A Taxonomy of Air-Cleaning Technologies Featuring Synexis

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 outside 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 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, 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, UVGI (ultraviolet germicidal irradiation), BPI (bipolar ionization) or PCO (photocatalytic oxidation) 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 (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 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 (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 254 nm 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 (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).

In the following section, we focus exclusively on solutions that deploy a chemically reactive antimicrobial substance into an occupied room to reduce the concentration of pathogens. We make particular reference to Synexis® products.

Dry Hydrogen Peroxide & In-Room Microbial Reduction with Synexis Devices

There are two primary benefits to deploying a chemically reactive antimicrobial substance within an occupied room to inactivate pathogens:

a. The antimicrobial substance can go virtually anywhere, so it can clean both air and surfaces.

b. The antimicrobial substance, even if not instant (i.e., even if it takes a bit of time for the antimicrobial substance to reduce the concentration of pathogens in the space) is applied continuously rather than on an episodic basis when humans leave the room.

Along with the benefits mentioned above come two significant constraints in the choice of an antimicrobial substance:

i. The disinfecting agent has to be safe for humans, since it is deployed in an occupied room.

ii. The disinfecting agent must have a suitable level of reactivity: it needs to be reactive enough to inactivate the pathogens in a relatively short amount of time, but not too reactive so that it has enough time to reach all places within a room. Some antimicrobial substances are too reactive and, therefore, unstable (e.g., may last only a fraction of a second), so they have no chance to spread throughout a room.

The human safety requirement severely restricts the choices of an antimicrobial substance to inactivate the pathogens; for example, we do not want people ingesting bleach. Thus, most of the solutions that try to inactivate pathogens in a room use an oxygen-based antimicrobial substance, since oxygen is an element that abounds in nature. Even then, one has to be careful, because some oxygen-based antimicrobial substances can still be harmful to humans. For example, ozone (O3 – 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 ppb (parts per billion).

What is Dry Hydrogen Peroxide . The Synexis devices use Dry Hydrogen Peroxide (DHP) as the antimicrobial substance. Hydrogen peroxide (H2O2) is a water molecule with an extra atom of oxygen and has well-known antimicrobial properties. Most people are familiar with the aqueous solutions of hydrogen peroxide; the bottles of hydrogen peroxide that people buy over the counter to apply as a topical antiseptic typically contain an aqueous solution with 3% hydrogen peroxide. Healthcare facilities often use higher concentrations for sanitization purposes.

The Synexis devices produce hydrogen peroxide in a pure, gaseous form (i.e., not in the form of aqueous solution or aqueous vapor or mist), hence the term "dry." This critical differentiating property allows Synexis devices to meet all of the requirements mentioned above for in-room solutions.

- Safety . Hydrogen peroxide occurs naturally in the air in small concentrations. The concentration of hydrogen peroxide found in the air in Synexis deployments varies between 0.5 ppb and 20 ppb along the physical path of the DHP, with concentration being highest near the device producing the DHP. Even at 20 ppb (at the high end), the concentration is 50 times lower than the OSHA safety limit of 1 ppm (or 1,000 ppb) specified in 29 CFR 1910.1000, Table Z-1. Thus, Synexis' deployment of DHP is within acceptable safety thresholds. In fact, the technology has been deployed safely for years in all kinds of congregation spaces, including healthcare facilities, senior living facilities, sports facilities, industrial facilities and daycare facilities.

- **Reactivity / Efficacy**. One of the biggest advantages of DHP is that it is effective even at the very low concentrations mentioned above. In aqueous forms, water molecules may "stand" between the hydrogen peroxide molecules and the pathogen molecules with which we would like the hydrogen peroxide molecules to react in order to inactivate the pathogen. Thus, aqueous solutions require much higher concentrations of hydrogen peroxide to be effective (which could trigger safety concerns); in contrast, DHP is effective at the much lower concentrations mentioned above. It should be noted that, even at a very low concentration of 1 ppb, there are still well over 20 billion molecules of H_2O_2 in every cubic centimeter (a cubic centimeter is slightly less than 1/16th of a cubic inch).

- Stability . The half-life of dry hydrogen peroxide is approximately 30 to 60 minutes. Thus, the DHP has enough time to go through ducts (if the producing device is installed in a duct), disperse everywhere in a room and attack pathogens in the air and on surfaces. DHP gets depleted over time as DHP molecules react with contaminants or with each other ($H_2O_2 + H_2O_2 \rightarrow 2\,H_2O + O_2$). Thus, the Synexis devices operate on a continuous basis to replenish the DHP in a room.

