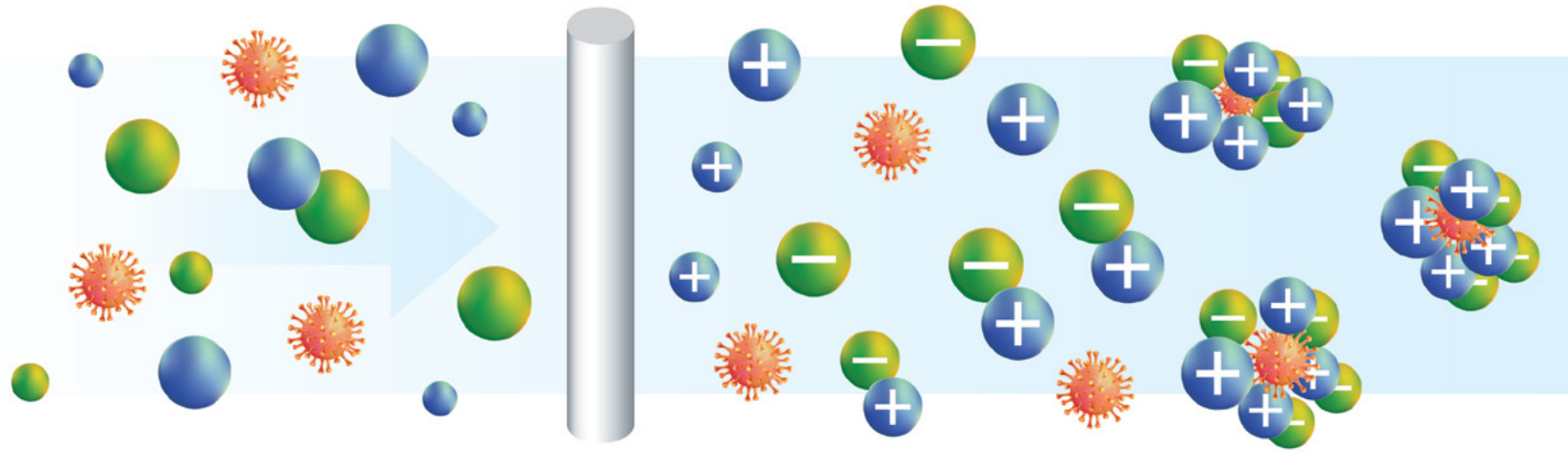
A Taxonomy of Air-Cleaning Technologies Featuring Bipolar Ionization



TRANE TECHNOLOGIES

Many pathogens (including the SARS-CoV-2 virus that causes COVID-19) are transmitted through droplets emitted when a person breathes, talks, sings, coughs or sneezes. Larger droplets tend to fall on the ground or other surfaces within a few seconds because of gravity; smaller droplets or aerosols can remain airborne for longer periods. A person can become infected when they inhale droplets emitted by a sick person or when they touch a contaminated surface and then their face and expose the mucous membranes of their eyes, nose or mouth. Although there is still some debate, the scientific community is increasingly accepting that, in addition to transmission through larger droplets, COVID-19 can be spread by airborne transmission of aerosolized particles[1].

There are four major approaches to manage indoor air quality and reduce the transmission of pathogens in an indoor environment:

