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September 24, 2007

Ms. Peggy L. Jenkins
California Air Resources Board
Research Division, Fifth Floor
1001 I Street, P.O. Box 2815
Sacramento, CA 95814

Re: Comments on Proposed Air Cleaner Regulation

Dear Ms. Jenkins:

We submit these comments on behalf of Ecoquest International, Inc. ("Ecoquest"), a manufacturer of indoor air cleaners.

As a starting point, Ecoquest supports the proposition that consumers should not be exposed to ozone concentrations that exceed the .05 ppm standard.

1. Regulation denies benefits of some ozone technologies.

The proposed regulation concedes in its definition of "industrial uses" (section 9480(a)(14)) there are times that people can benefit from using an air cleaner emitting a higher concentration of ozone on a temporary basis while a room is unoccupied, namely for "destruction of microbes," "chemical oxidation and disinfection," "odor...control," "mold remediation" and "fire and smoke damage remediation". These benefits can be obtained while the spaces are unoccupied, just as the benefits of house fumigation can be obtained while a house is tented and of course unoccupied.

The proposed regulation would effectively bar California consumers from pursuing these benefits by banning devices that could emit a higher ozone concentration than .05 ppm, regardless of whether they are used in unoccupied spaces.

We attach a peer-reviewed study done at Kansas State University (attachment 1) citing ozone's benefits as a disinfectant in combating e coli and other bacteria on food

preparation surfaces, and a peer reviewed study from the University of Cincinnati (attachment 2) showing a 98% reduction in aerosol contaminants from a photo catalytic process called RCI (Radiant Catalytic Ionization), which includes low level ozone emissions.

The proposed regulation would effectively ban even this low ozone air cleaning technology by imposing a test protocol using a sterile chamber not replicating ordinary living environments in which ozone that would remain at low levels in such real-world environments would accumulate to more than .05 ppm in 24 hours.

2. Lack of rational basis for proposed regulation.

The rationale behind the regulation's ban on devices that achieve the acknowledged benefits of ozone at higher levels in unoccupied spaces is that some consumers may not follow instructions or heed warnings to use the devices only when the space is unoccupied.

This ban would treat indoor air cleaners in a way that is virtually unique among consumer products.

Consumers of every other potentially injurious but beneficial product (pesticides, lawn fertilizer, barbeque lighter, pharmaceuticals) are allowed to use that product so long as adequate warnings are given.

The ban is not justified. First, as is the case with many consumer products, ozone at excessive levels naturally produces its own warning when used to excess. In this case, the warning is in the form of a pungent odor and immediate discomfort that would cause the consumer to turn off the device or exit the premises.

Second, the statement of reasons concedes there are no epidemiological studies on indoor ozone exposure. To fill this void, it extrapolates from outdoor studies, where air also includes significant other pollutants not found in high concentration indoors.

Ecoquest urges the Board to consider, instead of a ban, an aggressive strategy to provide warnings - not just on the package and instruction manuals, but on the device itself, including a requirement that the seller of a device orally point out the warnings in all three places and that the purchaser sign a

statement indicating he or she has read and understood the warnings.

3. Testing issues.

The main problem with the proposed UL 867 protocol is that it will produce readings of more than .05 ppm that would not occur in actual residential, office or hospital environments because low level ozone in those environments is used up in the process of oxidizing airborne and surface microbes and organic compounds - producing some of the beneficial results cited above.

By using a small, stainless steel test chamber, the UL 867 test will detect ozone accumulation that would never happen in the real world environment. The test in effect imposes a "zero ozone" requirement instead of a real world "less than .05 ppm" requirement.

The effect will be to deprive consumers of beneficial low ozone air cleaning technologies, such as Ecoquest's Radiant Catalytic Ionization (RCI) technology, and their ability to combat infectious organisms such as e-coli, avian influenza and MRSA.

This unfortunate result can be avoided, while fully protecting consumers, by allowing manufacturers to use an alternate test protocol geared to real world conditions. An example of such a test protocol is attached as attachment 3.

4. The proposed regulation is inconsistent with language of AB 2276.

If the Legislature had authorized a ban on all devices exceeding the .05 ppm standard, I suppose we would all go quietly away. But AB 2276 is quite clear: it authorized regulations "to protect public health from ozone emitted by indoor air cleaning devices...used in occupied spaces" (Health & Safety Code section 4198(a). (Emphasis added.) That phrase is repeated in the digest of the Legislative Counsel.

In an exercise of definitional fiat, the proposed regulation obliterates the statute's clear limitation to devices "used in occupied spaces" by defining "occupied space" to mean "an enclosed space intended to be occupied by people for extended periods of time, e.g., houses, apartments, hospitals and offices." This definition renders a space "occupied" regardless of whether it is in fact occupied and thereby creates a ban on

the use of ozone technology in unoccupied residential, office or hospital settings.

This interpretation of "occupied space" is a radical departure from the ordinary meaning of the phrase and is contrary to the interpretation of "occupied" used elsewhere in California law.

Merriam-Webster's Collegiate Dictionary, Eleventh Edition, defines "occupy" as:

> **1** : to engage the attention or energies of
> **2 a** : to take up (a place or extent in space) <this chair is *occupied*> <the fireplace will *occupy* this corner of the room> **b** : to take or fill (an extent in time) <the hobby *occupies* all of my free time>
> **3 a** : to take or hold possession or control of <enemy troops *occupied* the ridge> **b** : to fill or perform the functions of (an office or position)
> **4** : to reside in as an owner or tenant

Merriam-Webster's defines "intended" as:

> **1** : to direct the mind on
> **2** *archaic* : to proceed on (a course)
> **3 a** : **SIGNIFY**, **MEAN** **b** : to refer to
> **4 a** : to have in mind as a purpose or goal : **PLAN** **b** : to design for a specified use or future

(Available online at http://www.m-w.com/.)

Based on dictionary definitions alone, the proposed definition means that an "occupied space" includes enclosed spaces that were *designed for*, or had the *purpose* or *goal* of, being *taken up*, *filled*, *controlled*, or *held in possession by* people for extended periods of time. The inclusion of the "intended to be" language would have the effect of stretching the definition of "occupied space" from something more akin to requiring actual presence into something that applies to virtually *all* enclosed spaces. This is due to the fact that there are few, if any, enclosed structures that were *not* designed for, or have the purpose or goal of being taken up, filled,

controlled, or held in possession by people.

Courts have generally understood the term "occupied" to mean something closer to "actual presence" than the proposed definition would permit. For example, the California Supreme Court has stated, "[T]here is always the likelihood there will be a second person present in an *occupied* vehicle. (By definition, there will *always be one person*.)" (*People v. Ochoa* (2001) 26 Cal.4th 398, 462, emphasis added.) As such, California courts understand "occupied" spaces as requiring *actual* presence of at least one person; not merely spaces that were designed for or have the purpose or goal of being occupied by people regardless of whether or not people are actually present.

Oppositely, the proposed regulation appears to twist the definition of "occupied space" into something closer to "inhabited space." For example, in *People v. Tabios* (1998) 64 Cal.App.4th 1, 10, the court described an "**inhabited dwelling** house" as "one in which persons reside and *where* ***occupants*** *are generally in or around the premises.*" (Emphasis added.) By including the phrase "intended to be" in the definition of "occupied space", the proposed regulation deviates from the judicial definition of "occupied" [at least one person (*Ochoa*)] and largely conforms to the judicial definition of "inhabited" [occupants are generally in or around the premises (*Tabios*)], which sounds closer to the regulation's phrase "…space intended to be occupied by people for extended periods of time."

The distinction might be largely inconsequential if the authorizing legislation, AB 2276, had empowered the Board to regulate ozone emissions in *inhabited* spaces. But that is *not* what the legislation authorizes the Board to do. It only authorizes the Board to regulate ozone emissions in *occupied* spaces, nothing less, nothing more.

California statutes further recognize that there is a difference between places that are *intended* be occupied, and those that are *actually* occupied. For example, Penal Code § 246 creates a felony for "[a]ny person who shall…discharge a firearm at an inhabited dwelling house, occupied building, occupied motor vehicle, occupied aircraft, inhabited housecar…or inhabited camper." Section 246 goes on to define "inhabited" as "currently being used for dwelling purposes, *whether occupied or not*." (Emphasis added.)

For our purposes, the implication of Section 246 is that

California law recognizes a distinct difference between places that were designed for, or have the purpose or goal of being occupied (*inhabited* dwelling house, *inhabited* housecar, *inhabited* camper), and places that are *actually* occupied (*occupied* building, *occupied* motor vehicle, *occupied* aircraft).

Any attempt to define the term "occupied space" as both space that is actually occupied and space that is intended to be occupied blurs the distinction and deprives the word "occupied" of any real significance. This would be a departure from the normal use of the word "occupied", as demonstrated in *Ochoa* and Penal Code Section 246; and would create inconsistency between the usage of "occupied" in the Penal Code (<u>actual</u> presence) and the Health and Safety Code as construed by the proposed regulation (<u>possible</u> presence).

There is no reason to think the Legislature meant the term "occupied" to be interpreted differently than in Section 246.

5. <u>The proposed Regulation is not consistent with workplace standards</u>.

The Federal Food and Drug Administration regulation, 21 CFR Section 801.415(d), indicates that the .05 ppm limit "does not affect" the present workplace threshold limit of ".10 parts per million of ozone exposure for an 8-hour-day exposure of industrial workers as recommended by the American Conference of Governmental Industrial Hygienists." This standard is reflected in the Cal OSHA workplace standard, a "permissible exposure limit" of .1 ppm (8 CCR section 5155), which also contains a "short term exposure limit" (15 minute time weighted average exposure which is not to be exceeded at any time during the work day) of .3 ppm.

The proposed regulation, which through the back door bans devices that could result in concentrations over .05 ppm, imposes a stricter requirement than contemplated in the federal regulation and trumps the Cal OSHA standard.

The Cal OSHA standard is also instructive as to the Legislature's intent on the question of whether the regulation applies to spaces <u>when they are unoccupied</u>.

8 CCR § 5155 contains the Dept. of Industrial Relations regulations on ozone levels in the workplace. Read as a whole, it becomes clear that Section 5155 does <u>not</u> seek to regulate air

contaminants except when employees are present and subject to exposure.

8 CCR § 5139 contains the purpose of Article 107 (8 CCR §§ 5139-5155), and it states, "Article 107 sets up minimum standards for the prevention of harmful exposure of employees to dusts, fumes, mists, vapors, and gases." (Emphasis added.) Subdivision (a) of Section 5155 contains the scope of application of the section. Paragraph (a)(1) states, "This section establishes requirements for controlling employee exposure to airborne contaminants…at all places of employment in the state." (Emphasis added.)

Subdivision (b), which contains Section 5155's definitions, also demonstrates that Section 5155 is only concerned with employee exposure to contaminants specifically, and not with regulating air contaminants generally. The "ceiling limit" is defined as "The maximum concentration of an airborne contaminant to which an employee may be exposed at any time." (Emphasis added.) The "eight-hour time weighted average concentration" (TWA) is defined as, "An employee's exposure, as measured…in Appendix A, to an airborne contaminant during a workday." (Emphasis added.) The "short term exposure limit" is defined as, "A 15-minute time-weighted average exposure which is not to be exceeded at any time…" (Emphasis added.)

