Engineering and Optimizing a Modern Upper Air UVGI Solution

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1. COVID-19 HIGHLIGHTS AIRBORNE TRANSMISSION OF PATHOGENS

There is a growing body of evidence supporting the potential for airborne transmission as the major factor in the spread of SARS-CoV-2 (Nardell & Nathavitharana, 2020) (Allen & Marr, 2020). In an open letter last year, over 200 scientists expressed that studies show “beyond any reasonable doubt” that microdroplets are released during exhalation, talking and coughing, and that those droplets can stay aloft in the air and pose an infection risk at distances beyond 1-2m from infected individuals (Morawska & Milton, 2020). Additionally, Prather, et al. note that these droplets can remain suspended in the air like smoke for seconds to hours and accumulate in poorly ventilated indoor air (Prather, et al., 2020). While media attention and the sheer scale of the COVID-19 pandemic have brought airborne (community) transmission into the public consciousness, it is not a novel mode of transmission. Airborne transmission has been demonstrated for many pathogens including influenza (Ather, Mirza, & Edemekong, 2020), SARS-CoV-1 (Yu, et al., 2004) and MERS-CoV (Xiao, Li, Sung, Wei, & Yang, 2018) . Additionally, new viral diseases are likely to continue to emerge via animal-to-human host switching (Parrish, et al., 2008). Therefore, control of airborne disease transmission is of the utmost importance now, as society continues to battle COVID-19, and it will remain important moving forward to battle a variety of infectious diseases.

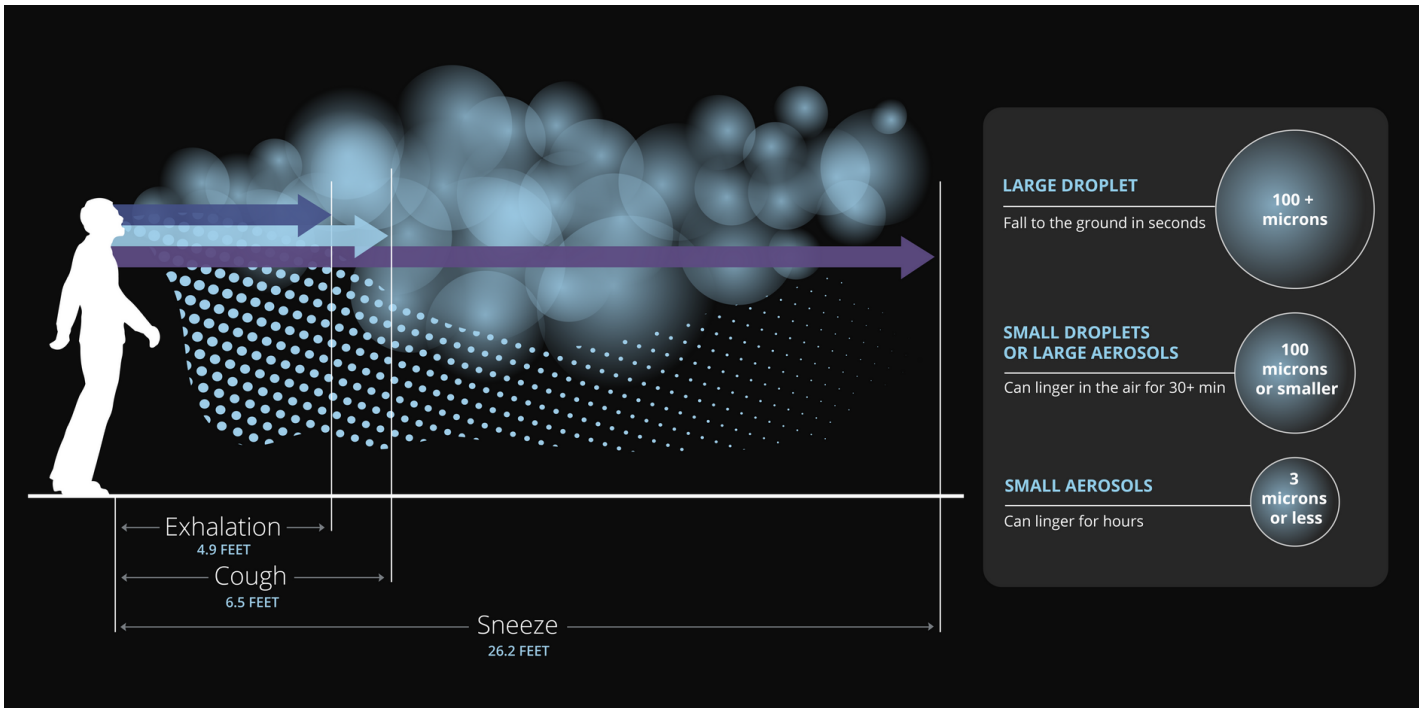


Figure 1: An adaptation of a diagram from The Wall Street Journal explaining aerosol transmission. (The Wall Street Journal, 2020)

2. UPPER AIR UVGI FOR AIRBORNE INFECTION CONTROL

Ultraviolet germicidal irradiation (UVGI) has a long history of use and has been proven to kill or inactivate a wide range of pathogens including E. coli, mycobacterium tuberculosis, staphylococcus aureus, salmonella typhimurium, adenoviruses, hepatitis, HIV-1, measles, mumps, cold viruses, influenza and varicella zoster (chickenpox) (Wells, Wells, & Wilder, 1941) (Kowalski , 2009) (Malayeri, Mohseni, Cairns, & Bolton, 2016). More recently, studies including Luminii's own testing (discussed below in section five) have proven that UVGI is highly effective at inactivating SARS-CoV-2 (Storm, et al., 2020) (Biasin , et al., 2020). Upper air UVGI is a proven technique for applying UV to the control of airborne pathogens (Mphaphlele, et al., 2015) (Miller, et al., 2002) (McDevitt, Milton, Rudnick, & First, 2008). Further, the US CDC has recently recommended the use of upper air UVGI to inactivate SARS-CoV-2 within occupied spaces (US CDC, 2021). Upper air UVGI works by creating a concentrated plane of light in the upper part of a room, above the heads of occupants. This enables the application of high levels of germicidal UV in the upper room, while keeping levels in the lower room below established safety thresholds. Vertical air mixing in the space created by HVAC systems, fans and/or natural convection moves air up through the germicidal zone and then back down into the lower room, providing continuous disinfection in the occupied space. The ability to provide continuous disinfection inside the occupied space sets upper air UVGI apart from in-duct UVGI systems that disinfect recirculated air but do little to prevent infection between two people sharing the same air in the same space (IES Photobiology Committee (Sliney, D. H., Chair), 2020). Figure 1 below shows an illustration of the germicidal zone created by upper air UVGI fixtures and uses arrows to illustrate how air is mixed between the upper and lower rooms.