- **DILUTE & EXHAUST.** These two approaches are typically used in combination to relocate pathogens gradually from the occupied space to the outside space. Increasing outdoor air ventilation, i.e., increasing the amount of fresh air (with an assumed lower concentration of pathogens) that is brought in from the outside, dilutes the concentration of pathogens in the indoor air. Increasing the amount of indoor air (along with the pathogens it carries) that is exhausted to the outside maintains building pressure and increases the rate at which pathogens are removed from the occupied space. This combined approach is effective for reducing the concentration of airborne pathogens, but it does not address contaminated surfaces and it may lead to increased energy consumption from the need to condition the outdoor air. In addition, uncontrolled ventilation can increase humidity levels in the room, which may contribute to the creation of mold and, under certain conditions, potentially facilitate the transmission of other pathogens. Furthermore, depending on the airflow within a room, vortices may be formed and some pathogens may find refuge in areas of the room with reduced airflow and stagnant air.
- **CONTAIN.** The third element is to manage indoor humidity as it can support growth of surface-bound and airborne microbes like certain viruses, bacteria and fungi. Keeping relative humidity levels within the ASHRAE®-recommended range of 40%-60% maximizes occupant comfort and can reduce the risk of microbial growth.
- **CLEAN.** The last and very important pillar includes either:
    - "Detaining" pathogens so that they cannot reach the occupants of the space. This is what filters do – as the air circulates through a filter, the filter retains a portion of the pathogens that reach the filter; the portion depends on the rating of the filter. Like the dilute and exhaust approach, the detention approach does not address contaminated surfaces or pockets of stagnant air. With respect to energy, filters that act at a microbial level (e.g., MERV 13 or HEPA) typically cause a higher pressure drop and thus increase energy consumption; however, this increase is usually smaller than the one associated with increased outdoor air ventilation.
    - Or "attacking/inactivating" the pathogen. For example, ultraviolet (UV) light or a chemically reactive antimicrobial substance can inactivate pathogens. There are two general ways of achieving inactivation:
        - **Bring the air to the inactivating agent.** For example, ultraviolet germicidal irradiation (UVGI), bipolar ionization (BPI) or photocatalytic oxidation (PCO) systems can be installed in an air handling unit and inactivate the pathogens as the air passes through the air handling unit. This approach does not address surface contamination or pockets of stagnant air.
        - **Bring the inactivating agent to the room.** The approach is similar to the previous one, but the inactivating agent (e.g., UV light, antimicrobial substance) is brought into the room. Some of these solutions allow the inactivation of pathogens on surfaces as well as in areas with reduced airflow.

With respect to the last approach mentioned above (bringing the inactivating agent to the room), we can identify two subcategories: solutions for unoccupied rooms and solutions for occupied rooms.

Unoccupied Spaces

Solutions for unoccupied rooms are able to use UV power levels and wavelengths that are potentially harmful to humans or chemicals that are potentially harmful/toxic to humans. Because of the potential harm to humans, these solutions can be applied only on an episodic basis when the room is not occupied, so they are unable to offer continuous protection during periods of occupancy.

Occupied Spaces

Solutions for occupied rooms can only use technologies that are within acceptable safety limits for humans. In terms of UV, there are upper-room UV technologies; these use UV light at wavelengths (usually 254 nm) and power levels that can be harmful to humans (just like solutions for unoccupied rooms) but shine the light along the ceiling so that humans are out of harm's way (i.e., not in the light path). The UV light inactivates a portion of the airborne pathogens that find themselves in the light path (the portion generally depends on the light energy)[2]; however, since the light cannot reach areas where humans may be located, it cannot clean surfaces. Some emerging products are starting to use Far-UVC light (e.g., 222 nm), which is purported to be both effective in inactivating pathogens[3] and within acceptable safety limits for humans, so it can be used for air and surfaces in occupied rooms. The Far-UVC technology is being validated – it does not have the established track record of products operating at 254 nm UV (but which can harm human eyes and skin).

Another technology for occupied rooms is Synexis®. Synexis devices produce hydrogen peroxide (H_2O_2) in a pure gaseous form (referred to as dry hydrogen peroxide or DHP, to distinguish it from other forms of hydrogen peroxide like aqueous solution, aqueous vapor or mist). Hydrogen peroxide has well-known antimicrobial properties. Synexis devices create DHP from ambient humidity using a proprietary variant of photocatalytic oxidation process. As a gas, DHP can disperse everywhere in a room and inactivate pathogens in the air and on surfaces through oxidation chemical reactions. Similar reactions can also reduce volatile organic compounds (VOCs). The non-aqueous nature of DHP allows it to be effective even at very low concentrations that are 50 (or more) times lower than the safety limit established by OSHA. Thus, DHP is both safe for humans in occupied spaces and effective[4].

Bipolar ionization is yet another technology for occupied spaces. It produces ions that act as an antimicrobial agent. We discuss this technology in detail in the following section.

