. Air samples were collected in triplicate from the chosen location onto agar plates, usually the center of the test chamber. The QuickTake 30 pumps were calibrated for a flow rate of 1 cfm (28 Lpm), and the collection period was 1 minute.

The sampled MS-2 bacteriophage was grown on double-layer tryptone yeast extract agar with *E. coli* (ATCC 15597) added to the top-layer as the bacteriophage host. The recovered organisms were enumerated after 30 hours of incubation. MS2 plates were quantified by counting the visible plaque forming units (PFU) on the sampling plates. To account for the potential that more than one bacteriophage could have landed in the same location on the plate (i.e., having gone through the same hole in the impactor), a positive hole correction was applied to these numbers before further data analysis (Macher 1989). The efficacy towards MS2 on surfaces was separately evaluated in the following manner. Petri dishes equipped with gaskets under the lid were treated with 20 µL MS2 diluted suspensions and allowed to air dry for 1-1.5 h and then placed at several locations about the chamber. At given time points, the petri dishes were tightly sealed using a pneumatic arm to protect them from further exposure to generated H_2O_2 or to collect natural decays at the same time point.

2.4 Test Sequences (In-duct versus In-Room Devices)

Two types of chamber decay tests, similar to AHAM AC-1, were derived using an environmental chamber, one for in-room devices and one for in-duct or duct-mounted devices.

In-Room Devices

1. Install air cleaner in the 1007 ft^3 or 4096 ft^3 chamber
2. Purge the chamber with ventilation system
3. Check for background levels of VOCs, ozone, particles
4. Inject microorganism challenge into the chamber
5. Mix the chamber well with the fan
6. Collect air samples over time to determine the natural decay rate; measure other by-products such as ozone, ions, particles, and formaldehyde as needed.
7. Purge the chamber with the ventilation system
8. Repeat steps 2-7 but this time with the air cleaner on prior to or following the injection of the microorganism
9. Calculate concentrations and decay rate.

In-Duct Devices

1. Set up the chamber with the bypass loop attached (1007 ft^3 or 4096 ft^3 chamber)
2. Install air cleaner in the bypass duct loop attached
3. Purge the chamber with ventilation system
4. Check for background levels of VOCs, ozone, particles
5. Turn on the air flow through the device and bypass loop
6. Inject microorganism challenge into the chamber
7. Collect air samples over time to determine the natural decay rate; measure other by-products such as ozone, ions, particles, and formaldehyde as needed.
8. Purge the chamber with ventilation system
9. Repeat steps 3-8 but this time with the air cleaner on prior to or following the injection of the microorganism
10. Calculate concentrations and decay rate.

3. RESULTS AND DISCUSSION

3.1 By-products: Ozone, Ions and Formaldehyde

Ozone is the byproduct that is most often mentioned for air cleaning devices because many electronic air cleaners, including both portable and duct-mounted devices, can generate high amounts of ozone. As a result, air cleaning devices, especially those sold in California, US, must qualify to comply with UL 867 and/or UL 2998 environmental standards to show low or no ozone produced. However, qualifying for zero ozone emission does not determine whether a device is functional, i.e., that the device neutralizes or inactivates contaminants, as claimed. A check of ozone during a contaminant removal test gives important information about the function of the device when it is working. Ozone was measured during the test sequence. The ozone levels measured during natural decay and during 60 min operation of the gas-phase H_2O_2 generator were both ~0.4-0.6 ppb, demonstrating that negligible ozone was generated by the air cleaner.

Ions output from air cleaners were measured systematically during our standard test methods because many technologies claim that ion production is an essential feature toward the achievement of high efficacies for microorganism inactivation. The ion counts remained under 2000 ions/cm^3 which is due to the charging inherent in the spraying process used to introduce MS2.

Formaldehyde exposure indoors is a problem in many parts of the world including the United States and is a potential breakdown product of the oxidation of organic species including microorganisms. (Kaden 2010). Formaldehyde levels remained under 7 ppb throughout the 60-min. test, demonstrating that formaldehyde levels remain very low with the gas-phase H_2O_2 generating device responding to a viral bioaerosol challenge.

3.2 Particle Measurements

As described above, an aqueous suspension of MS2 was sprayed into an environmental chamber producing an aerosol consisting of both MS2 and non-MS2 particles. Smaller particles in the 16-600 nm size range were measured using a Scanning Mobility Particle Sizer Spectrometer (SMPS). The average particle size remained <100 nm during the 60-min tests. The diameter of MS2 virus by itself is ~70-100 nm indicating that it is not present in the majority of the generated particles. Calculations based on the concentrations of virus injected into chamber and the SMPS particle concentration data show that about 1 in every 10000 particles that were measured likely contained a virus.