How DHP inactivates pathogens. DHP can attack various points on a pathogen, including lipid membranes, capsids, cell wall, and polar functional groups on the exterior protein structures of the various classes of microbe. Like all oxygen-based antimicrobial substances, DHP inactivates pathogens by chemically "releasing" the spare oxygen atoms (directly or indirectly). The "electron-hungry" oxygen "steals electrons" from and bonds with (i.e., oxidizes) carbon atoms found in the carbon chains that form the microbial elements mentioned above (lipid membranes, etc.). Through a series of chemical reactions, the end-result is that these carbon chains break and the pathogen is rendered inert; the product of the oxidation of carbon atoms is CO2 – the process is like a slow "burning" of carbon atoms in the microbe. Those with a penchant for chemistry may appreciate that DHP effectively disassociates into two hydroxyl radicals ; hydroxyl radicals are the antimicrobial substance through which photocatalytic oxidation (PCO) devices installed in air handling units sanitize the supply air going through the units. Thus, Synexis devices effectively turn the entire room into a giant PCO device.

How Synexis devices create DHP. Synexis devices generate DHP through photocatalytic oxidation (PCO). The direct products of PCO are hydroxyl radicals (OH), which are created from water molecules (humidity). Hydroxyl radicals are extremely reactive / unstable – they last for a fraction of a second. Thus, they do not meet the stability criterion mentioned above for antimicrobial substances intended to inactivate pathogens in the room. Synexis' proprietary differentiated technology combines unstable hydroxyl radicals into more stable DHP molecules in gaseous form . Thus, the DHP gas is able to last long enough to diffuse through the entire air volume of an occupied space and reach virtually all surfaces, so that it can inactivate both airborne and on-surface pathogens. This is how Synexis turns an entire room into a PCO air-cleaner, as mentioned above.

Experimental results . To validate the efficacy of the Synexis 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. Three Synexis device models were tested: the Sentry and the Sphere are intended for in-room installation and have their own fan; the Blade is intended for in-duct installation and uses the fans of the HVAC system. Just like the Sentry and the Sphere, the Blade also works by generating DHP that is dispersed in a room; therefore, it is recommended that the Blade be installed as close to the diffuser as possible.

The following graphs illustrate the results from an indicative sample of tests conducted with the MS2 Bacteriophage virus in the air and on surfaces. Synexis demonstrated efficacy for both air and 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 [4]. 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.

Figure 1 illustrates the reduction in airborne MS2 that Sphere and Sentry 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. For comparison purposes, the graph shows also the natural decay (percent reduction in virus concentration without any technology applied). In this experiment, there was no airflow from the HVAC system; one of the advantages of the Sphere and the Sentry is that they operate even when the HVAC system is off.

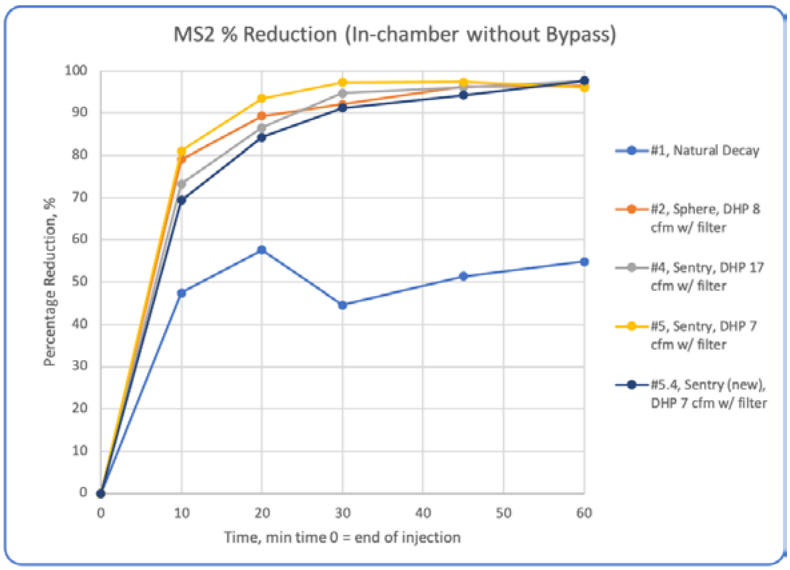

Figure 1: Inactivation of MS2 virus in air
by Sentry and Sphere without HVAC airflow

Figure 2 illustrates the reduction of the MS2 virus on surface achieved by Sphere and Sentry. The axes are the same as in the previous graph; note that, unlike the previous graph, the units on the horizontal axis are hours, not minutes. The airflow conditions are also the same (i.e., no airflow from the HVAC system). The inactivation of a virus on surface takes much longer than the inactivation in the air.