Bipolar Ionization (BPI)

What is Bipolar Ionization? Ionization has been studied for almost a century and air ionization products have been available in the market for decades, although the technology has evolved significantly over the years. Despite the length of time in the market and the familiarity of many consulting engineers with the technology, there is still limited understanding of some of the phenomena related to ionization and there are diverging opinions about the efficacy of the technology. The underlying science[5] is complex to begin with and this complexity is compounded by the existence of many variants of the technology (i) across manufacturers and (ii) across time, as the technology has evolved.

Bipolar ionization uses ions as antimicrobial agents. Ions are atoms or molecules that have gained or lost one or more electrons, so they are electrically charged. Ions form naturally in the environment from such energy sources as UV light, frictional charging by the wind, water droplet breakup (waterfalls, sea waves), electrical discharge from lightning, etc. Bipolar ionization (BPI) refers to technologies that use an artificial source of energy to produce both positively charged ions (cations) and negatively charged ions (anions). The ions are typically produced by applying voltage to electrodes to create an electric field; as the air passes through the electric field, some atoms or molecules in the air stream may lose or gain electrons and become ions. Different electrical arrangements give rise to different variants of bipolar ionization devices, e.g., corona discharge, dielectric barrier discharge, needlepoint bipolar ionization (NPBI®), etc. There are BPI devices that can be installed in an air handling unit or in a duct and stand-alone BPI devices (usually portable) that operate in a room.

Bipolar ionizers can have an effect both in the vicinity of the device, where the electric field is applied, and in the occupied room, as ions disperse throughout the space. One manufacturer that offers both tube-style and needlepoint-style products states[6] that "the tube-style has a plasma field around the tubes, but it also creates ions, absolutely creates ions and goes into the space; … the needlepoint, of course, only makes ions and those are delivered into the space as well." Air ions may be involved in four processes: (i) attachment to particles; (ii) contact with a surface; (iii) recombination with other ions; and (iv) reaction with gaseous molecules.

How Bipolar Ionization Reduces Contaminants. Bipolar ionization has been proven effective in removing particulates through a process called agglomeration. Ions attach to particles (dust, pollen, dander, etc.); the charged particles attract other particles of potentially opposite polarity to form larger particles. The particles eventually become large enough to fall on the floor, be captured by a filter or be attracted to other surfaces. This agglomeration phenomenon has been verified through direct observation of higher accumulation of dust on filters, floors, walls, etc. when the bipolar ionizer is in operation.

When it comes to inactivating pathogens and reducing volatile organic compounds (VOCs), the processes are more complex and not fully understood. The amount of energy required to remove an electron from an atom or molecule is called ionization energy or ionization potential; different atoms and molecules have different ionization potentials. Thus, the types of ions produced by a BPI device depend on the composition of the air and on the energy applied. At high energy levels, ionization generates, among other things, a complex mix of reactive oxygen species (superoxides, peroxides, hydroxyls, etc.), which are highly reactive and can remove hydrogen atoms from carbon chains directly or through a series of chemical reactions. The result is that the carbon chains in pathogens and volatile organic compounds break down, so the pathogen cells can be inactivated and the VOCs can be decomposed, ultimately becoming CO_2 and H_2O.

The complication in the process described above is that, at high energy levels, ozone is also produced. Ozone (O_3 – an oxygen molecule with an extra atom of oxygen) used to be a popular substance produced by air cleaners (ozone generators); however, it is now widely accepted that ozone is toxic and can cause harm to humans. Thus, the ASHRAE Standard 62.1-2019 *Ventilation for Acceptable Indoor Air Quality* requires that air-cleaning devices comply with the UL 2998 standard, which limits ozone emissions to 5 parts per billion (ppb). Many BPI products, particularly older device models, do not meet the UL 2998 requirements; they can only meet the older and less stringent UL 867 standard, which allows ozone emissions up to 50 ppb. Some newer BPI products limit the input energy below the level at which ozone is produced, so these products comply with UL 2998. However, the resulting ion cloud may be composed of less reactive ions. Thus, it is important to verify the compliance of a BPI product with UL 2998 and consider the test parameters under which any test results on efficacy were obtained.