Figure 2: An upper air UVGI application illustrating UV distribution and air mixing.

3. CURRENT UPPER AIR UVGI SOLUTIONS

There are a number of upper air UVGI solutions on the market, but most have two main limitations. First, current form factors are typically large (5”x6” in cross section or similar) and appear unsightly in architectural applications. The size and appearance of these solutions is mainly driven by the light source. Large reflectors are needed to focus the light emitted from a low-pressure mercury lamp and even then, the beam is not shaped precisely enough to sufficiently limit UV in the lower room. For that, deep, matte black louvers are used which add further to the size of the fixture and impart a somewhat industrial aesthetic. Second, most existing solutions employ potentially hazardous, low-pressure mercury lamps as their light source. Mercury from disposed lighting devices is considered a serious environmental issue with 128 countries having signed the Minamata Convention on Mercury which aims to protect humans and the environment from mercury’s adverse effects (Kadam, Nair, & Dhoble, 2019) (Minamata Convention on Mercury, 2021). While it makes sense that end users would look past these limitations during the COVID-19 pandemic, they will hinder adoption by aesthetically minded and environmentally conscious users moving forward.

4. A NEW APPROACH TO UPPER AIR UVGI

With the limitations of current upper air solutions in mind, Luminii sought to create a solution that would leverage their deep materials and optical design experience as well as their specialized manufacturing facilities. This approach yielded a solution based around a UV-C LED light engine rather than the more traditional mercury source. The small source made a minimalistic fixture form factor possible, allowing for seamless architectural integration and use in environments where existing solutions would be too intrusive. The mercury free nature of the LED light source created a fixture that aligns well with the missions and policies of environmentally conscious users.

One of the major challenges of any upper air UVGI system is beam shaping. While current solutions achieve this with large reflectors and louvers, Luminii’s solution utilizes multiple convex quartz lenses over the LEDs, optically coupling them with a custom PVD coated linear aluminum reflector to precisely re-construct the ray path. Leveraging the help of this refract-reflect system, Luminii is able to precisely control the ray path to deliver an intense ≈10 degree beam, without employing a large system of louvers that would hinder the aesthetic quality of the design (Figures 4 and 5). This allows the creation of a focused germicidal zone as shown above in Figure 1, making the system both safe and effective. Table 1 shows center beam intensity values for the Purifii AER W and a commercially available low-pressure mercury upper air solution. Figure 6 shows the beams emitted from both fixtures on a fluorescent card to illustrate relative size and shape.

Figure 3: Purifii AER W

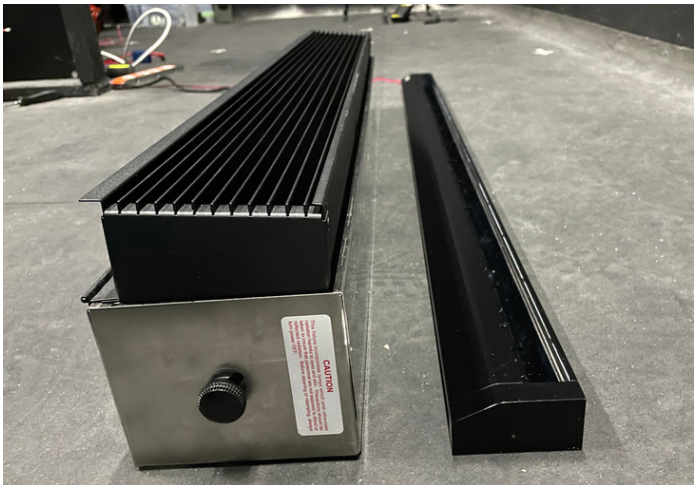


Figure 4: A traditional low-pressure mercury upper air fixture (left- manufacturer name has been obscured) next to a Purifii AER W fixture (right).

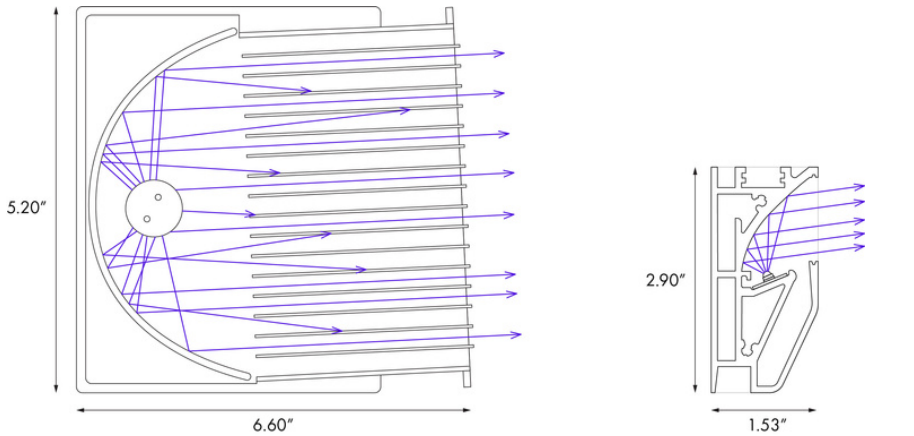


Figure 5: An illustration of the ray path in a traditional low-pressure mercury upper air fixture (left- optical efficiency of 4%) and the Purifii AER W (right- optical efficiency of 83%).

DISTANCE FROM FIXTURE	PURIFII IRRADIANCE (uW/cm^2)	TRADITIONAL DESIGN IRRADIANCE (uW/cm^2)	DIFFERENCE BETWEEN TRADITIONAL & PURIFII (%)
1′	1368	620	221%
3′	534	198	270%
5′	244	96	255%
9′	86	30	286%
16′	30		

Table 1: Irradiance measurements from Purifii AER W and a traditional low-pressure mercury upper air fixture.