Perhaps most dispositive is subdivision (c). Subdivision (c) contains the operative provisions of § 5155, which are set in terms of exposure limits, as opposed to generic air contamination limits. (Emphasis added.) Subdivision (c) sets a "permissible exposure limit," which caps the maximum employee exposure to airborne contaminants expressed as an eight-hour time-weighted average concentration (TWA). It also sets the "short term exposure limit" which caps the maximum employee exposure to airborne contaminants as expressed in a 15-minute TWA.

The most logical reading of these regulations is that they do not regulate the amount of air contaminants in the workplace when employees are absent; they only regulate the level of exposure to various contaminants that employees can be subjected to over the course of their work shift.

This position is further supported by the statutes that authorized the adoption of 8 CCR § 5155. Labor Code § 142.3 gives the Department of Industrial Relations general authority to adopt, amend, or repeal occupational health orders. Subdivision

(c) states, "Any occupational safety...order promulgated under this section shall prescribe...the forms of warning as are necessary to ensure that employees are apprised of all hazards to which they are exposed...[T]hese standards...shall provide for monitoring and measuring employee exposure...as may be necessary for the protection of employees..." (Emphasis added.)

Labor Code § 144.6 sets out the criteria to be considered by the Department of Industrial Relations when adopting standards concerning toxic materials or harmful physical agents. It states, "In promulgating standards...the board shall adopt that standard which most adequately assures, to the extent feasible, that no employee will suffer impairment of health or functional capacity even if such employee has regular exposure to a hazard regulated by such standard..." (Emphasis added.)

Again, the most logical reading of these authorizing statutes is that they only seek to empower the Department of Industrial Relations to adopt regulations that will limit employee exposure specifically, and not workplace air contaminants generally.

6. The proposed regulation is inconsistent with federal law.

Section 41986(a) of the Health and Safety Code, enacted by AB 2276, requires the state board to adopt regulations "consistent with federal law, to protect public health from ozone emitted by indoor air cleaning devices ... used in occupied spaces." (Emphasis added.) *See also section 4198 (e).[1]

The federal regulation declares that a device will be considered "adulterated and/or misbranded ... if it is used or intended for use under the following conditions:

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[1] "(e) It is the intent of the Legislature that this section be interpreted and applied in a manner that is consistent with federal law. The regulations adopted by the state board pursuant to this section shall be consistent with federal law. The state board may, to the extent a waiver is required, seek a preemption waiver from the federal government to authorize the state board to adopt regulations that are more stringent than federal law." (Emphasis added)

"(3) To generate ozone and release it into the atmosphere and does not indicate in its labeling the maximum acceptable concentration of ozone which may be generated (not to exceed 0.05 part per million by volume of air circulated through the devices) as established herein and the smallest area in which device can be used so as not to produce an ozone accumulation in excess of 0.05 part per million." (21 C.F.R. section 801.415(c)(3)). (Emphasis added.)

Read in the context of the standard in subsection (1), applicable to "enclosed space intended to be occupied by people for extended periods of time," the federal regulation recognizes a labeling or warning obligation for devices which are capable of exceeding the standard if not used properly. The proposed regulation goes beyond that regulatory framework, and is therefore inconsistent with it, by banning devices regardless of whether they are appropriately labeled and appropriate warnings are given.

7. The proposed regulation is not in compliance with the Administrative Procedures Act.

Under Government Code section 11349.1, the Office of Administrative Law is required to review proposed regulations to determine if they meet, among others, the following standards: authority and consistency. These terms are defined in Government Code section 11349:

"(b)'Authority' means the provision of law which permits or obligates the agency to adopt, amend, or repeal a regulation."

"(d)'Consistency' means being in harmony with, and not in conflict with or contradictory to, existing statutes, court decisions, or other provisions of law."

We have argued that the definition of "occupied space" is not authorized by AB 2276 and, in banning devices while used in unoccupied spaces, is not in harmony with the intent of that statute and in fact conflicts with it. It therefore renders the regulation in violation of the "authority" and "consistency" tests.

Furthermore, the provision of AB 2276 (Health and Safety Code section 41986(a)and (e)) which requires the board to adopt regulations "consistent with federal law" does not provide authority, as required by the Administrative Procedures Act, to

develop and adopt a regulation that is not consistent with federal law because it bans devices regardless of whether they are appropriately labeled or appropriate warning are given. Nor does such a regulation meet the consistency standard, because it is in conflict with, or contradictory to, the statute and the federal regulation.

8. Alternative proposal would protect consumers while preserving benefits.

As suggested above, we suggest the staff revise the regulation to include:

(1) Permission to develop an alternative test protocol replicating typical conditions of household, office or hospital environments; and

(2) Strict warning and labeling requirements to assure that consumers in both residential and commercial settings are fully informed that any device that could exceed the .05 ppm emissions concentration standard should not be used while the space is occupied. This should include a requirement that the dealer orally call these warnings to the purchaser's attention and obtain a signed statement from the purchaser that he or she received the oral briefing and understood it.

This approach would have three beneficial aspects:

- It would allow consumers the ability to obtain the benefits conceded by the regulation in the "industrial use" exception without having to hire expensive professional environmental remediation companies.

- It would treat consumers of air cleaning devices the same way we treat consumers of all other products that are safe when properly used but potentially dangerous when misused.

- It would narrow the market for buying non-conforming devices in other states and bringing them into California.

9. Conclusion.

This regulation on its face acknowledges benefits of ozone but limits them to "industrial use," is not based on epidemiological studies, is in conflict with legislative intent, which was to deal with "occupied" spaces, and would deny to consumers, including hospital patients threatened with infection, beneficial results of technology emitting very low ozone by using a test that is not performed under real-world conditions.

In the interest of achieving a regulation that does not exceed the legislative grant of authority and does not unnecessarily restrict the ability of California consumers to attack odors, smoke, mildew, bacteria and other contaminants in their own homes, we urge the Board to defer action on this regulation (the statutory deadline for which is December 31, 2008) and instruct staff to consider the above modifications.

We look forward to participating in further deliberations.

Sincerely,

Robert W. Naylor

Executive Summary
Kansas State University Testing
Biological Reduction through Photocatalysis and Ozone

Summary:

Testing has been performed at the Kansas State Food Science Institute in the Department of Animal Sciences & Industry, Kansas State University in Manhattan Kansas under the direction of Dr. James Marsden, Regent's Distinguished Professor of Meat Science. Kansas State is of America's foremost Universities for animal science and Dr. Marsden is known around the world as one of the top researchers and experts in food safety.

Ten of the most deadly forms of mold, fungi, bacteria and virus were subjected to a new and innovative Photocatalytic Reactor called Radiant Catalytic Ionization (RCI). These ten organisms were placed on a piece of stainless steel inside a test chamber and the RCI cell was turned on for 24 hours. Test results showed a 24-hour reduction ranging from 96.4% to 100%.

This testing validates the effectiveness and speed which RCI is able to treat the indoor environment using a natural process at safe levels of oxidation.

Discussion:

With most indoor airborne contaminants originating on surfaces, any efforts to control biological contamination in the indoor environment must address surfaces. Microorganisms such as Mold, Bacteria and Viruses thrive on surfaces in the presence of moisture, and for this reason the food industry has focused on controlling and eliminating pathogens in food contact areas.

Dr. Marsden has dedicated his life to improving food safety through understanding and controlling the spread of biological contamination. Marsden's research has recently focused on the use of advanced photocatalysis, a technology which develops oxidizers which actively reduce airborne and surface pathogens.

Ten microorganisms were chosen for analysis. Three samples of each microorganism were prepared and placed on a stainless steel surface, allowing analysis at 2 hours, 6 hours and 24 hours of exposure. The test organisms included:

- Staph *(Staphylococcus aureus)*
- MRSA *(Methycillin Resistant Staphylococcus aureus)*
- E-Coli *(Escherichia coli)*
- Anthrax family (*Bacillus* spp.)
- Strep *(Streptococcus* spp.)

- *Pseudomonas aureuginos*
- *Listeria monocytogenes*
- *Candida albicans*
- Black Mold *(Stachybotrys chartarum)*
- Avian Influenza H5N8

These organisms were subjected to air which was circulating through a proprietary photo catalytic reactor called Radiant Catalytic Ionization or RCI. Multiple parameters were monitored including temperature and humidity. The UV Lamp in the photo catalytic cell was positioned in the supply duct to insure there was no effect from the UVGI produced by the lamp. Understanding that Ozone is one of the oxidizers produced in this Photocatalytic process and the health concerns from exposure to excessive levels of ozone, the ozone level was monitored and never exceeded 20 parts per billion, well below EPA maximum level for continuous exposure.

In addition to the test chamber treated with RCI and the corona discharge ozone generator, a control chamber was set up to account for natural decay of the test organisms. Because some biological pathogens die-off on their own when exposed to air, any reputable study must account for such reductions. The test results shown in the report are the reductions in viable organisms with respect to the control sample.

The test results were astounding. After 24 hours of exposure the nine organism's viability was reduced between 96.4% and 100%. It should be noted that the double blind study accounted for natural decay. What was even more surprising to the researchers was how fast RCI reduced the pathogens. At the 2-hour sample the average reduction was well over 80%. At the 6-hour sample the average reduction was well over 90%.

An additional test was performed using a corona discharge ozone generator (Breeze AT) against *Candida albicans* at 50 parts per billion (the level deemed safe by the US EPA, OSHA and other international health & safety organizations). This test showed the ability of safe levels of ozone to reduce microbial contamination. It should be noted that although results showed the effectiveness of this safe level of ozone, it also showed that ozone alone is not as effective as the multiple oxidizers produced by the advanced Photocatalytic Oxidation device called RCI. One of the multiple oxidizers RCI produces is ozone but at an ozone level two to five times lower than using ozone alone.

This test report has been peer reviewed and is now scheduled for publication.

Efficacy of EcoQuest Radiant Catalytic Ionization Cell and Breeze AT Ozone Generators at Reducing Microbial Populations on Stainless Steel Surfaces

M. T. Ortega, L. J. Franken, P. R. Hatesohl, and J. L. Marsden
Department of Animal Sciences & Industry
K-State Food Science Institute
Kansas State University, Manhattan, KS 66506

Summary and Implications

This study was conducted to determine the potential use of EcoQuest Radiant Catalytic Ionization Cell for the inactivation of *Escherichia coli*, *Listeria monocytogenes*, *Streptococcus* spp., *Pseudomonas aeruginosa*, *Bacillus* spp., *Staphylococcus aureus*, *Candida albicans*, and *S. chartarum*, on stainless-steel surfaces at diverse contact times in a controlled airflow cabinet. In addition, the EcoQuest Breeze AT Ozone generator was evaluated under the same conditions for the inactivation of *Candida albicans* and *S. chartarum*. Better disinfection technologies for food contact surfaces are needed to control food borne pathogens in processing environments. Ozone technologies have only recently been approved for use on food contact surfaces. This study evaluated the application of gaseous ozone and other oxidative gases on stainless-steel surfaces against the microorganisms listed above. Both technologies reduced populations of all microorganisms tested on stainless-steel surfaces by at least 90% after 24 h exposure. The Radiant Catalytic Ionization Cell was more effective at reducing microbial counts for shorter exposure times than was the Breeze AT Ozone Generator.