Experimental results. To validate the efficacy of the BPI technology, Trane® conducted experiments at an independent laboratory (LMS Technologies, Inc.) in fall 2020. The experiments were conducted in a 1,007 cubic foot chamber with both airborne and surface-bound pathogens and under a variety of airflow conditions. The device tested was a needlepoint bipolar ionizer (NPBI)[7] intended for in-duct installation; the device utilizes the airflow of the HVAC system and is rated for airflows up to 6,000 cfm.

The following graphs illustrate the results from an indicative sample of tests conducted with the MS2 Bacteriophage virus in the air and on surfaces. The NPBI device demonstrated efficacy for air but not for surfaces. It should be noted that the MS2 virus is a small, non-enveloped virus; as such, it is more difficult to inactivate than an enveloped virus[8]. In laboratory tests, the MS2 is often used as a surrogate for the SARS-CoV-2, since SARS-CoV-2 is an enveloped virus and is expected to be inactivated faster than MS2.

Airborne pathogens. **Figure 1** illustrates the reduction in airborne MS2 that the NPBI device achieved. The horizontal axis shows the time elapsed since the injection of the MS2 virus in the air of the test chamber; the vertical axis shows the reduction in the virus concentration as a percentage of the initial concentration of the virus in the chamber at the time of injection. The graph shows three curves for BPI, one for each of three different filter arrangements: filter upstream of the device (MERV 8 filter upstream), filter downstream of the device (MERV 8 filter downstream), and

no filter at all. Most BPI manufacturers recommend placing the filter upstream of the BPI device. For comparison purposes, the graph shows also the natural decay (percent reduction in virus concentration without any technology applied). In this experiment, the airflow from the HVAC system was 101 cfm or 6 ACH (air changes per hour). Similar results (not shown in the graph) were obtained for Staphylococcus Aureus (staph), which was used as representative of bacteria; the staph reduction was slower than the MS2 reduction for both natural decay and BPI, which was expected, since bacteria are generally more difficult to inactivate than viruses.

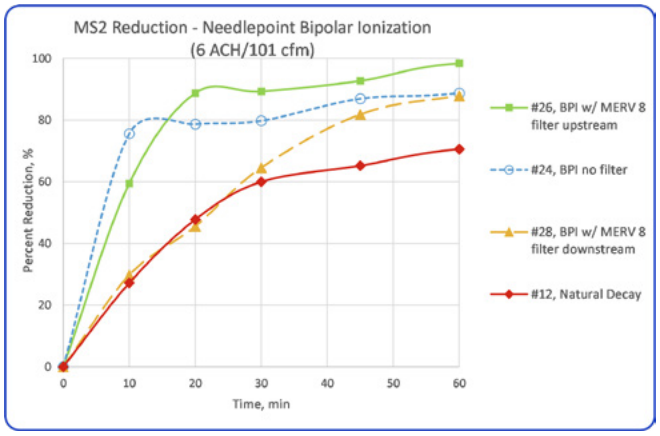


Figure 1: Inactivation of MS2 virus in air by NPBI device with airflow of 6 ACH.

Figure 2 illustrates the ion concentration in the chamber during the test mentioned above. The device had been operating for an hour before the injection of the contaminant. The injection of the MS2 started at time -12 min and lasted until time 0. As can be seen in the graph, the concentration of ions was about 6,000 ions/cc before the start of the MS2 injection; in the experiment where the filter was placed downstream of the device, the pre-injection ion concentration was much lower, which is expected, since ions stick to filters. Upon injection of the MS2, the concentration of ions in the chamber dropped quickly, which shows that ions were interacting with the contaminant. It should also be noted that the amount of ozone produced during the experiment was not significant, although our measurement was incidental and not in accordance with the procedure prescribed in UL 2998.