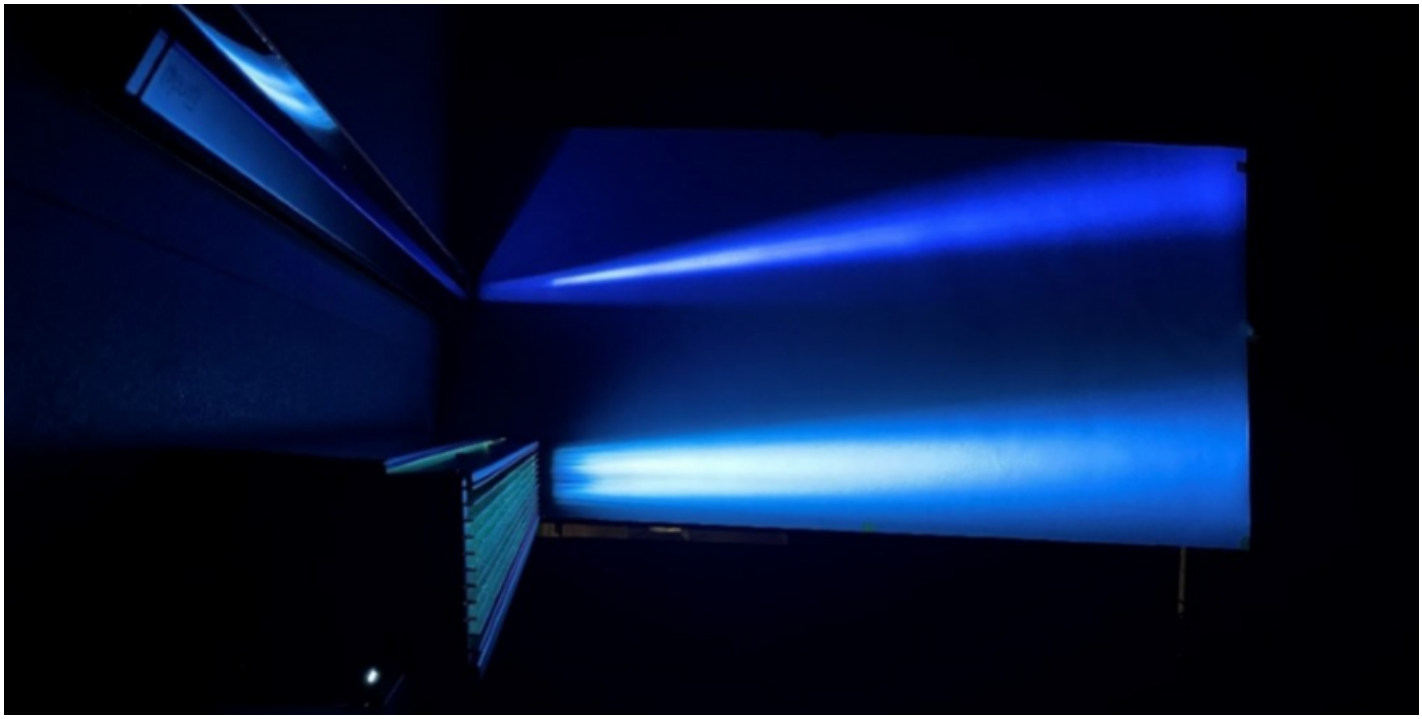


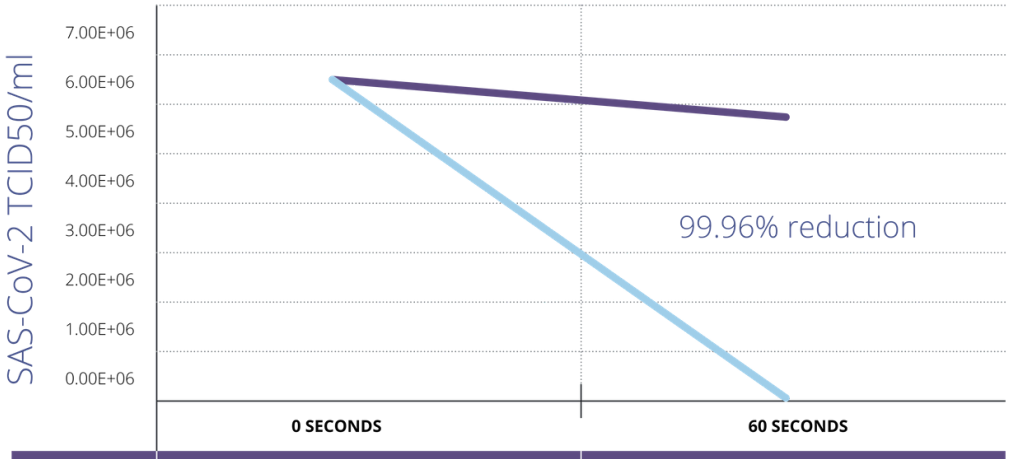
Figure 6: Beams emitted from a Purifii AER W (top) and a traditional low-pressure mercury upper air fixture (bottom).

5. VALIDATION OF EFFICACY

To confirm the efficacy of the Luminii upper air system, a third party BSL3 lab tested the system under laboratory conditions meant to simulate an interior architectural environment. Innovative Bioanalysis performed three sets of experiments that demonstrated the system's effectiveness at inactivating SARS-CoV-2. SARS-CoV-2 was chosen as the target pathogen for these experiments because of the limited availability of published literature on SARS-CoV-2 UV dose response and the immediate need for effective systems to help control the current COVID-19 pandemic. The experiments demonstrated a large reduction in virus present.

The first set of testing evaluated the 275nm LED's effectiveness at inactivating virus on a surface. The experimental procedure consisted of two control slides and two experimental slides, with each group exposed to a different dose of UV. Glass slides were inoculated with a high concentration of viral media and allowed to dry for 11 minutes. The experimental samples were then exposed to a dose of the UV. The slides were then rinsed with viral media solution and analyzed for remaining viral concentration. The Luminii LEDs were tested at two different power levels, with their output measured and confirmed before experimentation. The low driver had a measured peak spectral emission at 275nm with an irradiance of 170 μW/cm^2 at the sample. The resulting dose for the 60 seconds of exposure was 10 mJ/cm^2. The high driver had a measured peak spectral emission of 276nm with an irradiance of 732μW/cm^2 at the sample. The resulting dose for the 60 seconds of exposure was 44 mJ/cm^2. The resulting reductions in viral concentration from the surface testing can be found in Figure 7. The samples were only tested for a 4-log reduction, so a much lower concentration of virus would be expected for the high driver test based on the delivered UV dosage, but was not detectable in the experiment.