INTRODUCTION

The food and beverage industries face a number of issues when it comes to producing a safe, wholesome product. Foodborne pathogens such as *E. coli* 0157:H7, *Listeria moncytogenes,* and *Salmonella* spp. have been a growing concern throughout the years. Processors are also concerned about spoilage microorganisms that shorten shelf life and cost companies millions every year in spoiled product. Industries impacted include the meat, seafood, poultry, produce, baking, canned foods, dairy, and almost all other segments of the market.

The U.S. Department of Agriculture estimates the costs associated with food borne illness to be about $5.5 to $22 billion a year. This doesn't include the billions lost every year due to spoiled product, which must be disposed of or sold as a lesser valued product. Better disinfection and microbiological control measures are needed in almost every area of the food industry.

As a disinfectant, ozone has a tremendous ability to oxidize substances. It's thousands of times faster than chlorine and disinfects water three to four times more effectively. As it oxidizes a substance ozone will literally destroy the substance's molecule. It can oxidize organic substances such as bacteria and mildew, sterilize the air, and destroy odors and toxic fumes. Ozone has been used by industry for many years in numerous applications such as odor control, water purification, and as a disinfectant (Mork, 1993). Recent government approval of ozone for use with foods and food contact surfaces has opened the door to many more exciting possibilities for this technology.

In June 2001, the U.S. Food and Drug Administration approved the use of ozone as a sanitizer for food contact surfaces, as well as for direct application on food products. Prior to that time, chlorine was the most widely used sanitizer in the food industry. Ozone may be a better choice for disinfection of surfaces than chlorine. Chlorine is a halogen-based chemical that is corrosive to stainless steel and other metals used to make food-processing equipment. Chlorine can also be a significant health hazard to workers; when mixed with ammonia or acid cleaners, even in small amounts, a toxic gas can form.

Chlorine is a common disinfect used in meat processing and is effective and safe when used

at proper concentrations. However, chlorine is far less effective than ozone and can result in the production of chloroform, carbon tetrachloride, chloromethane, and tri-halomethanes. In contrast, ozone leaves no residual product upon its oxidative reaction.

An important advantage of using ozone in food processing is that the product can be called organic. An organic sanitizer must be registered as a food contact surface sanitizer with the U.S. Environmental Protection Agency (EPA). Ozone has such an EPA registration, and is approved by FDA as a sanitizer for food contact surfaces and for direct application on food products.

Ozone has become more accepted for use in food processing in recent years and is being used in more than just surface applications. A recent U.S. FDA recommendation (2004) stated that "ozone is a substance that can reduce levels of harmful microorganisms, including pathogenic *E. coli* strains and *Cryptosporidium*, in juice. Ozone is approved as a food additive that may be safely used as an antimicrobial agent in the treatment, storage, and processing of certain foods under the conditions of use prescribed in 21 CFR 173.368."

MATERIALS AND METHODS

Preparation of Cultures:

The following bacteria and fungi cultures were used for the study: *Bacillus globigii* (ATCC # 31028, 49822, 49760), *Staphylococcus aureus* (ATCC # 10832D, 25178, 11987), *Candida albicans* (ATCC # 96108, 96114, 96351), *Stachybotrys chartarum* (ATCC # 18843, 26303, 9182), *Pseudomonas aeruginosa* (ATCC# 12121, 23315, 260), *Escherichia coli* (ATCC# 27214, 19110, 67053), *Streptococcus pneumoniae* (ATCC# 27945, 29514, 10782), and *Staphylococcus aureus* - methicillin resistant (ATCC# 33591). Cultures were revived using ATCC recommended instructions.

Bacteria, yeast, and mold strains were individually grown in tripticase soy broth (TSB; Difco Laboratories, Sparks, MD) and YM broth (Difco Laboratories), respectively, to mid-exponential phase followed by a wash and re-suspension in 0.1% peptone water. The cultures were combined by specie type to ca. 10^8 CFU/ml.

Preparation of Samples and Ozone Treatment:

The microbial species used to validate the ozone generators were tested as microbial cocktails inoculated onto 6.3 x 1.8 cm on #8 finish stainless-steel coupons (17.64 cm^2 double sided area). Four stainless steel coupons were dipped per microbial inoculum and vortexed 15 sec to optimize microbial dispersion. Using sterile binder clips, stainless steel coupons were suspended on a cooling rack contained inside a laminar flow cabinet for 1 h to dry. The initial microbial populations attached to the stainless steel coupons ranged from 5 to 6 log CFU/cm^2. The inoculated stainless steel coupons were transferred to a controlled airflow test cabinet (Mini- Environmental Enclosure, Terra Universal, Anaheim, CA) at 26°C and 46% relative humidity (ambient conditions), and treated using the EcoQuest Radiant Catalytic Ionization Cell for 0, 2, 6, and 24 h. The EcoQuest Breeze AT Ozone generator was evaluated separately for treatment periods of 0, 2, 6 and 24 h. Ozone levels were monitored throughout the study (Model 500, Aeroqual, New Zealand).

Sampling:

At the end of the ozone contact time the coupons were vortexed for 30 sec in 30 ml of 0.1% peptone water. Samples inoculated with bacterial cultures were serially diluted, plated on tripticase soy agar (TSA; Difco Laboratories), and incubated for 24 h at 35°C. After preparing serial dilutions, samples inoculated with yeast were plated on potato dextrose agar (PDA; Difco Laboratories) and those inoculated with mold cultures were plated on cornmeal plates. Both PDA and cornmeal plates were incubated 30°C for 5 days. Following incubation, data for each microorganism were reported as colony-forming units per square centimeter (CFU/cm^2).

RESULTS AND DISCUSSION

Reductions in microbial populations on #8 finish stainless steel coupons following 0, 2, 6, and 24 h exposure to the EcoQuest Radiant Catalytic Ionization Cell are presented in Figure 1. Exposure to ozone levels of 0.02 ppm for 2 h reduced all microbial populations tested by at least 0.7 log CFU/cm^2. Longer exposure times resulted in greater reductions, with the greatest reductions found after 24 h exposure. After 24 h exposure, mean microbial reductions for each organism were as follows: *S. aureus* (1.85 log CFU/cm^2), *E. coli* (1.81 log CFU/cm^2), *Bacillus* spp. (2.38 log CFU/cm^2), *S. aureus* met^r (2.98 log CFU/cm^2), *Streptococcus* spp. (1.64 log CFU/cm^2), *P. aeruginosa* (2.0 log CFU/cm^2), *L. monocytogenes* (2.75 log CFU/cm^2), *C. albicans* (3.22 log CFU/cm^2), and *S. chartarum* (3.32 log CFU/cm^2).

Reductions in microbial populations following treatment of stainless steel coupons with the EcoQuest Breeze AT Ozone generator are shown in Figure 2. Reductions of at least 0.2 and 0.4 log CFU/cm^2 were observed after 2 and 6 h of ozone exposure, respectively. After 24 h exposure, mean reductions for *C. albicans* and *S. chartarum* were 1.48 and 1.32 log CFU/cm^2, respectively.

The EcoQuest Radiant Catalytic Ionization Cell and EcoQuest Breeze AT Ozone generators reduced microbial populations on stainless steel surfaces within 2 h under ambient conditions, with greater reductions associated with longer exposure times. The Radiant Catalytic Ionization Cell was more effective than the Breeze AT Ozone Generator at reducing microbiological populations at shorter exposure times of 2 and 6 hours. This study demonstrated that ozone gas has the potential to be an effective surface disinfectant for use in food processing applications. Testing is currently ongoing to evaluate non-treated controls. Phase II of the project, scheduled to be completed by the end of this year, will evaluate the effectiveness of the system for eliminating airborne contamination using the same microorganisms and oxidative technologies.

REFERENCES

Mork, D.D. 1993. *Removing sulfide with ozone.* Water Contamination & Purification. 34-37.

U.S. Food and Drug Administration [FDA] 2004. *Recommendations to processors of apple juice or cider on the use of ozone for pathogen reduction purposes.* Accessed 27 July 2005 at http://www.cfsan.fda.gov/~dms/juicgu13.html.

Fig. 1 Decontamination of highly polished stainless steel surfaces using the *EcoQuest Radiant Catalytic Ionization Cell*

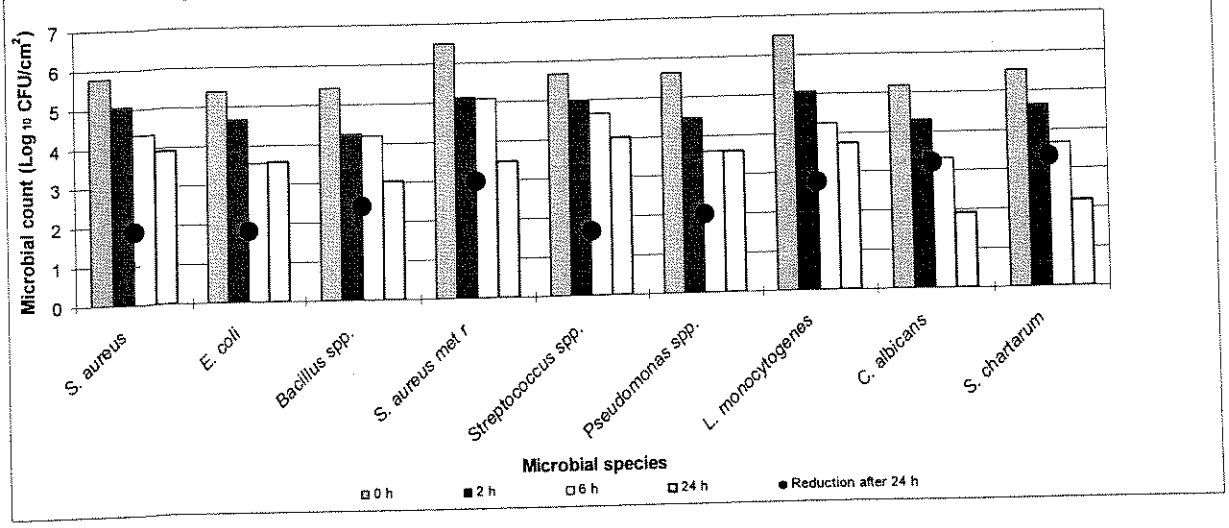
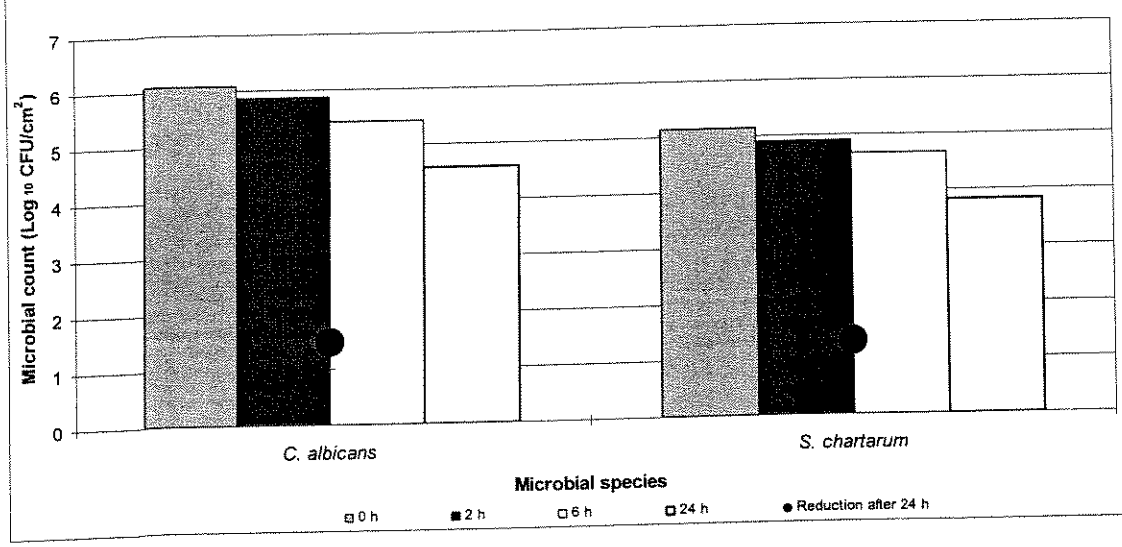


Fig 2. Ozone decontamination on highly polished stainless steel surfaces using the *EcoQuest Breeze AT Ozone* generator



Executive Summary
University of Cincinnati Test Results
EcoQuest Fresh Air Technology

Summary:
Testing of EcoQuest's Fresh Air Technology has been performed over an 18 month period at the Center for Health-Related Aerosol Studies in the Department of Environmental Health at the University of Cincinnati under the direction of Dr. Sergey Grinshpun, Professor.