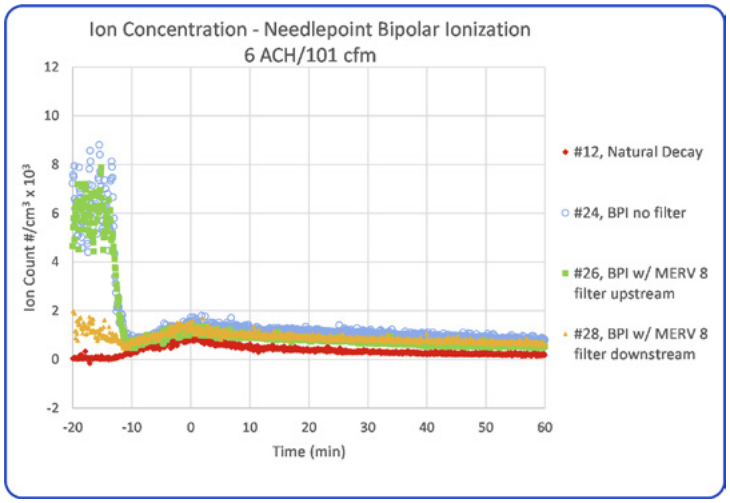


Figure 2: Ion concentration in the test chamber during MS2 in-air test at 6 ACH.

The left graph in **Figure 3** illustrates the reduction in airborne MS2 that the NPBI device achieved with an HVAC airflow of 336 cfm or 20 ACH (air changes per hour). The axes and the curves have the same interpretation as in the previous test (**Figure 1**). The concentration of ions in this experiment followed a pattern very similar to that shown in **Figure 2**, except that the pre-injection concentration of ions in the chamber was much higher (between 20,000 ions/cc and 40,000 ions/cc); once again, the ion concentration dropped significantly upon injection of MS2. The higher concentration of ions under the higher HVAC airflow can potentially be explained by the fact that the ions are spaced farther apart as they are generated by the device, so the neutralizing recombination of positive and negative ions is reduced. The right graph in **Figure 3** shows a comparison of the MS2 inactivation rates achieved by the NPBI device for different HVAC airflows. Given the much higher number of ions that reach the chamber under the higher HVAC airflow, it was unexpected that the rate of reduction in MS2 did not exhibit a corresponding increase.

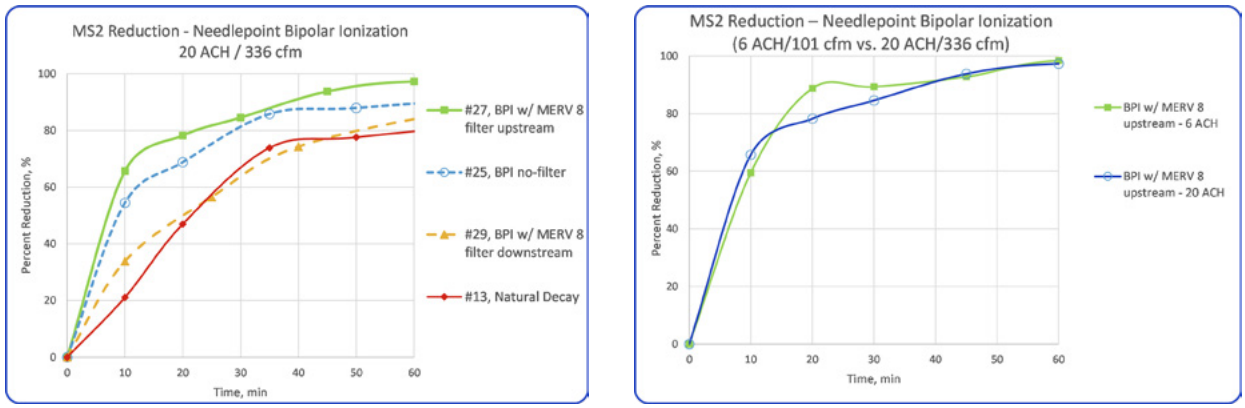


Figure 3: Inactivation of MS2 virus in air by NPBI device with airflow of 20 ACH (left); comparison of MS2 inactivation in air for different airflows (right).