SARS-CoV-2 Surface Disinfection - Low Power

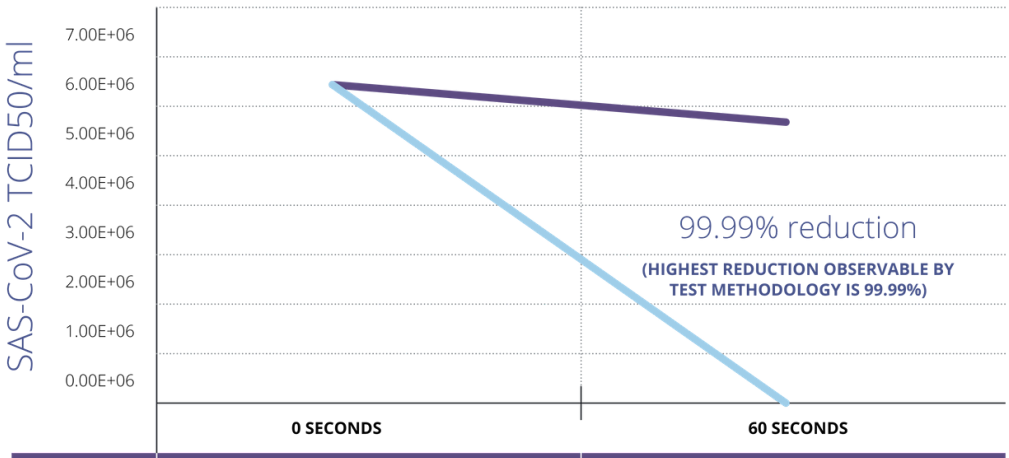


	0 SECONDS	60 SECONDS
CONTROL	6.32E+06	5.83E+06
LOW DRIVER	6.32E+06	2.58E+03

Exposure Time

Percent Reduction: 60 Seconds: 99.96%

SARS-CoV-2 Surface Disinfection - High Power



	0 SECONDS	60 SECONDS
CONTROL	6.32E+06	5.83E+06
HIGH DRIVER	6.32E+06	6.32E+02

Exposure Time

Percent Reduction: 60 Seconds: 99.99%

Figure 7: UV surface inactivation test results for SARS-COV-2.

The second set of testing evaluated the Purifii AER WALL device's efficacy against aerosolized SARS-CoV-2. The testing was performed in an 8'W x 8'H x 10'L sealed chamber with the fixture mounted centered on one 8' wall. The air in the chamber was mixed using a customized system designed to simulate airflow from an HVAC system. Unlike typical HVAC systems that exhaust a portion of circulated air, the custom system only recirculated air within the room to create a well-mixed space for testing.

Testing was performed by nebulizing a viral stock in the room to a concentration of 6.32 X 10^6 TCID50/mL. A control test was performed with only the air flow system running and the experimental test was performed with both the air flow system and the UV upper air device running. Samples were taken at 5 minutes, 10 minutes and 30 minutes through a vacuum sampling system and incubated to report viral inactivation. Results can be found in Figure 8.

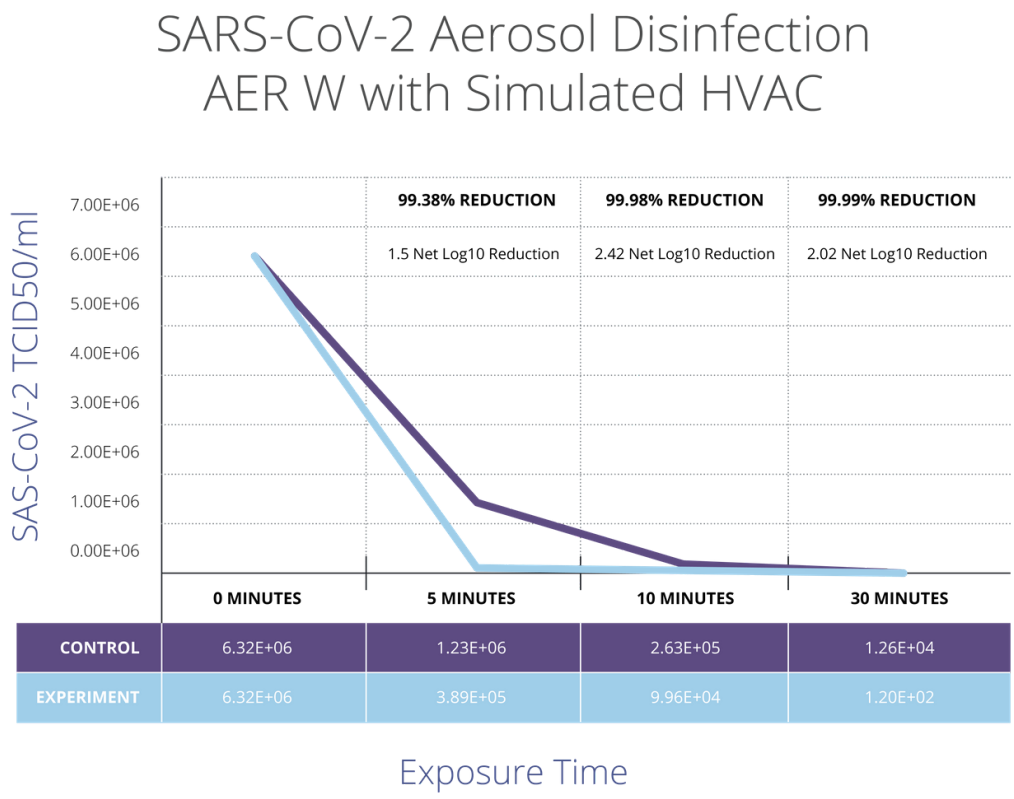


Figure 8: UV aerosol inactivation test results for SARS-COV-2 with simulated HVAC system.