Testing included two technologies used in the Fresh Air system; Negative Ionization and Photocatalysis (an innovative proprietary Photocatalytic Reactor called Radiant Catalytic Ionization).

Each technology was evaluated independently:

- Fresh Air Ionization technology was able to reduce airborne particles from indoor air by up to 250 times over natural decay (gravity)
- Fresh Air Radiant Catalytic Ionization (RCI) was able to inactivate approximately 90% of airborne microorganisms in less than 60 minutes. The microorganisms tested were MS2 Virus and B. Subtilis (used as a surrogate for Anthrax).

Dr. Grinshpun also concluded that the combination of the two technologies provided a much more significant reduction of airborne biocontaminants than either of the two technologies working independently. This conclusion validates the synergistic effect of Fresh Air's multiple technology strategy.

About the Author:
Dr. Grinshpun is one of the most respected scientists in this important field of Aerosol Studies. Through his career, Dr. Grinshpun authored or co-authored about 390 scientific publications, including 120+ original articles in peer-reviewed journals, 90 book chapters and full proceeding papers, as well as about 180 conference abstracts. He has served as a reviewer, panel member or consultant to several federal agencies and professional associations nationally and internationally as well as for major companies and research institutions. He has also served on the Editorial Boards of four journals with international circulation. Dr. Grinshpun's accomplishments in aerosol research were recognized through the International Smoluchowski Award from the European Aerosol Assembly (1996, The Netherlands), the AIHA Outstanding Aerosol Paper Award (1997, USA), and the David L. Swift Memorial Award (2001, USA). He also received two John M. White Awards from AIHA (1997, 1998, USA) for his contribution to respiratory protection studies and Best Practice Award from the US Department of HUD (2000) for his studies of leaded particles in indoor air.

About the University:

University of Cincinnati is one of America's foremost Universities for Environmental Health.

About the Testing:
The testing by Dr. Grinshpun and his team focused on controlling aerosol contaminants in the indoor air through the application of two technology strategies:

1. Particle Concentration Reduction due to Unipolar Ion Emission
2. Microbial Inactivation due to the Photocatalytic reaction promoted by a Photocatalytic process called RCI (Radiant Catalytic Ionization)

The Results:
The paper concludes that the utilization of two mechanisms; ionization and oxidation, provide for significantly less exposure to potentially harmful contaminates in the air than either mechanism independently.

This conclusion is supported by showing ion induced air cleaning removes about 80% of viable airborne pathogens from a room air in 30 min, and the RCI-induced photoxidation inactivates about 90% of the remaining airborne microorganisms. The combination of both mechanisms resulted in an overall aerosol exposure reduction after 30 min by a factor of about 50, or an overall reduction/inactivation of approximately 98%.

The two active contaminants evaluated were:

1. *B. subtilis* bacteria
2. MS2 virions

Publication:
This research was peer reviewed and published in the journal of Environmental Science and Technology, January 2007, pages 606-612.

Environ. Sci. Technol. 2007, 41, 606–612

Control of Aerosol Contaminants in Indoor Air: Combining the Particle Concentration Reduction with Microbial Inactivation

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An indoor air purification technique, which combines unipolar ion emission and photocatalytic oxidation (promoted by a specially designed RCI cell), was investigated in two test chambers, 2.75 m^3 and 24.3 m^3, using nonbiological and biological challenge aerosols. The reduction in particle concentration was measured size selectively in real-time, and the Air Cleaning Factor and the Clean Air Delivery Rate (CADR) were determined. While testing with virions and bacteria, bioaerosol samples were collected and analyzed, and the microorganism survival rate was determined as a function of exposure time. We observed that the aerosol concentration decreased ~10 to ~100 times more rapidly when the purifier operated as compared to the natural decay. The data suggest that the tested portable unit operating in ~25 m^3 non-ventilated room is capable to provide CADR-values more than twice as great than the conventional closed-loop HVAC system with a rating 8 filter. The particle removal occurred due to unipolar ion emission, while the inactivation of viable airborne microorganisms was associated with photocatalytic oxidation. Approximately 90% of initially viable MS2 viruses were inactivated resulting from 10 to 60 min exposure to the photocatalytic oxidation. Approximately 75% of viable *B. subtilis* spores were inactivated in 10 min, and about 90% or greater after 30 min. The biological and chemical mechanisms that led to the inactivation of stress-resistant airborne viruses and bacterial spores were reviewed.

Introduction

Exposure to respirable airborne particles and microbial agents may cause various health problems. Numerous techniques have been developed to reduce the exposure to indoor particles. Aerosol control in confined, poorly ventilated spaces, when the air exchange with filtration cannot be successfully applied, represents a particular challenge. Another challenge is to decrease the indoor concentration of specific airborne contaminants, e.g., viable biological particles. While some indoor air purification techniques aim solely at the aerosol concentration reduction, others are designed to inactivate viable bioaerosols (e.g., viruses, bacteria, and fungi).

Some commercial air cleaners generate excessive ozone (either as a primary biocidal agent or as a bi-product); these devices have raised public health concerns (*1*). Among various guidelines for ozone exposures, the following thresholds have been specified for occupational environments: 0.2 ppm for 2 h (*2*), 0.05–0.10 for 8 h (*2*), 0.1 ppm for 8 h (*3*), and 0.05 ppm for instantaneous (no time limit specified) exposure (*4*). For comparison, the outdoor air standard is 0.08 ppm for 8 h (*5*). Ozone generators can inactivate viable microorganisms; however, the inactivation occurs at concentrations significantly exceeding health standards (*6, 7*).

Photooxidation involving UV radiation and TiO_2 as a photocatalyst has been applied for gas-phase detoxification of organic contaminants (*8, 9*) and for inactivating microorganisms in water (*10–12*). Some effort has been made to explore its application for air cleaning inside a closed-loop system (*13, 14*). The investigators reported significant photocatalytic inactivation of stress-resistant *Serratia marcesens* that occurred when aerosolized bacteria circulated in a closed-loop duct equipped with a TiO_2 filter for a relatively long period of time. Pal et al. (*15*) found similar effect for *Escherichia coli, Microbacterium* sp., and *Bacillus subtilis*; Keller et al. (*16*) reported considerable inactivation of airborne *E. coli* passing through a photoreactor coated with TiO_2 film. The biocidal effect of the photocatalytic oxidation can be attributed to photogenerated valence-band holes, hydroxyl radicals, hydrogen peroxide, and other reactive oxygen species. Lin and Li (*17*) tested the viability change in airborne bacteria and fungi exposed to photooxidation inside a small photoreactor for a very short time, on the order of a second. No significant decrease in the colony forming unit (CFU) count was observed during such a short time.

To our knowledge, no data are available on the effectiveness of portable UV/TiO_2-based air purifiers to inactivate viable airborne microorganisms in indoor air environments. These data are needed to assess the feasibility of photocatalytic oxidation for air purification in residential and occupational settings. Furthermore, for hybrid air purifiers, which involve several air cleaning mechanisms, no sufficient information is available to differentiate their particle removal efficiency and the biocidal capabilities, which both aim at reducing the bioaerosol exposure in indoor air.

In this study, we investigated a novel air purification technique that combines different aerosol/bioaerosol control mechanisms: unipolar ion emission and photocatalytic oxidation promoted by the "radiant catalytic ionization (RCI)" technique. Unipolar ion emission has been shown earlier to reduce the particle concentration in indoor air (*18–20*), but no scientific data are available on the efficiency of the hybrid-type technique.

Experimental Section

The indoor air purification process was investigated in the experimental facility shown in Figure 1. The particle removal was determined by measuring the concentration of challenge aerosols size-selectively in real-time. When testing with viable bioaerosols, the microorganism survival rate was also determined. The experimental protocols validated in our previous studies (*18, 19, 21*) were adopted. The experiments were conducted when a freestanding hybrid air purifier was

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10.1021/es061373o CCC: $37.00 © 2007 American Chemical Society
Published on Web 12/05/2006

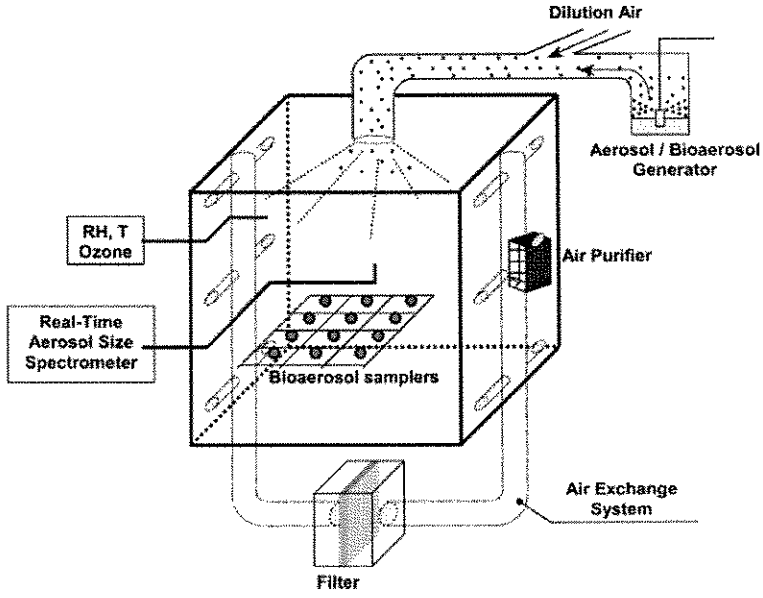


FIGURE 1. Experimental setup.

operating inside the chamber and when it was turned off. The challenge aerosol was generated from a liquid suspension using a Collison nebulizer (BGI Inc., Waltham, MA) and charge-equilibrated by passing through a 10-mCi Kr^{85} charge equilibrator (3M Company, St. Paul, MN). After being mixed with clean, HEPA-filtered air at a specific temperature (T = 24–26 °C) and relative humidity (RH = 21–30%), the aerosol entered the chamber. Following a 10–15-minute adjustment period established to achieve a uniform aerosol concentration pattern, the experiment began ($t = 0$).