Surface-bound pathogens. **Figure 4** illustrates the results of an experiment with MS2 on surface. The horizontal axis shows time in hours. The vertical axis shows relative MS2 concentration, i.e., the concentration of MS2 on the surface divided by the initial concentration of MS2 on the surface when the experiment started. The HVAC airflow during this experiment was 101 cfm or 6 ACH. As can be seen in the graph, the NPBI device did not exhibit faster reduction compared to natural decay. It should be noted that the concentration of ions in the chamber remained stable throughout the test and was at the same level as the pre-injection concentration for the in-air MS2 test with the same HVAC airflow (6 ACH) mentioned earlier, which confirms that the device was operating properly. Thus, it appears that the NPBI device was ineffective against MS2 on surface under these test conditions.

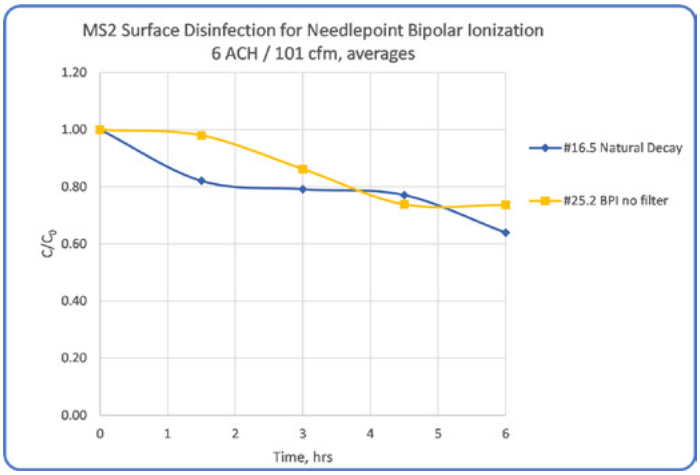


Figure 4: Testing of NPBI device against MS2 virus on surface with airflow of 6 ACH.

We are aware of claims by BPI manufacturers that they have achieved reduction of SARS-CoV-2 on surfaces. At this time, Trane has not been provided enough information to reconcile the results of the various tests. Numerous potential factors could explain the different outcomes. MS2 is a small non-enveloped virus, so it is harder to inactivate than SARS-CoV-2 (which is enveloped). The experimental setup may have been different – parameters such as the size of the chamber, the distance from the device, the airflow, the sample preparation method, etc. may have been different.

Volatile organic compounds (VOCs). **Figure 5** illustrates the results of an experiment with formaldehyde (CH_2O) in the air. The horizontal axis shows time in minutes and the vertical axis shows the formaldehyde concentration in ppb. The HVAC airflow during the test was 101 cfm (or 6 ACH). The concentration of ions in the chamber remained stable during the entire test (i.e., even after the injection of formaldehyde) and at a level consistent with levels observed during previous tests with the same HVAC airflow (i.e., around 6,000 ions/cc). As can be seen in the graph, the decay of formaldehyde with the NPBI device is practically indistinguishable from the natural decay. Very similar results were also obtained with toluene (C_7H_8), another VOC: the decay with the NPBI device was indistinguishable from the natural decay and the concentration of ions in the chamber remained stable during the entire test.

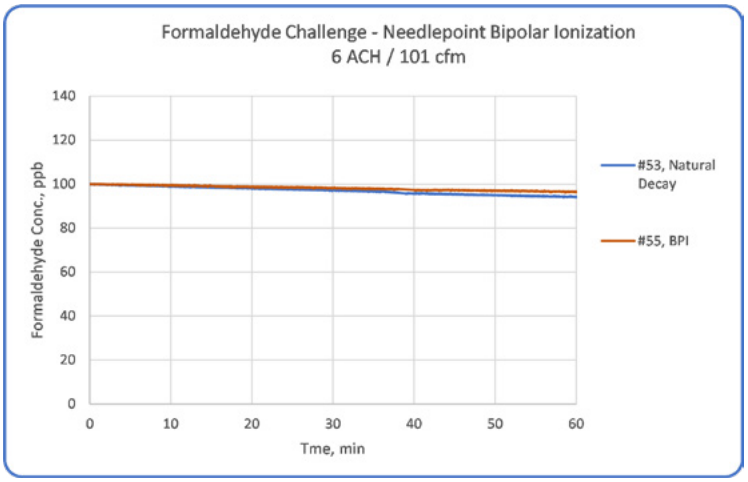


Figure 5: Testing of NPBI device against formaldehyde with airflow of 6 ACH.