The third set of testing used a larger 8'W x 8'H x 20'L chamber with one AER W fixture mounted on each 8' wall. For this test, there was no air mixing in the chamber during the experiment. Testing was performed by nebulizing a viral stock in the room to a concentration of 6.32 X 10^6 TCID50/mL. One control test was performed by running the test with the AER W fixtures off, and the experimental test was performed with both fixtures on. Results shown in Figure 9 show a net reduction of 4.25-log (99.994%) in 20 minutes.

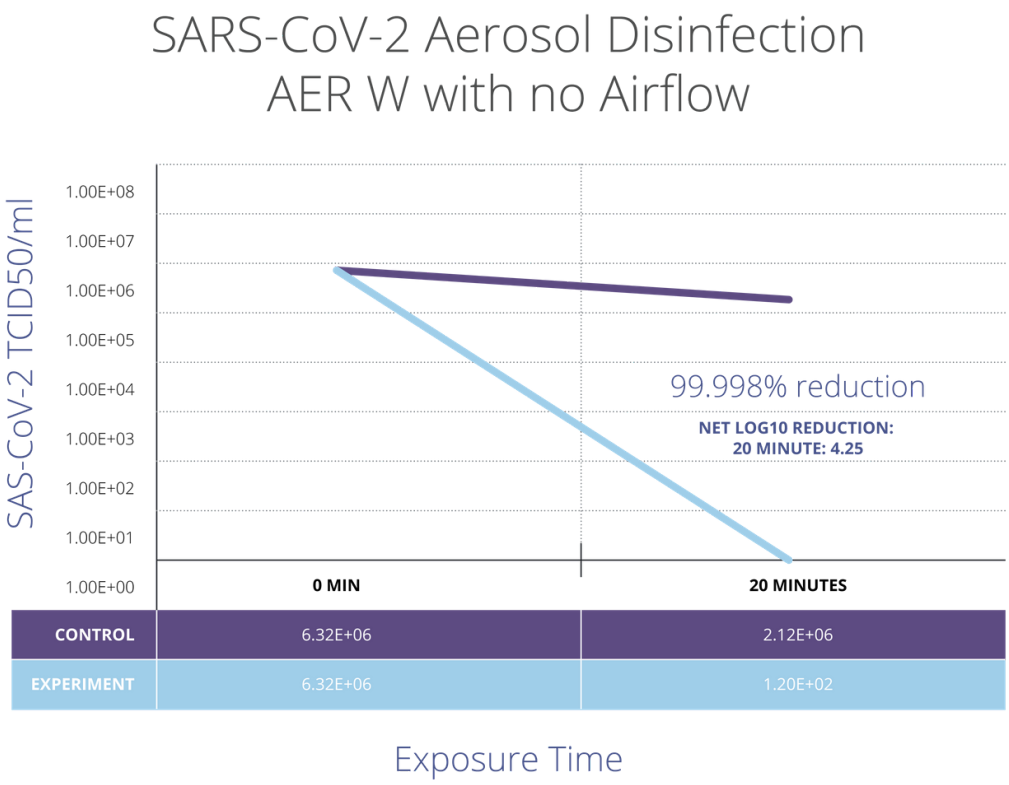


Figure 9: UV aerosol inactivation test results for SARS-COV-2 with no air mixing.

6. ESTIMATING EFFECTIVENESS

In addition to detailed experimentation to prove the efficacy of their upper air system in the lab, Luminii, with support from outside experts in the field, has refined a calculation tool to estimate system effectiveness in real world settings. The tool uses well established, published methods to calculate disinfection efficiency based on UVGI system inputs and then estimates the infection risk for a variety of pathogens by applying the Wells-Riley infection risk model (Riley, Murphy, & Riley , 1978).

Ultraviolet Germicidal Irradiation Handbook: UVGI for Air and Surface Disinfection by Wladyslaw Kowalski summarizes several UVGI calculations that are repeatedly used in published studies on upper air UVGI (Kowalski , 2009). Luminii's calculation tool draws on this work and automates much of the process to enable rapid calculation of UVGI effectiveness. In general, pathogens (in addition to odors, CO2, and other contaminants) are removed from a room through a ventilation system. In the US, ASHRAE Standard 62.1 determines the ventilation requirements for acceptable indoor air quality for commercial buildings (ASHRAE, 2019). A standard metric for ventilation rate is air changes per hour (ACH) which represents the number of times the volume of air inside a room is replaced with fresh, outside air per hour. For a room with an upper air UVGI system installed, effective air changes per hour (eACH) can be used as a metric to gauge the level of disinfection resulting from the UV system. Based on a space's size, type, UVGI fixture quantity, UVGI fixture placement and a few other inputs, the tool calculates multiple parameters of germicidal effectiveness including the eACH that result from the system.

While ventilation requirements have changed over the years, the 2020 pandemic has led to ASHRAE recommending increased mitigation of infectious aerosols through increased ventilation and through UVGI to supplement outside airflow (ASHRAE, 2020). The eACH calculated describes to what extent the Purifii system enhances existing air changes for a given pathogen in a space.

An important input in UVGI effectiveness is the pathogen's k constant (also referred to as Z constant in literature). It represents the susceptibility of a specific pathogen in a certain suspension media (air, water or surface) to being inactivated by ultraviolet light (Kowalski , 2009). Aerosolized pathogens are typically easier to inactivate than when suspended in a liquid, indicated by a larger k constant, lending to the effectiveness of upper room UVGI (Kowalski , 2009). As of the creation of the calculator tool, there is a lack of conclusive research on an aerosol k constant for SARS-CoV-2, however, initial research appears consistent with values for SARS-CoV-1 calculated at $0.377 \pm 0.119\, m^2/J$, so this value is currently used (Walker & Ko, 2007) (Beggs & Avital, 2020). Pathogens such as mycobacterium tuberculosis and coronavirus are easier to inactivate with UVGI systems than influenza, resulting in greater risk reduction benefit from a UV system as illustrated in the below application examples.