In most of the tests, the aerosol concentration, C, and particle size distribution, $\Delta C/\Delta\log(d)$, were measured with an electrical low-pressure impactor (ELPI, TSI Inc./Dekati Ltd, St. Paul, MN), which utilizes the cascade impaction principle and also has a direct-reading capability to determine the concentration of particles of different aerodynamic sizes in 12 channels (each channel = impaction stage), from 0.041 to 8.4 μm (midpoint). When the experiments were conducted with viral aerosol that included particles smaller than the lower limit of the ELPI, we used a wide-range particle spectrometer (WPS; MSP Inc., Shoreview, MN). The WPS is a high-resolution real-time instrument combining differential mobility analysis, condensation particle counting, and laser light scattering to measure the diameter and number concentration of aerosol particles ranging from 10 nm to 10 μm.

For every measured particle size, d, the aerosol concentration at $t = 0$ was set to exceed the background level (obtained before the challenge aerosol was generated) by about 100-fold. First, the natural concentration decay was characterized by recording $C_{natural}$ (d, t) every 10 s with the ELPI and every 2.5 min with the WPS. Subsequently, the test aerosol was generated and mixed in the chamber again to reach the same initial concentration level. At $t = 0$, the air purifier was turned on and the concentration C_{AP} (d, t) was monitored during and up to 120 min (or until the particle count decreased below the limit of detection). To quantify the efficiency of the particle removal exclusively due to the air purifier operation, the Air Cleaning Factor (ACF) was determined size-selectively as a function of time:

$$\mathrm{ACF}(d, t) = \frac{C_{\mathrm{natural}}(d, t)}{C_{\mathrm{AP}}(d, t)} \tag{1}$$

In addition, the overall particle removal rate was calculated as

$$\lambda(d, t) = \frac{1}{t}\ln\left[\frac{C(d, t=0)}{C(d, t)}\right], \tag{2}$$

and the particle removal rate (exclusively due to air purifier) was defined following the first-order kinetics as

$$\mathrm{PRR}(d, t) = \frac{1}{t}\ln\left[\frac{C_{\mathrm{AP}}(d, t=0)}{C_{\mathrm{AP}}(d, t)}\right] - \frac{1}{t}\ln\left[\frac{C_{\mathrm{natural}}(d, t=0)}{C_{\mathrm{natural}}(d, t)}\right] \tag{3}$$

In case C_{AP} (d, $t = 0$) = $C_{natural}$ (d, $t = 0$),

$$\mathrm{PRR}(d, t) = \frac{1}{t}\ln[\mathrm{ACF}(d, t)] \tag{4}$$

This was needed to determine the Clean Air Delivery Rate (CADR), which, according to the ANSI/AHAM (American National Standards Institute/Association of Home Appliance Manufacturers) standard, is defined as

$$\mathrm{CADR}(d, t) = V \times \mathrm{PRR}(d, t)\ [\mathrm{m}^3/\mathrm{h}] \tag{5}$$

The CADR concept allows for comparison of air cleaning efficiencies of a freestanding air purifier and a closed- loop ventilation/air-filtration system in an air volume V (note that PRR is a function of V).

Two nonbiological challenge aerosols, NaCl and smoke, were used to study the particle removal by the air purifier. The generated particles were primarily in the size range of 0.02–2.0 μm, which includes ultrafine and fine fractions and represents most of the known viruses and bacteria. MS2 virus and *Bacillus subtilis* bacterial spores were the main biological challenge aerosols. Selected experiments were performed with *Pseudomonas fluorescens* bacteria.

MS2 bacteriophage, a 27 nm tailless non-enveloped icosahedral RNA-coliphage, relatively stable against environmental stress, has been used in the past as a simulant of most mammalian viruses, and it is known as an indicator for enteric viruses (*22–26*). Stock suspension of MS2 virus was prepared by adding 9 mL of Luria–Bertani broth to freeze-dried phage vial (ATCC 15597-B1). This suspension was

filtered using a membrane filter of 0.2 μm porosity and serially diluted so that the nebulizer suspension had 10^8–10^9 PFU/mL (PFU = plaque forming unit). MS2 phage titer was determined by following a modified plaque assay protocol of Adams (*27*); *Escherichia coli* (ATCC 15597, strain C3000) was used as the host organism.

B. subtilis is a gram-positive spore-forming bacterium with rod-shaped spores of approximately 0.7–0.8 μm in width and 1.5–1.8 μm in length (*28*). *B. subtilis* spores have previously been used in laboratory studies as a surrogate of environmentally resistant, pathogenic bacteria (*29–31*). Freeze-dried bacterial spores of *B. subtilis* (obtained from the U.S. Army Edgewood Laboratories, Aberdeen Proving Ground, Maryland) were activated at 55–60 °C for 25 min and then washed two times with sterile deionized water by vortexing followed by centrifugation at 7000 rpm for 7 min at room temperature. The total bacterial concentration in suspension was adjusted to 10^8–10^9 per mL using a hemacytometer. The viable bacteria were enumerated by cultivating on trypicase soy agar (TSA) media at 30 °C for 18 h; the viable (culturable) concentration in the nebulizer suspension was of the same order of magnitude as the total concentration, i.e., 10^8–10^9 CFU/mL (CFU = colony-forming unit). *P. fluorescens* bacteria (used in selected tests) are relatively sensitive to environmental stresses. Prior to aerosolization, vegetative cells of *P. fluorescens* (ATCC 13525) were cultured in trypticase soy broth at 28 °C for 18 h and washed similarly as *B. subitilis* spores.

When testing with biological particles, air samples were collected using Button Samplers (SKC Inc., Eighty Four, PA) equipped with gelatin filters (SKC Inc.) and operated at a flow rate of 4 L/min for 5 min. Eight Button Samplers were utilized in each test generating one blank, one background sample, three samples taken at $t = 0$, and the other three taken at a specific time interval; four time intervals were tested: t = 10, 15, 30, and 60 min. Additional selected experiments were performed by using a BioSampler (SKC Inc. Eighty Four, PA) to collect *P. fluorescens* and *B. subtilis*. The BioSampler efficiently collects viable bacteria (*29*) while the liquid medium minimizes the desiccation stress. As its cutoff size is too high to efficiently sample small MS2 virions, the BioSampler was not used as an alternative to gelatin filters for collecting MS2 virus.

The samples were analyzed for viable airborne virions (PFU) and bacteria (CFU) to quantify the percentages of those survived over time t. These were obtained with and without operating the air purifier. Our preliminary tests showed that the air purifier's operation considerably reduces the total bioaerosol concentration in the chamber due to ion emission. Therefore, the ion emitter was temporarily disabled in the hybrid unit when testing virus and bacteria inactivation to ensure sufficient number of microorganisms for determining the viable count at the end of the test.

An aliquot of 200 μL of dissolved gelatin filter extract was used for plaque assay to determine the number of airborne active (viable) virions (PFU/cm^3). Similarly, extract was cultivated on TSA plates to obtain the airborne concentration of viable bacteria (CFU/cm^3).

Additional testing was initiated to examine whether the biocidal effect of the air purifier took place indeed in the aerosol phase (and not after microorganisms were collected on filters). For this purpose, aerosolized microorganisms were collected on eight gelatin filters during 5 min in the chamber without air purifier. Four filters were analyzed for viable microorganisms immediately after this test, while the other four were exposed to the air purifier in the chamber for 10, 15, 30, and 60 min and then analyzed. The comparison of two sets allowed examining if the microorganism inactivation occurred on filters during the collection process.

The ozone level and the air ion concentration were monitored in real-time in the chamber using an ozone monitor (PCI Ozone & Control Systems, Inc., West Caldwell, NJ) and an air ion counter (AlphaLab Inc., Salt Lake City, UT), respectively. The air temperature in the test chamber was 24 ± 2°C and the relative humidity ranged from 22 ± 2% to 28 ± 2% as monitored with a thermo/hygrometer pen (Fischer Scientific Co., Pittsburgh, PA).

The purifier prototype (Ecoquest International Inc., Greeneville, TN) used in the study utilized an ion emitter and a specially designed RCI cell. The former produces negative ions into indoor air, where they are acquired by aerosol particles. It is important to note that this method is different from air cleaning by charging particles at the entrance of the purifier and subsequently collecting them on metal electrodes by electrostatic precipitation. The RCI cell features a flow optimized target structure comprising matrices of elongated tubular elements made of polycarbonate and arranged in a parallel orientation on opposite sides or alternatively on four sides of a broad-spectrum UV light source. The UV lamp utilizes argon gas with mercury and carbide filaments with a spectral output between 100 and 367 nm. Besides, a coating was applied to the target structure of the cell comprising hydrophilic properties and containing the following grouping of materials: titanium dioxide, rhodium, silver, and copper. As a result, a photocatalytic oxidation forms reactive species, such as hydroxyl radicals, valence-band holes, superoxide ions, and hydrogen peroxides.

The tests were conducted in two indoor test chambers, including a large walk-in chamber (24.3 m^3) that simulated a residential room and a smaller chamber (2.75 m^3) that simulated a confined space (e.g., bathroom, small office area, or automobile cabin). The particle removal was investigated in both chambers, whereas the bioaerosol viability tests were performed in the smaller chamber that was made of stainless steel and allowed bio-decontamination. The air purifier was tested in non-ventilated chambers (no air exchange) as it is known that portable air cleaners are primarily beneficial in poorly ventilated spaces (*20, 21*). Air exchange was introduced only when testing the closed-loop ventilation/air-filtration system equipped with an HVAC filter to compare its performance to that of the portable air purifier in terms of CADR. The ventilation/air-filtration system was also deployed to clean the test chamber between experiments. In most of the tests, the air purifier operated in the corner of the chamber, facing the center. A separate experiment was carried out to examine whether its location and orientation affected the ACF.

Results and Discussion

Particle Removal from Air. Figure 2 shows the evolution of the concentration and particle size distribution of NaCl aerosol when the air purifier operated in the large test chamber. As seen from this example, the aerosol concentration of 0.1 μm particles decreased by a factor of 28 in 1 h and by a factor of about 250 in 2 h; the corresponding decreases for 1 μm particles were approximately 10- and 50-fold. When testing with smoke particles, the aerosol concentration decreased even more rapidly. The above levels of the aerosol concentration reduction are considerably greater than those predicted by either tranquil or stirred natural decay models (*32*). This result was obtained when both the air ion emitter and the RCI cell operated in the unit. Interestingly, statistically the same particle reduction effect ($p > 0.05$) was observed when the RCI cell was turned off and only the ion emitter operated. The latter finding provides the evidence that the particle removal was achieved as a result of unipolar ion emission but not due to photocatalytic reactions.

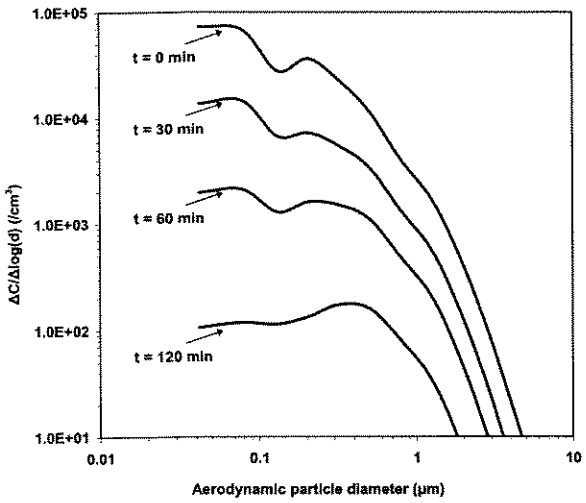


FIGURE 2. Particle concentration and size distribution of NaCl aerosol as measured with the ELPI in the 24.3 m³ chamber with the air purifier operating facing the chamber's center at 1.7 m from the measurement point. No ventilation in the chamber. The initial total aerosol concentration = 1.50 × 10⁵ /cm³.