3.3 Microbial Inactivation by Gas-Phase H_2O_2 Generators

An infectious-to-humans microorganism presents aerosolization, sampling, and handling issues. Even some Biosafety Level 1 organisms can present health risks when aerosolized at room or test duct quantities even though they are essentially harmless in liquid suspension. Thus, testing is conventionally accomplished by using surrogate organisms, usually ones with similar characteristics to the desired microorganism. The common viral surrogate MS2, which is a BSL1 organism, was used for these tests. It should be noted that the MS2 bacteriophage virus is a small, non-enveloped virus. Non-enveloped viruses are expected to be more difficult to inactivate than an enveloped virus (Firquet 2015). MS2 is often used as a surrogate for SARS-CoV-2 because SARS-CoV-2 is an enveloped virus and is expected to be inactivated faster than MS2.

It is more complicated to work with viruses than bacteria, since viruses need to replicate in a host to show viability. Thus, growth plates need to be inoculated with *Escherichia coli* (*E. Coli*) first and then used to sample MS2. After growth, the lack of colony growth for *E. coli* indicates viable MS2. The results are quantified as plaque forming units (PFU); the data in this paper are normalized and presented as percent reduction of MS2. The experimental details and subtleties of preparing the MS2 injection, releasing, and analyzing air samples are provided above.

Both in-duct and in-room gas-phase H_2O_2 generators were tested for MS2 inactivation efficacy in a 1007 ft^3 chamber. Figure 3 provides the MS2 challenge response curves for the in-duct device with an air flow of 101 CFM and corresponding to an air exchange rate of 6 ACH. Figure 3 also provides the MS2 challenge response curves for the in-duct device with an air flow of 336 CFM and corresponding to an air exchange rate of 20 ACH. The error bars in all graphs are based on a single standard deviation of the triplicate samples for each test at each time point. Chamber air sampling was performed with impactors at specific time intervals with time = 0 being set as the time-point immediately following the end of the MS2 injection. As can be seen from the data, MS2 in the absence of the air cleaner exhibited a natural decay rate with approximately 70% of the initial active viral concentration becoming inactivated at 60 minutes. When the gas-phase H_2O_2 generator was positioned in the duct adjacent to the diffuser as close to the room as possible, the device gives a faster rate of inactivation than natural decay resulting in a larger overall percent reduction of MS2 (~95%). The data shows that 70% reduction in MS2 was achieved at 20 minutes for the in-room device compared to 60 minutes for natural decay. Importantly, the repositioning of the gas-phase H_2O_2 generator deeper into the duct and further away from air re-entry to the room resulted in no significant inactivation compared with the natural decay. Similar results were also observed for the in-duct unit adjacent to the diffuser when the air flow was increase to 336 CFM (20 ACH), albeit with a lower final efficacy towards MS2 (~88%). Using the data between 0 and 20 minutes for Figure 3, it is estimated that the in-duct device reduces airborne MS2 at a rate that is 1.5-2.0 times faster than natural decay. The requirement of the placement near the diffuser suggests that a gas-phase H_2O_2 generating device needs to be placed either as near as possible to a duct outlet or placed within a space.