Additionally, the tool estimates infection risk using the same approach as the infection risk model created by the University of Colorado (Jimenez, 2020), which draws upon several previously published works on aerosol transmission (Miller, et al., 2020) (Riley, Murphy, & Riley , 1978) (Buonanno, Stabile, & Morawska, 2020) (Buonanno, Morawska, & Stabile, 2020). The model uses the analytical solution of an indoor infectious dosage model (Miller, et al., 2020) to inform the Wells-Riley infection model for both masked and unmasked cases. The calculator was generalized beyond SARS-CoV-2 to demonstrate the benefits of UVGI to reduce the spread of influenza A and tuberculosis to all members of a space. The quantity of infectious aerosols released, known as quanta emission rate, constitutes the largest source of variability in infection risk models. Superspreading case studies compared to other measurements constitute uncertainty as large as a factor of 5 or 10 and are highly influenced by respiratory activity and exhalation rate (Jimenez, 2020). To make more conservative estimates, the calculator uses typical values for quanta emission rather than superspreading case studies. To account for different respiratory activities, an approach similar to Buonanno's estimation of airborne viral emission for SARS-CoV-2 was applied to Influenza A and Tuberculosis:

$$ER_j = c_v c_i IR \int_0^{10\mu m} N_{d(D)dV_{d(D)}} \approx c_v c_i IR \sum_{i=1}^{n} \left(N_{i,j} V_i\right)$$

where the quanta emission rate (ER, quanta hr^{-1}) for a particular expiratory activity (j, e.g. oral breathing, talking, yelling) is the product of the viral load (c_v) a conversion factor for viral load to quanta (c_i), inhalation rate (IR) and the amount of aerosolized particles ($N_i V_i$)(Buonanno, Stabile, & Morawska, 2020). While the viral load and conversion factors for SARS-CoV-2 have been studied during the pandemic, this approach is generalized for other pathogens by using previously studied oral breathing emission numbers (ER_0) with the following equation:

$$ER_j = ER_0 \left(\frac{IR}{IR_0}\right) \sum_{i=1}^{n} N_i V_i$$

Due to the large variation in emission rates and the assumption of a well-mixed space, numbers produced from any risk calculation should be used more for comparison, like we compare risk with and without UVGI, rather than for absolute infection risk percentages. Taking into account these considerations, Luminii's UVGI system delivers efficient risk reduction equivalent to large changes in a space's ventilation.

Below we model four application examples to demonstrate how the calculator can be used to characterize system performance in real architectural applications.

APPLICATION EXAMPLE 1- CAFÉ

Figure 10: Purifii AER W installed in a café.

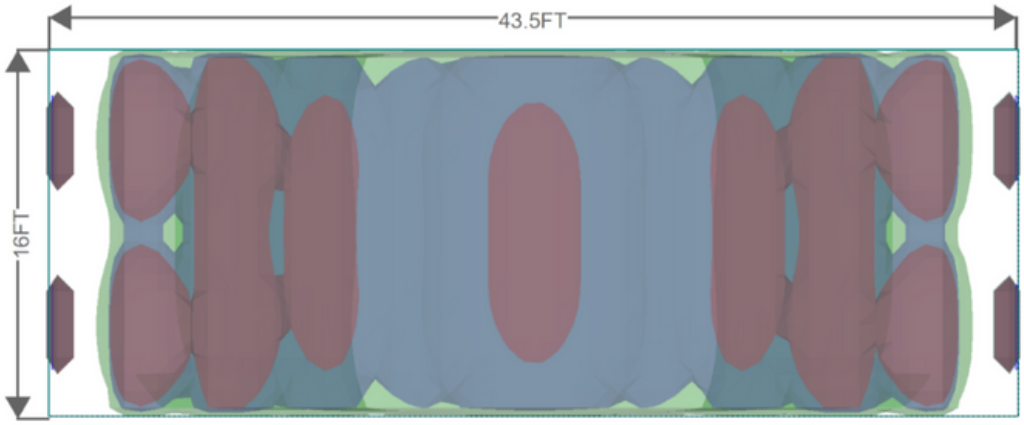


Figure 11: Plan view showing 10 (green), 30 (blue) and 50 (red) µW/cm^2 fluence rate distribution in the cafe.

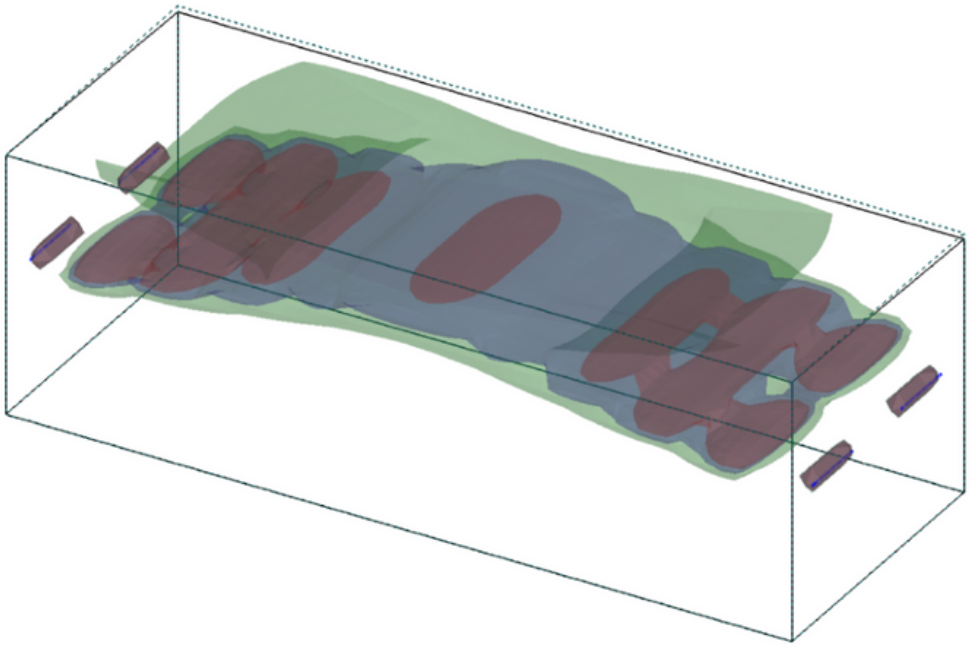


Figure 12: Isometric view of fluence rate distribution in the cafe.