This finding agrees with previously published data on the effect of unipolar air ionization on the airborne concentration (*18*–*21*). The air purification is particularly efficient at higher initial aerosol concentrations (> 10^4 particles/cm³) that ensure adequate interaction between the air ions and aerosol particles. As mentioned above, the effect is expected to be much more pronounced in non-ventilated environments than in ventilated ones.

The aerosol reduction was especially high for the particles of $d \leq 0.3$ μm. E.g., when the air purifier with an ion output of ~10^{12} e/sec continuously operated in a corner of the 24.3-m³ chamber facing the center for 2 h, ACF reached ~30–70 for $d = 0.08$–0.3 μm and ~13–16 for $d = 0.8$–2 μm (in the tests conducted with NaCl and smoke as challenge aerosols). The same ACF levels may be achieved more rapidly in indoor environments of smaller volumes and slower in larger spaces. The experimental trends agree with the ion-induced aerosol removal model (*20*).

The ACF was found to depend not only on the operation time and the particle size but also on the location/orientation of the purifier in the chamber. For example, a corner location facing the center of the room was found preferable as opposite to the orientation facing the wall. The difference in ACF obtained for the center and corner locations was significant and increased with the operation time. The shaded area in Figure 3 presents the ion-induced Air Cleaning Factor when the particle size-selective data were integrated over the measured sizes of NaCl particle up to 2.5 μm and averaged over the three selected locations/orientations in the 24.3-m³ chamber: in the corner facing the center, in the center, and at 80 cm from the wall facing it.

Figure 4 presents the CADR values achieved by operating the tested air purifier for five selected sizes of NaCl and smoke particles acting as aerosol contaminants in the non-ventilated 24.3 m³ chamber. The CADR ranges approximately from 42.1 ± 0.1 to 62.1 ± 1.8 m³/h for NaCl particles of $d = 0.04$–1.99 μm, and from 72.4 ± 0.9 to 115.5 ± 10.8 m³/h for smoke particles of the same size range. The difference may be attributed to different ability of NaCl and smoke particles to acquire electric charges from air ions, which results in their different mobilities and subsequently different migration velocities. The above explanation seems valid given that unipolar ion emission was shown to be the major mechanism causing the aerosol particle concentration reduction.

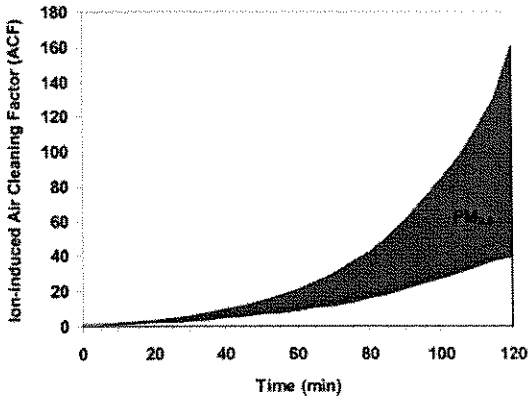


FIGURE 3. The ion-induced Air Cleaning Factor (ACF) for $PM_{2.5}$ NaCl as measured with the ELPI and integrated for different locations and orientations of the air purifier in the 24.3 m³ chamber. No ventilation in the chamber. The initial $PM_{2.5}$ aerosol concentration = (0.356–1.50) × 10^5/cm³.

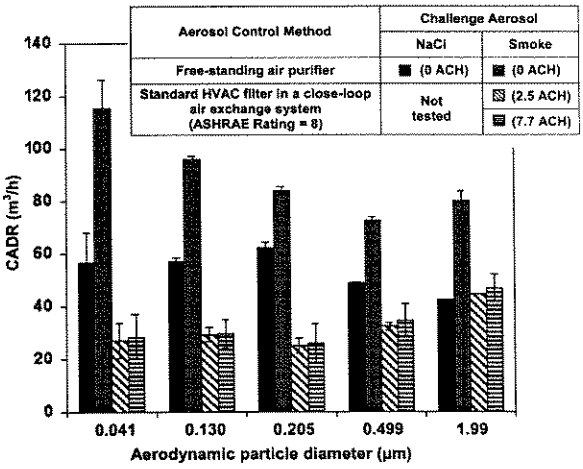


FIGURE 4. Clean Air Delivery Rate (CADR) determined for the NaCl and smoke aerosols as measured with the ELPI in the non-ventilated 24.3 m³ chamber. The performance of the air purifier is compared to that of a standard HVAC filter (ASHRAE rating = 8) installed in the closed-loop air exchange system of the chamber.

In addition, Figure 4 presents the CADR values achieved by the closed-loop air exchange system equipped with a standard ASHRAE rating 8 HVAC filter at two air exchange rates, 2.5 and 7.7 ACH. The data suggest that the tested portable air purifier operating in about 25 m³ non-ventilated room is capable to provide a CADR more than twice greater than the conventional central HVAC system with the rating 8 filter. Obviously, more efficient particulate filters provide more rapid reduction of aerosol contaminants and may perform better than the tested air purifier. For example, compared to the portable unit, HEPA filter installed in the closed-loop air exchange system of the 24.3 m³ chamber provided approximately 4- and 3-fold greater CADRs at 2.5 and 7.7 ACH, respectively, when challenged with NaCl particles, and 2.2- and 1.4-fold greater when challenged with smoke particles. However, HEPA filters are rarely used in residential central HVAC systems because of the high-pressure drop and the loading effect on their performance.

The particle removal from indoor air by the hybrid air purification technique was also investigated in the smaller (2.75 m³) chamber, which otherwise was utilized primarily for assessing the viable microorganism inactivation. The CADR values obtained with MS2 virions from the WPS measurements were 73 ± 5 m³/h, which is in the CADR-

TABLE 1. Percentage of Airborne Microorganisms Survived over Time t in the 2.75 m³ Chamber with the RCI-cell Operating in it, as Measured via PFU Count (for MS2 Virus) or CFU Count (for *Bacillus subtilis* Endospores)[a]

exposure time, t (min)	percentage (mean ± SD) of airborne microorganisms survived in the chamber with air purifier operating during time t	
	MS2 virus, $[PFU/cm^3]_t/[PFU/cm^3]_{t=0}$	*Bacillus subtilis* endospores, $[CFU/cm^3]_t/[CFU/cm^3]_{t=0}$
10	9.3 ± 2.0 (n = 5)	24.1 ± 3.7 (n = 2)
15	9.2 ± 4.3 (n = 12)	15.7 ± 1.7 (n = 3)
30	8.3 ± 1.1 (n = 8)	7.9 ± 1.1 (n = 3)
60	10.3 ± 1.7 (n = 5)	10.1 ± 1.3 (n = 3)

[a] Bioaerosol sampling was conducted with the Button Sampler equipped with gelatin filters. n = number of replicates.

range obtained for NaCl and smoke particles in the large chamber for the viral sizes. This suggests the feasibility of using nonbiological particles to determine the ion-induced aerosol reduction of bio-particles of the same size range. Furthermore, this finding implies that, at least for the particle size range representing MS2 virions, PRR due to ion emission in indoor air environment is inversely proportional to the air volume [see eq 5].

Ozone. In both test chambers (non-ventilated), the ozone concentration gradually increased as the purifier was continuously operating. In the 24.3-m³ chamber, it increased from 0.006 to 0.05 ppm in about 35 min, while in a smaller (2.75-m³) chamber the same increase occurred in approximately 5 min. However, once an air exchange was introduced (as low as 1 ACH), the ozone concentration in the 24.3-m³ chamber did not significantly increase as compared to the initial level ($p > 0.05$). Our monitoring data obtained with the tested unit operating in a non-ventilated room of ~100 m³ (not presented here) suggest that the ozone level can be kept below 0.05 ppm while the unit continuously operates for many hours.

Some air purifiers utilizing ion emission and, to a greater extent, the photocatalytic oxidation may cause greater increase of indoor ozone concentration than the tested one. The use of such devices in confined occupied air spaces may not be appropriate as their continuous operation may eventually lead to excessive ozone levels and, in the presence of certain chemical compounds, produce nanoparticles (*33*). Although the unipolar ion emission has a potential to suppress this effect, it seems important to keep the ozone level below existing thresholds. We believe that the solution can be found by implementing an intermittent regime (as an alternative to continuous one), which allows the air purifier operating until the ozone reaches a certain level, after which the ozone-generating element is automatically turned off to allow the ozone concentration to drop; then the cycle can be repeated.

Microbial Inactivation. Table 1 summarizes the microbial inactivation results. Only approximately 10% of initially viable MS2 virions survived 10−60 min exposure to the purifier in the chamber and about 90% were inactivated. When the natural concentration decay of aerosolized MS2 was monitored in the chamber (with no purifier operating), we found that the concentration of active viruses was relatively stable: the decrease did not exceed 20.3 ± 0.9% during 1 h. The data suggest that the viral inactivation occurs rather quickly since the percent of survived virions did not show dependence on the exposure time for t = 10−60 min. Thus, a relatively short time may be sufficient to reduce the percent of viable viruses in an air volume by a factor of 10 while those that survived showed remarkable resistance to the continuing stress. When aerosolized virions are exposed to photocatalytic oxidation, the hydroxyl radicals can affect the protein capsid and binding sites, thus disabling the virus's subsequent interaction with the host and formation of PFUs (*34*). Additionally, the TiO_2 photocatalytic cell may produce oxidative damage to the virus capsid (*35*) and the radicals may cause alteration in the virus's genetic material (*36, 37*). Our findings suggest that the hybrid air purifier may be used continuously for short time intervals or in intermittent regime to achieve considerable virus inactivation rate. On the other hand, a prolonged operation of the air purifier is believed to be advantageous in environments with a continuous supply of "fresh" active virions.

Approximately 75% of airborne *B. subtilis* spores exposed to the air purifier were inactivated during the first 10 min, 85% during the first 15 min, and about 90% or greater after 30 min (Table 1). Between 30 and 60 min of exposure, we did not observe significant decrease in the number of survived spores (similar to the trend found for virions), which suggests a nonlinearity of the effect. The natural decay in the culturable count was not significant ($p > 0.05$) during 1 h, as measured using the Button Samplers equipped with gelatin filters. However, the overall standard deviation of the data obtained in these control tests was as high as 58% and the CFU counts from filters were close to the detection limit. To address this issue, we measured the natural decay of viable *B. subtilis* spores with the BioSampler at $t = 0$ and at $t = 2$ h. It was confirmed that the viability was constant within about ±20% in the absence of the air purifier.

In bacteria, the inactivation process by reactive hydroxyl radicals can proceed in five reaction pathways:

- oxidation of coenzyme A causing inhibition of cell respiration and cell death (*38*);
- destruction of the outer membrane of bacterial cells (*12*);
- oxidation of unsaturated phospholipid in bacterial cell membrane (*39*);
- leakage of intracellular K^+ ions (*11*); and
- detrimental effects on DNA and RNA (*36, 37*).