The inability of the needlepoint bipolar ionization device to reduce VOCs (formaldehyde, toluene) has serious ramifications for the applicability of the technology to the Indoor Air Quality Procedure (IAQP) in ASHRAE Standard 62.1: if the technology cannot reduce VOCs, it cannot supplant outdoor air ventilation, so it cannot conserve energy.

Discussion of results and hypotheses. The inefficacy against VOCs also raises questions about the mechanisms through which NPBI reduces contaminants. It should be noted that the concentration of ions observed in the chamber (about 6,000 ions/cc) is considered abundant by the BPI manufacturers. A basic stoichiometric calculation shows that, at 100 ppb, formaldehyde molecules outnumbered the ions in the chamber by about 400,000,000:1. Thus, the ions had plenty of "targets" to react with and the fact that the ion concentration during the test remained stable at the pre-injection level strongly suggests that the ions do not interact with formaldehyde. BPI manufacturers often mention the ionization energy of formaldehyde (10.87 eV) and the fact that this energy is below the purported energy limit of their devices (12.7 eV) as evidence that their devices can ionize formaldehyde. What is the result of that ionization? Cation CH_2O^+? If so, what happens to this cation next? Does it reclaim its electron and revert to an uncharged formaldehyde molecule? What is the mechanism through which a chemical reaction would take place to break down CH_2O (presumably oxidize it to HCOOH first and eventually to CO_2)?

The inefficacy of NPBI for MS2 on surface and for formaldehyde in air gives rise to the hypothesis that the ions produced by this device may not have the strength to extract hydrogen atoms from carbon chains. If the ions were able to inactivate MS2 in the air by breaking the carbon chains, why wouldn't they be able to do the same on surface, even if at a slower pace? Is it possible that the reduction of MS2 in the air happened through agglomeration of the aerosolized particles (which would be consistent with the observed reduction of ions in the chamber upon injection) rather than through a chemical reaction? It should be noted that a well-known BPI manufacturer has stated[9], "So we never ionize oxygen and, therefore, we don't generate ozone as a byproduct." Was the manufacturer referring to any kind of oxygen (including dioxygen) or possibly only to atomic oxygen? If there is no form of reactive oxygen, how will formaldehyde break down? Is it possible that, in an effort to reduce ozone and meet UL 2998, BPI manufacturers reduced the production of reactive oxygen species to the point where the effectiveness of the technology was reduced? Validation of these hypotheses will require further investigation.

Conclusions

In the tests that Trane conducted, NPBI demonstrated efficacy for in-air pathogens like MS2 (virus) and Staphylococcus Aureus (bacteria). In the tests conducted, we did not see efficacy for pathogens on surface and for VOCs (volatile organic compounds), so we are inconclusive about the applicability of the technology to these situations and feel that further investigation is needed.

Our overall conclusions are in line with the following comment[10] by ASHRAE regarding Bipolar Ionization / Corona Discharge / Needlepoint Ionization and Other Ion or Reactive Oxygen Air Cleaners and the response provided by the CDC to an inquiry from the ASHRAE Epidemic Task Force:

- *Air cleaners using reactive ions and/or reactive oxygen species (ROS) have become prevalent during the COVID-19 pandemic. New devices that are not mentioned elsewhere in this guidance likely fall into this category.*
- *Technologies utilize various methods to create reactive ions in air that react with airborne contaminants, including viruses. The design of the systems can be modified to create mixtures of reactive oxygen species (ROS), ozone, hydroxyl radicals and superoxide anions.*
- *Systems are reported to range from ineffective to very effective in reducing airborne particulates and acute health symptoms.*
- *Convincing scientifically-rigorous, peer-reviewed studies do not currently exist on this emerging technology; manufacturer data should be carefully considered.*
- *Systems may emit ozone, some at high levels. Manufacturers are likely to have ozone generation test data.*