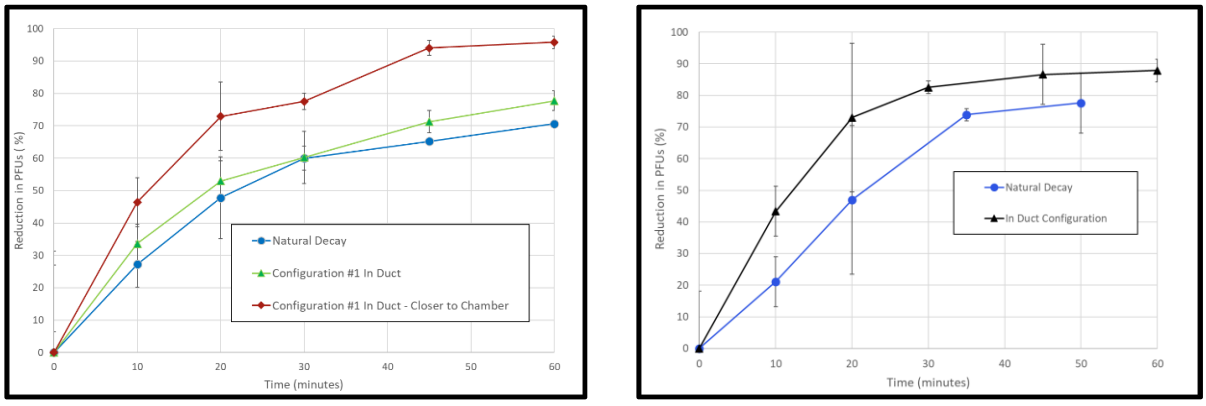

Figure 3. ***Left.*** MS2 challenge data for an in-duct gas-phase H_2O_2 generator at 101 CFM 6 ACH, 1007 ft^3 chamber. ***Right.*** MS2 challenge data for an in-duct gas-phase H_2O_2 generator at 336 CFM, 20 ACH, 1007 ft^3 chamber

The next evaluation was conducted to quantify the efficacy towards MS2 for the in-room gas-phase H_2O_2 generating device in a 4096 ft^3 testing chamber. Figure 4 provides the MS2 challenge response curves for an in-room device with an air flow of 410 CFM, corresponding to an air exchange rate of 6 ACH for the larger chamber. MS2 in the absence of the air cleaner exhibited a natural decay with ~72% of the initial viral concentration after 60 minutes. When the

gas-phase H_2O_2 generator was positioned in the room, the device gives a faster rate of inactivation than natural decay resulting in a larger overall percent reduction of MS2 (~88%). The data shows that 70% reduction in MS2 is achieved at 20 minutes for the in-room device compared to 50-60 minutes for natural decay. These results were independent of whether or not the air cleaner was working in the room for 1 hour prior to MS2 injection.

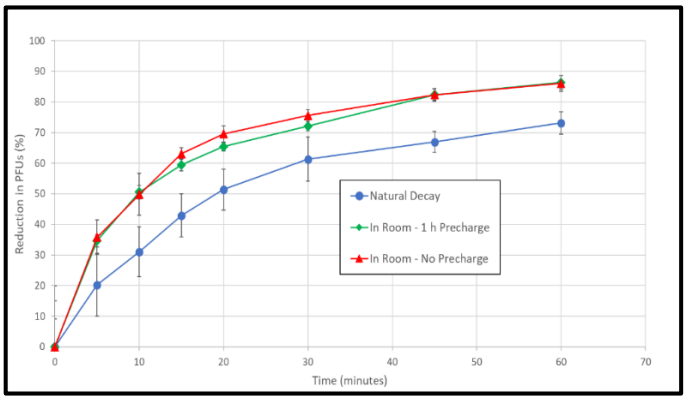

Figure 4. MS2 challenge data for an in-room H_2O_2 generator at 410 CFM, 6 ACH, 4096 ft^3 chamber.

The in-duct device data presented above demonstrates that the position of the unit is critically important. This behavior can be explained by the relatively high reactivity of H_2O_2 which can diminish its effective lifetime. For instance, H_2O_2 is known to react with metal surfaces such as those provided by the metal ductwork in the bypass duct. As the pathlength between the device and the room becomes longer, the H_2O_2 concentration could possibly become diminished (due to reactions with the metal ducting) to a point where MS2 inactivation is minimal or no longer even occurs. The primary reported effectiveness of gas-phase H_2O_2 generating device is their surface cleaning capability for various microorganisms including viruses, bacteria, and fungi. Evaluations were conducted in which closable petri dishes containing MS2 were placed throughout the environmental chamber to measure the decay data for MS2 with and without exposure to gas-phase H_2O_2 generating devices. Figure 5 provides the performance for an in-room device. The data shows that surface deactivation of MS2 by gas-phase H_2O_2 generating devices is highly prevalent at one hour of exposure to H_2O_2.

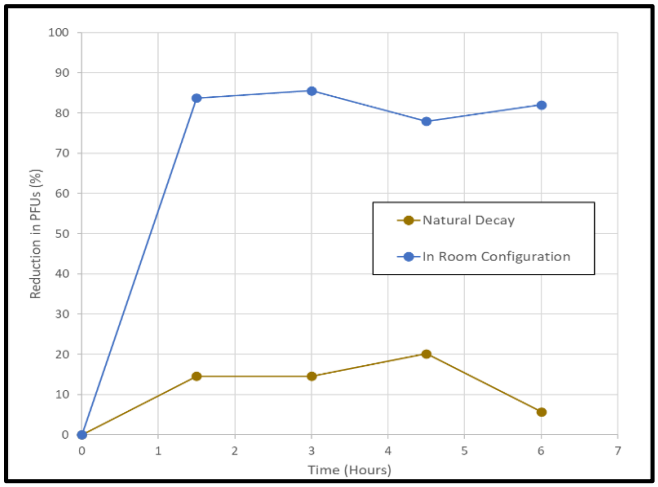

Figure 5. Surface MS2 deactivation data for an in-room H_2O_2 generator.