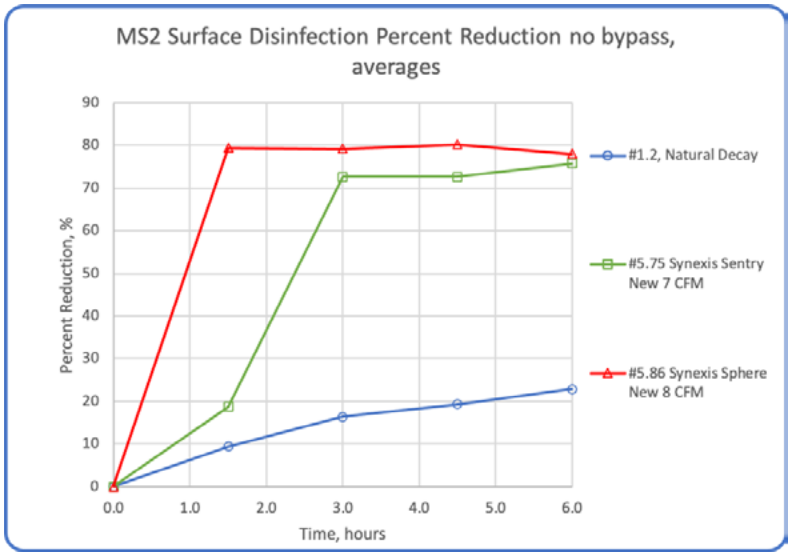

Figure 2: Inactivation of MS2 virus on surface
by Sentry and Sphere without HVAC airflow

Figure 3 illustrates the reduction in airborne MS2 virus that the Sphere and the Sentry achieved under an HVAC airflow of 6 ACH (air changes per hour). Note that the HVAC airflow is independent of and should not be confused with the small airflow caused by the internal fan in the Sentry or Sphere device. The latter is intended to diffuse the DHP into the room.

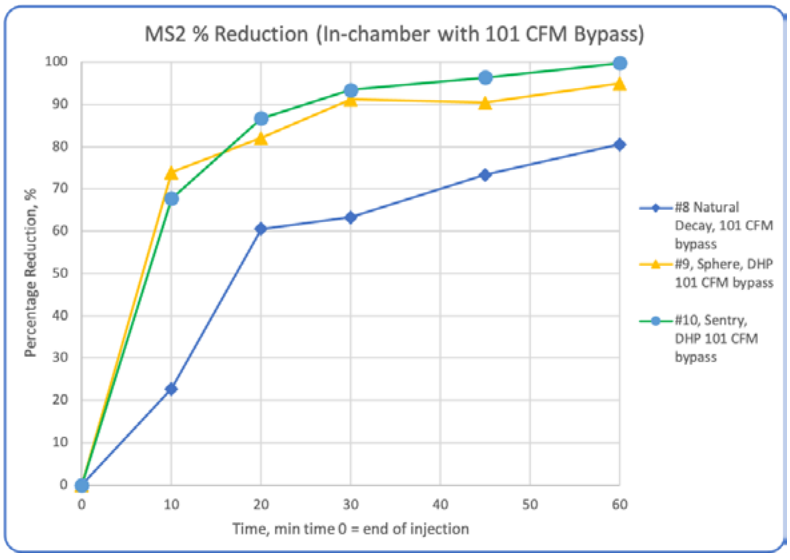

Figure 3: Inactivation of MS2 virus in air by
Sentry and Sphere with HVAC airflow of 6 ACH

Figure 4 illustrates the reduction in airborne MS2 virus that the Blade achieved under an HVAC airflow of 20 ACH (air changes per hour). Note that, since the Blade does not have its own fan, the DHP that the Blade generates is carried into the room by the HVAC airflow. In general, higher HVAC airflows slow down the effect of Synexis devices. This is because DHP molecules are polar and stick to the surfaces of coils, fans, ducts, etc. as they go through the HVAC system; thus, with fewer DHP molecules in the room, the virus inactivation process is slower.