Response to the ASHRAE Epidemic Task Force from the CDC:

> *Thank you for your question. Although this was pointed out in the earlier CDC responses, it is important for me to re-emphasize that CDC does not provide recommendations for, or against, any manufacturer or manufacturer's product. While bi-polar ionization has been around for decades, the technology has matured and many of the earlier potential safety concerns are reportedly now resolved. If you are considering the acquisition of bi-polar ionization equipment, you will want to be sure that the equipment meets UL 2998 standard certification (Environmental Claim Validation Procedure (ECVP) for Zero Ozone Emissions from Air Cleaners) which is intended to validate that no harmful levels of ozone are produced. Relative to many other air cleaning or disinfection technologies, needlepoint bi-polar ionization has a less-documented track record in regard to cleaning/disinfecting large and fast volumes of moving air within heating, ventilation, and air conditioning (HVAC) systems. This is not to imply that the technology doesn't work as advertised, only that in the absence of an established body of evidence reflecting proven efficacy under as-used conditions, the technology is still considered by many to be an "emerging technology." As with all emerging technologies, consumers are encouraged to exercise caution and to do their homework. Consumers should research*

the technology, attempting to match any specific claims against the consumer's intended use. Consumers should request efficacy performance data that quantitatively demonstrates a clear protective benefit under conditions consistent with those for which the consumer is intending to apply the technology. Preferably, the documented performance data under as-used conditions should be available from multiple sources, some of which should be independent, third party sources.

DISCLAIMER: There is evidence from ASHRAE and other sources that HVAC technologies can mitigate the risk of exposure to infectious aerosols in built environments; however, the transmission of SARS-CoV-2 and mitigation of COVID-19 in buildings is yet to be tested and confirmed.

[1]*For more information on the transmission of SARS-CoV-2, see https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/how-covid-spreads.html.*

[2]*The 254 nm light damages the DNA or RNA of the pathogens, so that they cannot reproduce. A dose of 40 mJ/cm² of 254 nm light is considered sufficient to inactivate 99.99% of any pathogenic microorganism.*

[3]*The 222 nm light is believed to damage the proteins on the surface of a virion that bind to specific receptor proteins on the surface of host cells; this damage prevents viral infection.*

[4]*For more information on air cleaning, including a white paper about Synexis and DHP, please visit https://trane.com/wellsphere.*

[5]*An introductory discussion of the physics and chemistry of ionization can be found in S. L. Daniels, ""On the ionization of air for removal of noxious effluvia" (Air ionization of indoor environments for control of volatile and particulate contaminants with nonthermal plasmas generated by dielectric-barrier discharge)," in IEEE Transactions on Plasma Science, vol. 30, no. 4, pp. 1471-1481, Aug. 2002, doi: 10.1109/TPS.2002.804211. A similar version of the paper can be found at https://www.plasma-air.com/resources/397.*

[6]*See webinar "A Deep Dive into Bi-Polar Ionization (BPI)" by Larry Sunshine of Plasma Air, https://www.usgbcwm.org/event/viewers-choice-a-deep-dive-into-bi-polar-ionization-bpi/, at time 57' 14'' into the video clip, during the Q&A session.*

[7]*The device was a Phenomenal Aire® Series C6.0 Cold Plasma Generator manufactured by Top Product Innovations (https://www.topproductinnovations.com/); the core NPBI component of the device is manufactured by Global Plasma Solutions® (https://globalplasmasolutions.com/).*

[8]*Generally, enveloped viruses are more easily inactivated than large non-enveloped viruses and large non-enveloped viruses are more easily inactivated than small non-enveloped viruses.*

[9]*Global Plasma Solutions (GPS®), https://www.achrnews.com/articles/143337-needlepoint-bipolar-ionization-can-it-mitigate-spread-of-covid-19-virus.*

[10]*https://www.ashrae.org/technical-resources/filtration-disinfection#bipolar.*

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