4. CONCLUSIONS

A potential standard testing methodology for microbiological challenges was provided for evaluating both in room and in duct air cleaning devices to determine their safety, applicability, and efficacy. In-duct and in-room gas-phase

H_2O_2 generating devices were evaluated using this testing method and the devices were shown to exhibit various levels of effectiveness versus natural decay of the MS2 challenge. The efficacy of the gas-phase H_2O_2 generators toward airborne challenges, subtracting out the natural decay of the virus, was observed to be up to25% after 60 min for both in duct and in room devices. At 101 CFM, the in room and in duct devices reach 70% MS2 reduction three times faster than natural decay with rates that are estimated to be 1.5-2.0 times faster. In addition, we observed that an in-room device shows very good performance toward inactivating MS2 virus on contaminated surfaces. Since the MS2 virus is an enveloped virus, it could be expected that these devices would show greater efficacy against non-enveloped viruses, such as SARS-CoV-2. The results shown here provide baseline microorganism efficacy data for gas-phase H_2O_2 generators that can be applied toward device optimization for specific microorganisms and different sizes of indoor spaces.

This work demonstrates that it is possible to collect useful information about devices, like gas-phase H_2O_2 generators, in relatively straight-forward chamber testing that utilize a bypass duct. The methodology presented here provides a foundation that can be built upon to understand and benchmark the performance, safety, and applicability of various air cleaning technologies more comprehensively. The proposed testing methodology can be used as a potential starting point in the development of improved standards of testing for air cleaners and better understanding of safety and performance of various IAQ cleaning technologies

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REFERENCES

AHAM AC-1-2013. 2013. Method for Measuring Performance of Portable Household Electric Room Air Cleaners, Association of Home Appliance Manufacturers.

ASHRAE Standard 52.2-2017, Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size, ASHRAE, Inc., Atlanta, GA 30329.

ASHRAE Standard 62.2-2019, Ventilation for Acceptable Indoor Air Quality, ASHRAE, Inc., Atlanta, GA 30329.

ASHRAE. 2016. Standard 145.2 "Laboratory Test Method for Assessing the Performance of Gas-Phase Air Cleaning Systems: Air Cleaning Devices," Atlanta, GA

ASHRAE. 2021. "Equivalent Outdoor Air Calculator." ASHRAE Epidemic Task Force. https://docs.google.com/spreadsheets/d/1GUCcjAyhzrTATHD8SQvNcF7JnuWKpadSVT6LA_8SUII/edit#gid=0

Burkhead, Bob. 2018. "Chamber Testing," Status Report for ASHRAE SSPC 52.2, presented at the ASHRAE SSPC 52.2 committee meeting, January 20.

Das, M, Aneja, V.P. 1994. Analysis of Gaseous Hydrogen Peroxide Concentrations in Raleigh, North Carolina. *Journal of Air and Waste Management Association*, 44, 176-180.

Firquet, S., Beaujard, S., Lobert, P.E., Sané, F., Caloone, D., Izard, D., Hober, D. 2015. Survival of Enveloped and Non-Enveloped Viruses on Inanimate Surfaces. *Microbes Environ.*, 30, 2, 140-144.

Foarde, K.K., E.A. Myers, J.T. Hanley, D.S. Ensor, and P.F. Roessler. 1999. Methodology to perform clean air delivery rate type determinations with microbiological aerosols. *Aerosol Science and Technology* 30:235–245.

Half-Life of Vaporized Hydrogen Peroxide (VHP) During Remediation of the U.S. Department of State SA-32 Diplomatic Pouch and Mail Facility. STERIS Corporation - June 22, 2006.

Howe, R.F., Gratzel, M. EPR Study and Hydrated Anatase Under UV Irradiation. 1987. *J. Phys. Chem.*, 1987, 91, 3906-3909.