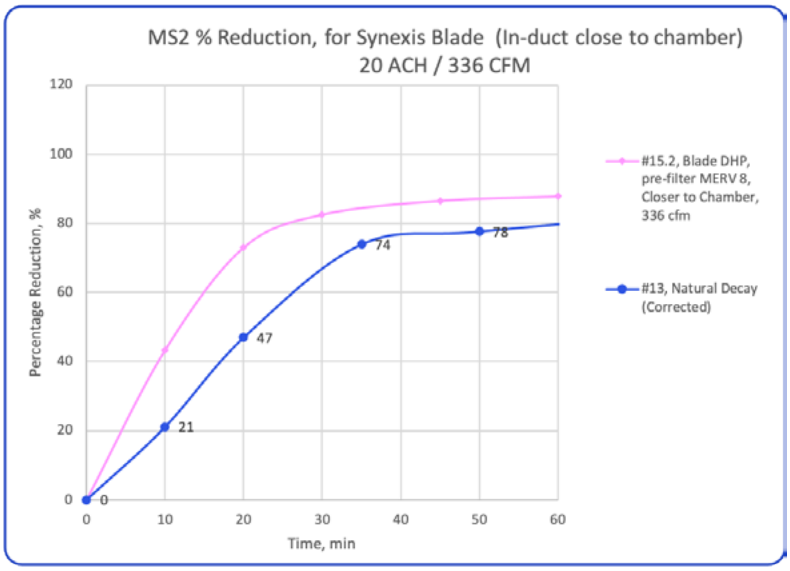

Figure 4: Inactivation of MS2 virus in air by *Blade with HVAC airflow of 20 ACH*

Figure 5 illustrates the reduction of the MS2 virus on surface achieved by Blade under an HVAC airflow of 6 ACH (air changes per hour).

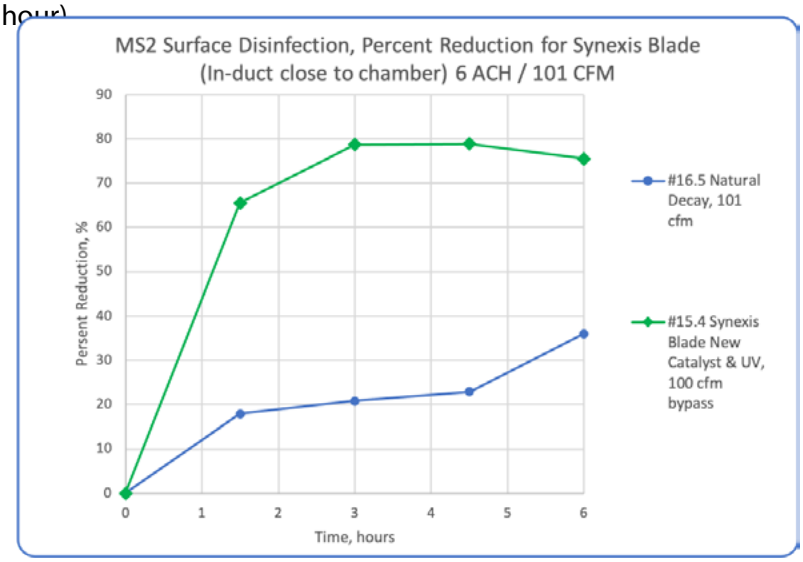

Figure 5: Inactivation of MS2 virus on surface *by Blade with HVAC airflow of 6 ACH*

Application considerations. The Synexis technology needs to be considered within the entire context of your IAQ strategy. Factors such as the volume of a room, the air changes per hour, the surfaces in a room, the number and location of occupants, etc. can affect the deployment of Synexis' technology. A Trane® Indoor Air Quality representative can help you assess the needs of your building, determine if Synexis is the right solution and, if so, recommend the appropriate arrangement to be deployed (number of devices, location of devices, etc.)

Learn more at trane.com/iaq

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]In chemical terms, H2O2 → 2OH*

[5]For those with a penchant for chemistry, here is how DHP is produced. First, photons hit the catalyst and produce free electrons (e-) and holes (h+, i.e., an electron *deficit). Holes react with water molecules in the air to produce hydroxyls: 2h+ + 2H2O* → 2H+ + 2OH*. Two hydroxyls combine into DHP – the way this reaction is achieved *is a major differentiator for Synexis: 2OH** → H2O2 (oxidation reaction). A corresponding reaction produces DHP from ambient oxygen: 2e- + 2H+ + O2 → H2O2 (reduction reaction).

[6]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.

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