One reason that the inactivation of *B. subtilis* endospores was time-dependent is their thick membrane layer containing peptidoglycans. This is consistent with the study of Matsunaga et al. (*40*), who found that photooxidation of coenzyme A by the TiO_2 photocatalyst was not entirely effective against the algae *Chlorella vulgaris* in water because of its thicker cell wall. Some other self-defense mechanisms of bacteria against the oxidation stress, including synthesis of superoxide dismutase enzymes, can also slow down the inactivation process (*41*).

Although the time was a factor in the bacterial spore inactivation, the viability loss occurred relatively quickly for both the MS2 virus and *B. subtilis*. This can be attributed to rapid interaction of valence-band holes (h^+) ($TiO_2 + h\nu \rightarrow h^+ + e^-$.) with the organic substances, which are present in the viral and bacterial outer walls or membranes. The above-mentioned interaction likely occurs before considerable number of hydroxyl radicals ($^{\bullet}OH$) is generated in the air volume. Although previous studies (*11, 12*) emphasized the role of hydroxyl radicals ($H_2O + h^+ \rightarrow {}^{\bullet}OH + H^+$), these radicals may not be the primary factor in microbial inactivation, particularly in the air. Furthermore, since our experiments were conducted in relatively dry air (RH < 30%), water molecules were not predominant species in contact with the catalyst, and thus the contribution of hydroxyl radicals was likely much lower than in liquids. Shang et al. (*9*) have concluded that in the gas phase, organic compounds, such as heptane, can readily interact with photogenerated holes while the interaction with water vapor molecules is not as prominent. Alberici and Jardim (*8*) have reported that the valence-band holes generated from TiO_2 photooxidation are capable of oxidizing any organic compound. The process also produces hydrogen peroxide ($O_2 + e^- \rightarrow O_2^{\bullet-}$; $O_2^{\bullet-} + H^+ \rightarrow HO_2^{\bullet}$; $2HO_2^{\bullet} \rightarrow O_2 + H_2O_2$), which can freely penetrate into cell membranes and walls and cause microbial inactivation

(*42*). Further biochemical studies on the role of gas-phase TiO_2 oxidation on the airborne microorganisms as well as studies on the reaction kinetics at the aerosol phase seem worthwhile to further examine the above interpretations.

Experiments with *P. fluorescens* revealed CFU counts below the detection limit both in the test and control samples. In contrast to *B. subtilis* endospores, even a very short exposure to ambient air (RH < 30%) considerably decreased the viability of aerosolized *P. fluorescens* vegetative cells, which are known to be stress-sensitive. Perhaps, microorganisms sensitive to desiccation stress are more usable for this kind of test if the test is performed at higher relative humidity levels.

Additional control experiments were performed to investigate if the viability decrease found for MS2 virus and *B. subtilis* spores occurred in the aerosol phase or on the sampling filter. For MS2, we found that 1835 ± 270 PFU/mL and 1855 ± 325 PFU/mL developed when filter extracts were cultivated from unexposed and 10-min exposed gelatin filters, respectively. For *B. subtilis*, we observed 1770 ± 275 CFU/mL and 1125 ± 410 CFU/mL in extracts taken from unexposed and 60-min exposed filters, respectively. No significant changes in either viral or bacterial viability occurred as a result of a non-aerosol exposure ($p > 0.05$). Thus, these findings confirm that the viral and bacterial inactivation observed in our tests indeed occurred in the aerosol phase and was not associated with the inactivation on filters.

Combined Effect (Sample Calculation). It was concluded that the particle removal took place solely due to unipolar ion emission, while the inactivation of viable airborne MS2 virions and *B. subtilis* spores occurred due to the photocatalytic reaction promoted by the RCI cell. Both mechanisms working simultaneously in a hybrid type air purifier may result in considerable decrease of the exposure to pre-existing viable aerosol biocontaminants in indoor environment. Ozone produced by the RCI cell is not believed to cause significant microbial inactivation because its level was not sufficient. Tseng and Li (*43*) referred to 3.43 ppm as an appropriate level for airborne MS2 virus, and Li and Wang (*44*) did not observe any inactivation of airborne *B. subtilis* spores at O_3 as high as 20 ppm.

The following estimate was made based on the experimental data obtained in this study. Assuming that the ion-induced air cleaning removes about 80% of viable airborne pathogens from a room air in 30 min and the RCI-induced photoxidation leaves only 10% of the remaining airborne microorganisms viable, the overall aerosol exposure to the viable pathogen in this room after 30 min is reduced by a factor of about 50.

The observed rapid inactivation of microorganisms makes unnecessary to run the RCI cell continuously. The data suggest that it can be used "part-time" for 10−30 min and "rest" for about 1−2 h until the background ozone level is reached (proposed above as an intermittent regime), while the ion emission can take place continuously to keep the aerosol concentration decreasing.

Acknowledgments

The investigation was partially supported by the EcoQuest International. The participation of Dr. K. Y. Kim was partially funded by the Korea Research Foundation Postdoctoral Fellowship Program. This support is greatly appreciated. We also thank Dr. Taekhee Lee for the technical assistance. **Disclaimer:** Reference to any companies or specific commercial products does not constitute or imply their endorsement, recommendation or favoring by the authors or the University of Cincinnati.

Literature Cited

(1) EPA (U.S. Environmental Protection Agency). *Ozone generators that are sold as air cleaners: an assessment of effectiveness and health consequences*; http://www.epa.gov/iaq/pubs/ozonegen.html; Accessed on May 22, 2006.

(2) ACGIH (American Conference of Governmental Industrial Hygienists). *Threshold Limit Values for Chemical Substances and Physical Agents & Biological Exposure Indices*; ACGIH: Cincinnati, OH, 2004; p. 44.

(3) OSHA (Occupational Safety & Health Administration). *Regulations (Standards 29 CFR): Air Contaminants, 1915.1000*; http://www.osha.gov/pls/oshaweb; Accessed on May 31, 2006.

(4) FDA (U.S. Food and Drug Administration). *Labeling Regulatory Requirements for Medical Devices*; HHS publication FDA 89-4203; U.S. Governement Printing Office: Washington, DC, 1989.

(5) EPA (U.S. Environmental Protection Agency). *National Ambient Air Quality Standards (1997)*; http://www.epa.gov/air/criteria.html; Accessed on May 24, 2006.

(6) Foarde, K. K.; VanOsdell, D. W.; Steiber, R. S. Investigation of gas-phase ozone as a potential biocide. *Appl. Occup. Environ. Hyg.* **1997,** *12,* 535−542.

(7) Li, C. -S.; Wang, Y. -C. Surface germicidal effects of ozone for microorganisms. *AIHA J.* **2003,** *64,* 533−537.

(8) Alberici, R. M.; Canela, M. C.; Eberlin, M. N.; Jardim, W. F. Catalyst deactivation in the gas phase destruction of nitrogen-containing organic compounds using TiO_2/UV-VIS. *Appl. Catal., B* **2000,** *793,* 1−9.

(9) Shang, J.; Du, Y.; Xu, Z. Photocatalytic oxidation of heptane in the gas-phase over TiO_2. *Chemosphere* **2002,** *46,* 93−99.

(10) Matsunaga, T.; Tomoda, R.; Nakajima, T.; Nakamura, N.; Komine, T. Continuous sterilization system that uses photosemiconductor powders. *Appl. Environ. Microbiol.* **1988,** *54,* 1330−1333.

(11) Saito, T.; Iwase, T.; Horie, J.; Morioka, T. Mode of photocatalytic bactericidal action of powdered semiconductor TiO_2 on Streptococci mutants. *J. Photochem. Photobiol.* **1992,** *14,* 369−379.

(12) Sunada, K.; Kikuchi, Y.; Hashimoto, K.; Fujishima, A. Bactericidal and detoxification effects of TiO_2 thin film photocatalysts. *Environ. Sci. Technol.* **1998,** *32,* 726−728.

(13) Goswami, D. Y.; Trivedi, D. M.; Block, S. S. Photocatalytic disinfection of indoor air. *Trans. ASME* **1997,** *119,* 92−96.

(14) Goswami, T. K.; Hingorani, S.; Greist, H.; Goswami, D. Y.; Block, S. S. Photocatalytic system to destroy bioaerosols in air. *J Adv. Oxidation Tech.* **1999,** *4,* 185−188.

(15) Pal, A.; Min, X.; Yu, L. E.; Pehkonen, S. O.; Ray, M. B. Photocatalytic inactivation of bioaerosols by TiO_2 coated membrane. *Int. J. Chem. Reactor Eng.* **2005,** *3,* A45.

(16) Keller, V.; Keller, N.; Ledoux, M. J.; Lett, M.-C. Biological agent inactivation in a flowing air stream by photocatalysis. *Chem. Commun.* **2005,** *23,* 2918−2920.

(17) Lin, C. -Y.; Li, C. -S. Effectiveness of titanium dioxide photocatalyst filters for controlling bioaerosols. *Aerosol Sci. Technol.* **2003,** *37,* 162−170.

(18) Grinshpun, S. A.; Mainelis, G.; Trunov, M.; Adhikari, A.; Reponen, T.; Willeke, K. Evaluation of ionic air purifiers for reducing aerosol exposure in confined indoor spaces. *Indoor Air* **2005,** *15,* 235−245.

(19) Lee, B. U.; Yermakov, M.; Grinshpun, S. A. Unipolar ion emission enhances respiratory protection against fine and ultrafine particles, *J. Aerosol Sci.* **2004,** *35,* 1359−1368.

(20) Mayya, Y. S.; Sapra, B. K.; Khan, A.; Sunny, F. Aerosol removal by unipolar ionization in indoor environments. *J. Aerosol Sci.* **2004,** *35,* 923−941.

(21) Grinshpun, S. A.; Adhikari, A.; Lee, B. U.; Trunov, M.; Mainelis, G.; Yermakov, M.; Reponen, T. Indoor air pollution control through ionization. In *Air Pollution XII*; Brebbia, C. A., Ed.; WIT Press: Southampton, U.K., 2004; pp 689−704.

(22) Kekez, M. M.; Sattar, S. A. A new ozone-based method for virus inactivation: preliminary study. *Phys. Med. Biol.* **1997,** *42,* 2027−2039.

(23) O'Connel, K. P.; Bucher, J. R.; Anderson, P. E.; Cao, C. J.; Khan, A. S.; Gostomski, M. V.; Valdes, J. J. Real-time fluorogenic reverse transcription-PCR assays for detection of bacteriophages MS2. *Appl. Environ. Microbiol.* **2006,** *72,* 478−483.

(24) Jones, M. V.; Bellamy, K.; Alcock, R.; Hudson, R. The use of bacteriophage MS2 as a model system to evaluate virucidal hand disinfectants. *J Hosp. Infect.* **1991,** *17,* 279−285.

(25) Havelaar, A. H.; van Olphen, M.; Drost, Y. C. F-specific RNA bacteriophages are adequate model organisms for enteric viruses in fresh water. *Appl. Environ. Microbiol.* **1993,** *59,* 2956−2962.

(26) Allwood, P. B.; Malik, Y. S.; Hedberg, C. W.; Goyal, S. M. Survival of F-specific RNA coliphage, feline Calicivirus, and *Escherichia coli* in water: a comparative study. *Appl. Environ. Microbiol.* **2003,** *69,* 5707−5710.

(27) Adams, M. H. *Bacteriophages*; Interscience Publishers, Inc: New York, 1959.