If we consider a café with a front of house area of approximately 700 square feet, four fixtures are required to cover the space. For the layout shown in Figures 11 and 12 , the four fixtures generate a total average fluence rate of 5.63 μW/cm^2 for the entire space. Based on ASHRAE guidelines, the café would have ventilation that generates 1.9 ACH (bringing in a volume of outside air equivalent to 1.9 times the volume of the space per hour). If we consider that patrons typically spend an hour with 20 total people in the space who are standing and talking, then if one person infected with COVID-19 were in the space there would be a 1% chance of infection to all people in the space. By installing Luminii's UVGI system, the risk of infection goes down to 0.1%. This 90% infection risk reduction is created by increasing the effective ventilation rate to 38.5 ACH, larger than any typical ventilation system alone would generate for this space. Even after vaccines have contained the COVID-19 pandemic, UVGI systems will continue to be an effective means of fighting various airborne infections. For example, consider influenza A (the flu); there is a 4% chance of infection to everyone in the store with one infected person that is reduced to 0.9% with the UVGI system, reducing the risk of infection by 75%.

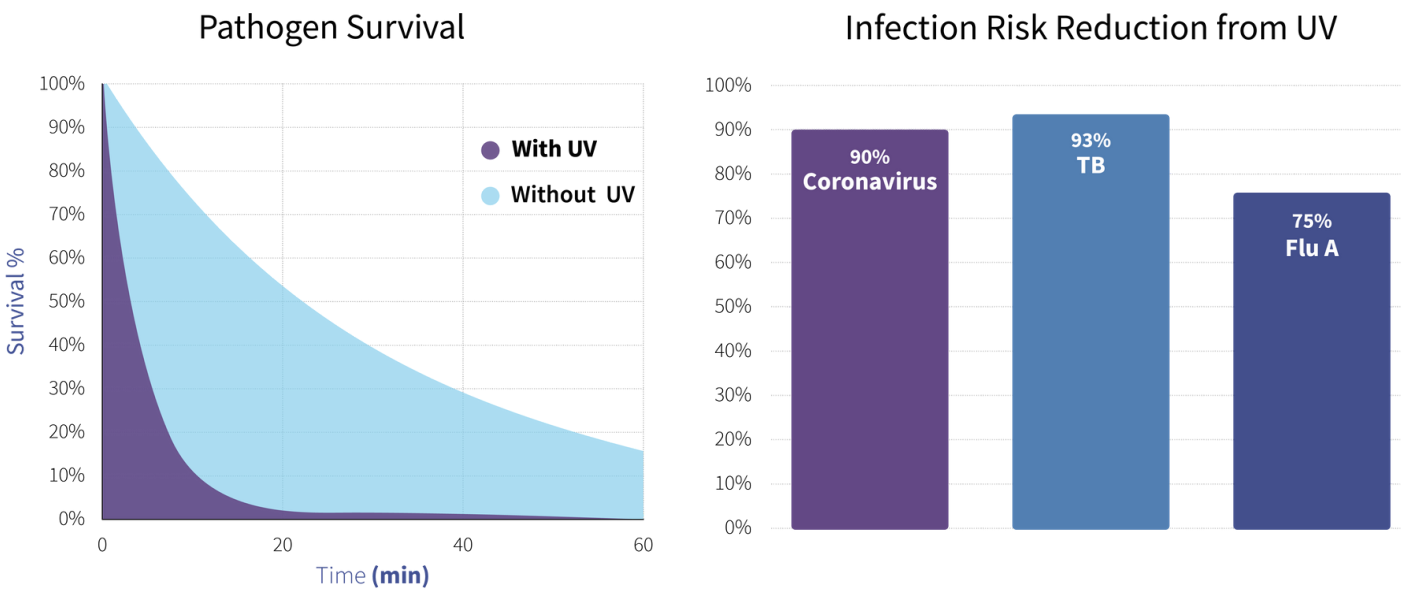


Figure 13: Comparison of pathogen survival and infection risk reduction in a typical café. Left shows the pathogen decay over time for SARS-CoV-2; right shows the infection risk reduction caused by the UVGI system for various airborne infections.

APPLICATION EXAMPLE 2- K-12 CLASSROOM

Figure 14: Purifii AER W installed in a K-12 classroom.

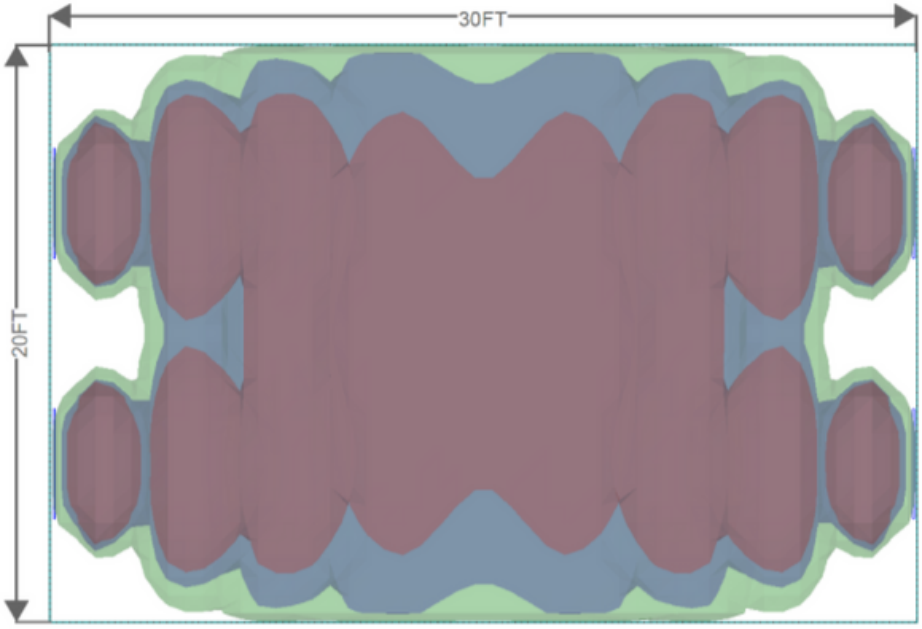


Figure 15: Plan view showing 10 (green), 30 (blue) and 50 (red) µW/cm^2 fluence rate distribution in the classroom.