Ishibashi, K., Nosaka, Y., Hashimoto, K., Fujishima, A. 1998. Time-Dependent Behavior of Active Oxygen Species Formed on Photoirradiated TiO_2 Films. *J. Phys. Chem. B*, 102, 2117-2120.

Jacoby, W.A., et. al. 1996. Heterogeneous Photocatalysis for Control of Volatile Organic Compounds in Indoor Air. *Journal of the Air and Waste Management Association*, 46, 891-898.

Kaden, D.A, Mandin C., Nielsen G.D., et al. Formaldehyde. 2010. WHO Guidelines for Indoor Air Quality: Selected Pollutants. Geneva: World Health Organization; 2010. 3.

Kormann, C., Bahnemann, D.W., Hoffmann, M.R. 1988. Photocatalytic Production of H_2O_2 and Organic Peroxides in Aqueous Suspensions of TiO_2, ZnO, and Desert Sand. *Environ. Sci. Tech*, 22, 798-806.

Macher, J. M. 1989. Positive-Hole Correction of Multiple-Jet Impactors for Collecting Viable Microorganisms, *Am. Ind. Hyg. Assoc. J.* 50:561–568.

Murakami, Y., et al. 2006. Direct Detection of OH Radicals Diffused to the Gas Phase from the UV-Irradiated Photocatalytic TiO_2 Surfaces by Means of Laser-Induced Fluorescence Spectroscopy. *J. Phys. Chem. B*, 110, 16808-16811.

Noguchi, T., Fujishima, A., Sawunyama, P., Hashimoto, K. 1998. Photocatalytic Degradation of Gaseous Formaldehyde Using TiO_2 Film. *Env. Sci. Tech.*, 32, 3831-3833.

Nosaka, Y., Nosaka, A.Y. 2017. Generation and Detection of Reactive Oxygen Species in Photocatalysis. *Chemical Reviews*, 117, 11302-11336.

NRCC. 2011. Method for Testing Portable Air Cleaners. NRCC-54013. Prepared for: Government of Canada, Clean Air Agenda, Indoor Air Initiative. Evaluation of IAQ Solutions in Support of Industry Innovation, pp. 1-43, March.

Perry, J.L., et al. 2011. A Comparison of Photocatalytic Oxidation Reactor Performance for Spacecraft Cabin Trace Contaminant Control Applications. 41st International Conference on Environmental Systems, 1-8.

Pistochini, T., et al, 2022. Energy and Long-range Airborne Disease Transmission Impacts of Ventilation and Filtration Methods in Classrooms. *Journal of Building Engineering*, submitted paper

Professional Standard of the Republic of China: Test of Pollutant Cleaning Performance of Air Cleaners. 2010. Issued by the Ministry of Housing and Urban-Rural Development of the People's Republic of China. December 20.

Schneider, J., Matsuoka, M., Takeuchi, M., Zhang, J., Horiuchi, Y., Anpo, M., Bahnemann, D.W. 2014. Understanding TiO_2 Photocatalysis: Mechanisms and Materials. *Chem. Rev.*, 114, 9919−9986.

Stone, D., Whalley, L.K., Heard, D.E. 2012. Tropospheric OH and HOO Radicals: Field Measurements and Model Comparisons. *Chem. Soc. Rev.*, 41, 6348–6404.

Tatsuma, T., Tachibana, S., Fujishima, A. 2001. Remote Oxidation of Organic Compounds by UV-Irradiated TiO_2 via the Gas Phase. *J. Phys. Chem. B*, 105, 6987-6992.

Tatsuma, T., Tachibana, S., Miwa, T., Tryk, D.A., Fujishima, A. 1999. Remote Bleaching of Methylene Blue by UV-Irradiated TiO_2 in the Gas Phase. *J. Phys. Chem. B*, 103, 8033-8035.

Tsang, C.H.A., et al., 2019. Titanium Oxide-Based Photocatalytic Materials Development and Their Role in Air Pollutants Degradation. *Environmental International*, 125, 200-228.

UL Standard 2998: ED 3., Environmental Claim Validation Procedure (ECVP) for Zero Ozone Emissions for Air Cleaners, Underwriters Laboratories, Northbrook, IL.

UL Standard 867: ED5. The Standard for Safety for Electrostatic Air Cleaners, Underwriters Laboratories, Northbrook, IL.

Zheng, J., Springston, S.R., Weinstein-Lloyd, J. 2003. Quantitative Analysis of Hydroperoxyl Radical Using Flow Injection Analysis with Chemiluminescence Detection. *Analytical Chemistry*, 75, 4696-4700.