(28) Johnson, B.; Martin, D. D.; Resnick, I. G. Efficacy of selected respiratory protective equipment challenged with *Bacillus subtilis* subsp. *niger*. *Appl. Environ. Microbiol.* **1994**, *60*, 2184–2186.
(29) Lin, X; Reponen, T. A.; Willeke, K.; Grinshpun, S. A.; Foarde, K.; Ensor, D. Long-term sampling of airborne bacteria and fungi into a non-evaporating liquid. *Atmos. Environ.* **1999**, *33*, 4291–4298.
(30) Lin, X.; Reponen, T.; Willeke, K.; Wang, Z.; Grinshpun, S. A.; Trunov, M. Survival of airborne microorganisms during swirling aerosol collection. *Aerosol Sci. Technol.* **2000**, *32*, 184–196.
(31) Mainelis, G.; Grinshpun, S.; Willeke, K.; Reponen, T.; Ulevicius, V.; Hintz, P. Collection of airborne microorganisms by electrostatic precipitation. *Aerosol Sci. Technol.* **1999**, *30*, 127–144.
(32) Hinds, W. C. *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles*, 2nd ed.; John Wiley & Sons, Inc.: New York, 1999.
(33) Grinshpun, S. A.; Toivola, M.; Lee, S.-A.; Reponen, T. Formation of Nanoparticles in indoor air at an increased ozone level. In *Abstracts of the 24th Annual Meeting of the American Association for Aerosol Research*, Austin, Texas, U.S.A., October 17–21, 2005; AAAR: Mt. Laurel, NJ, 2005; p 327.
(34) Von Sonntag, C. Disinfection by free radicals and UV-radiation. *Water Supply* **1986**, *4*, 11–18.
(35) Turchi, C. S.; Ollis, D. F. Photocatalytic degradation of organic water contaminants: mechanisms involving hydroxyl radical attach. *J. Catal.* **1990**, *122*, 178–192.
(36) Dunford, R.; Salinaro, A.; Cai, L.; Serpone, N.; Horikoshi, S.; Hidaka, H.; Knowland, J. Chemical oxidation and DNA damage catalyzed by inorganic sunscreen ingredients. *FEBS Lett.* **1997**, *418*, 87–90.
(37) Hidaka, H.; Horikoshi, S.; Serpone, N.; Knowland, J. *In vitro* photochemical damage to DNA, RNA, and their bases by an inorganic sunscreen agent on exposure to UVA and UVB radiation. *J. Photochem. Photobiol., A* **1997**, *111*, 205–213.
(38) Vohra, A.; Goswami, D. Y.; Deshpande, D. A.; Block, S. S. Enhanced photocatalytic inactivation of bacterial spores on surfaces in air. *J. Ind. Microbiol. Biotechnol.* **2005**, *32*, 364–370.
(39) Maness, P. C.; Smolinski, S.; Blake, D. M.; Huang, Z.; Wolfrum, E. J.; Jacoby, W. A. Bactericidal activity of photocatalytic TiO_2 reaction: toward an understanding of its killing mechanism. *Appl. Environ. Microbiol.* **1999**, *65*, 4094–4098.
(40) Matsunaga, T.; Tamoda, R.; Nakajima, T.; Wake, H. Photoelectrochemical sterilization of microbial cells by semiconductor powders. *FEMS Microbiol. Lett.* **1985**, *29*, 211–214.
(41) Rincón, A. G.; Pulgarin, C. Photocatalytical inactivation of *E. coli*: effect of (continuous-intermittent) light intensity and of (suspended-fixed) TiO_2 concentration. *Appl. Catal., B* **2003**, *44*, 263–284.
(42) Marquis, R. E.; Sim, J.; Shin, S. Y. Molecular mechanism of resistance to heat and oxidative damage. *J. Appl. Bacteriol. Symp. Suppl.* **1994**, *76*, 40S–48S.
(43) Tseng, C.-C.; Li, C.-S. Ozone for inactivation of aerosolized bacteriophages. *Aerosol. Sci. Technol.* **2006**, *40*, 683–689.
(44) Li, C.-S.; Wang, Y. C. Inactivation effects of airborne ozone for bioaerosols. *J. Environ. Health* **2006**, submitted.

Received for review June 8, 2006. Revised manuscript received September 19, 2006. Accepted October 20, 2006.

ES061373O

Proposed Test Protocol for Air Purification Devices
Which Intentionally Generate Ozone

UL 867 has been chosen by the Air Resource Board staff as the protocol for all Air Purification equipment to test for ozone emissions. Whether the current version of UL 867 is selected, or some revised version apparently being shepherded through the private UL process by ARB staff, UL 867 is inadequate and not the best test protocol under any revision,

By way of background, UL 867 was originally designed decades ago for testing electrical appliances to insure the "Incidental Ozone" output created by their electrical motors is not excessive. Many electrical appliances including copiers, any equipment with electrical motors, and even traditional electrostatic precipitators (electronic air filters with a particulate collection device that removes particles from a flowing gas, such as air, using the force of an induced electrostatic charge can produce excessive incidental ozone if improperly designed. UL 867 was never intended to be the single standard for testing air purification equipment also designed to intentionally emit ozone through any technology, old or new.

To summarize UL 867: compliance is checked by placing the equipment in a sealed room (walls covered with polyethylene) measuring approximately 8'x12'x10'. The unit is placed in the center of the room on a table approximately 2.5' above the floor. The pick up tube for the ozone measuring equipment is placed approximately 2" in front of the unit and located directly in the "worst case" air flow. The unit being tested is adjusted to provide the maximum ozone level (maximum output with lowest air flow setting). Ozone measurements are recorded over a 24 hour period. The standard requires that at no time can the ozone measurement exceed 0.05 ppm. A simple visualization of this process amply demonstrates that UL 867 solely was intended for incidental ozone emissions.

To bring things into perspective, using UL 867 for determining acceptability of air purification equipment which also intentionally generates ozone would be equivalent to developing a test protocol for a radiant wall heater which specifies a maximum temperature of 80 degrees F measured 2" from the face of the heater. Meeting such a protocol would render the heater virtually useless.

Further, any standard for evaluating ozone emissions from indoor air cleaning devices should recognize the universally accepted scientific reality of the highly reactive nature of ozone and the fact that ozone will readily react with organic compounds in a room environment. The end-products of the chemical reactions that occur when ozone reacts with biological compounds are oxygen and water. When ozone reacts with mold, bacteria, viruses or volatile organic compounds (VOC's), the microorganism is oxidized and inactivated. In any typical indoor environment, there is ample biological material to facilitate the rapid conversion of ozone to oxygen. Therefore, testing should not be done in a "sterile" environment, but rather under conditions that represents the conditions that exist in a typical indoor environment.

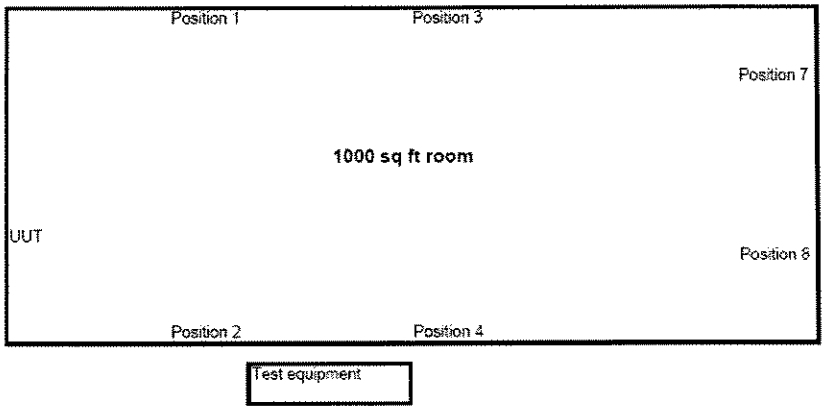
Using UL 867 as the default standard to test new air cleaning products and technologies designed to also produce low levels of safe ozone over the past decade has resulted in even a very small amount of otherwise safe levels of ozone to build up to levels that exceeded the Federal 0.05 ppm limit. In fact, we submit that this default use of UL867 has contributed to the current confusion over the safety of newer air purifiers that compete with the more traditional electrostatic precipitators and HEPA filters endorsed by the California Lung Association.

To summarize this important point, reliance on UL 867 has helped to fuel the current debate over air cleaners that emit ozone, because creating ozone in a sealed environment for testing purposes, without having anything in that environment to react with will allow even a very small amount of ozone to build to levels that will exceed the 0.05 ppm limit, thereby guaranteeing the air purifier or cleaner to fail the UL 867 testing protocol.

A More Realistic Test Protocol

We submit that a more realistic test should be devised and approved by the Board that assesses the true functionality of ozone producing air purifiers in a real world environment, unlike the UL 867. Not all environments are created equal nor will any two be the same, but a conservative approach can be taken to include basic household and/or office furnishings including carpet, drapes, and a humidity level of 50% to better represent the organic compounds (loading) in a room environment.

In order to assess ozone creation vs. dissipation, effectively insuring the air purifier does not create more ozone than can be dissipated in a natural environment, the unit should be tested in an environment representative of where it is to be used. A realistic approach would be to place the unit in a "furnished" room, sized according to the rated output for the unit to be tested. For this assessment, a volumetric approach to measurement should be taken:



In most cases, manufacturers of air purification devices which include technology that intentionally generates ozone, include the ability to scale the ozone output based upon the area or volume of the space being treated. For certification purposes, two tests should be performed:

1. Lowest setting for the smallest space the purifier is designed to go into, and
2. Highest setting for the largest space the purifier is designed to go into.

Appropriate consumer labeling should be required to inform the user of proper operation of the device and minimum space requirements in square footage for safe operation while the space is occupied.

The diagram above shows a typical setup for a 1000 sq ft room. For this test, the unit is placed along a wall of a furnished room (as outlined above), on a table top approximately 6' above the floor. An ozone measurement device (preferably capable of measuring a minimum of 6 locations simultaneously) is setup outside the chamber and connected to sampling tubes located at positions1 and 2 which represents 250sqft of area, positions 3 and 4 which represents 500 sq ft of area and positions 7 and 8 which represents 1000 sq ft of area (note: positions 5 and 6 which would normally represent 750 sq ft of area have been omitted for this test, but could also be measured if so desired). The Unit Under Test (UUT) is configured such that the worst case scenario is represented (Ozone concentration set to match room size and fan set to lowest speed) and powered on. Ozone measurements are recorded at each position for a 24 hr period and compared to the following three criteria:

1. Average Ozone Concentration may not exceed .05 ppm. The average concentration is defined as the average of positions 1 thru 6 over the 24 hr period, and this value shall not exceed the average concentration limit of 0.05 ppm.
2. Maximum 8-hour Ozone Exposure may not exceed .08 ppm. The EPA guidelines reflect an 8 –hour Permissible Exposure Level of .08 ppm over any 8 hr period. For the ozone exposure test, the ozone concentration should be measured at each of the six measurement locations and the ozone concentration at any of these locations cannot exceed the EPA's 0.08ppm limit for any 8 hr period nor can it exceed a level of 0.1ppm at any time.
3. Maximum Instantaneous Ozone Exposure may not exceed 0.10 ppm. The EPA guidelines reflect a maximum ozone exposure level at any time of 0.10 ppm. For the maximum ozone exposure test, the ozone concentration should be measured at each of the six measurement locations and the ozone concentration at any of these locations cannot exceed the EPA's limit of 0.10 ppm at any time.

We are prepared to work with the Board and interested parties to help implement this or similar alternative test protocol.