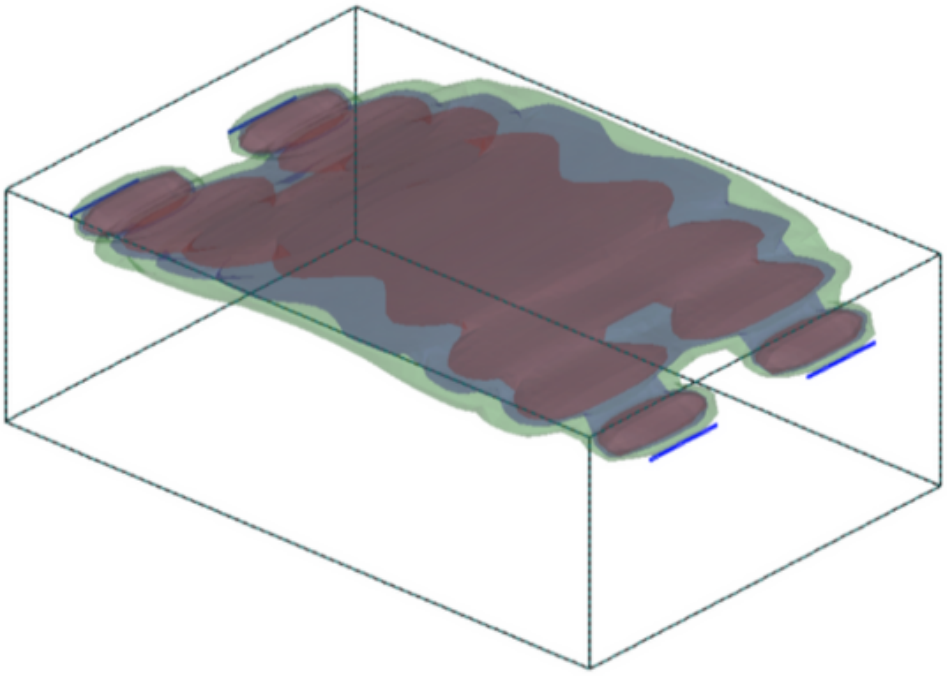


Figure 16: Isometric view of fluence rate distribution in the classroom.

A similar benefit can be seen for a classroom environment. For a typical 600 square foot K-12 classroom, ASHRAE guidelines dictate a 2.7 ACH ventilation rate. Considering students and teachers typically spend a total of 6 hours in class per day with 12 people per class (assuming reduced occupancy based on current social distancing guidelines), the calculator can evaluate the infection risk and risk reduction. If a teacher were infected with COVID-19, then students in the class have a 10-50% chance of infection that goes down to 1-9% with Luminii's UVGI system. If a student were the infected person, the rest of the class would have a 2-9% chance of infection based on how much the student talks and engages during class that drops to 0.3-1% with the UVGI system. This 86% risk reduction results from increasing the total air changes per hour (baseline ACH plus eACH) to 25.8 with 4 Luminii fixtures as laid out in Figures 15 and 16. Quanta exhalation rate is highly dependent on respiratory activity, so a teacher talking loudly to the class results in a larger infection risk than a student who spends most of the time listening to a lecture. Similarly, for Influenza A, a sick teacher poses a 40% risk of infection to the class compared to 10% with UVGI and a student poses a 7% risk compared to 2% with UVGI. UVGI systems can help make teachers and students alike safer and reduce the spread of infections across schools.

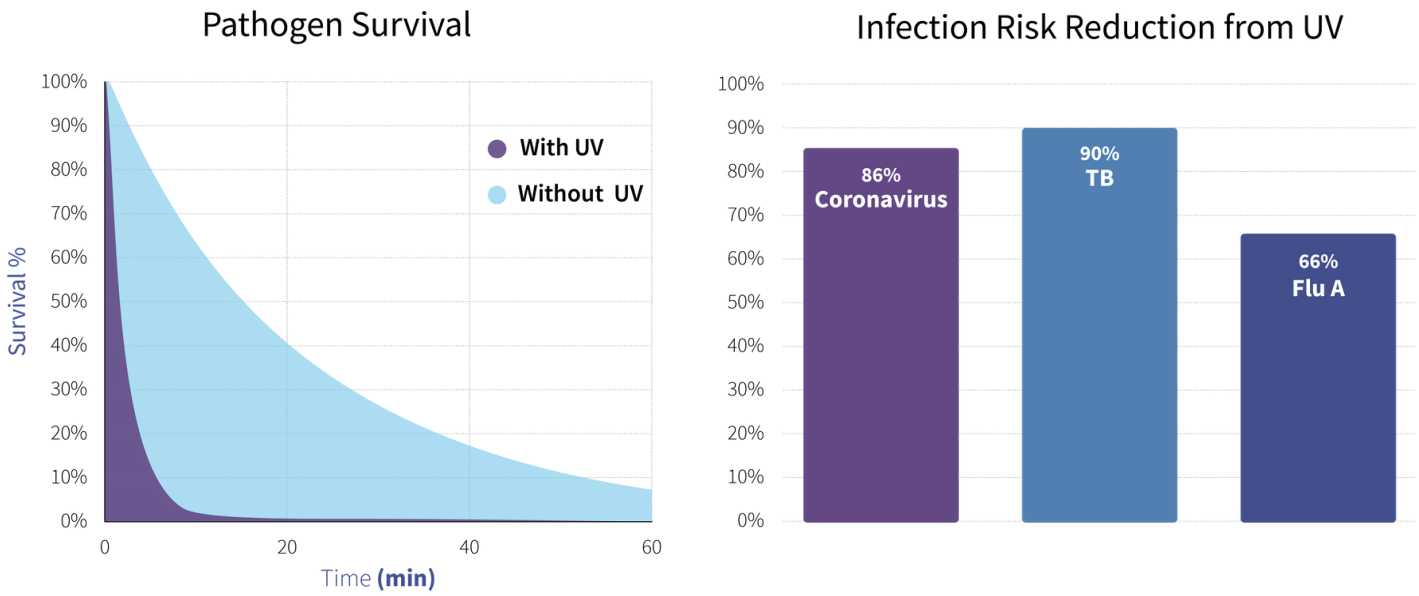


Figure 17: Comparison of pathogen survival and infection risk reduction in a classroom. Left shows the pathogen decay over time for SARS-CoV-2; right shows the infection risk reduction caused by the UVGI system for various airborne infections.

APPLICATION EXAMPLE 3- GROUP CYCLING CLASS

Figure 18: Purifii AER W installed in a group cycling space.

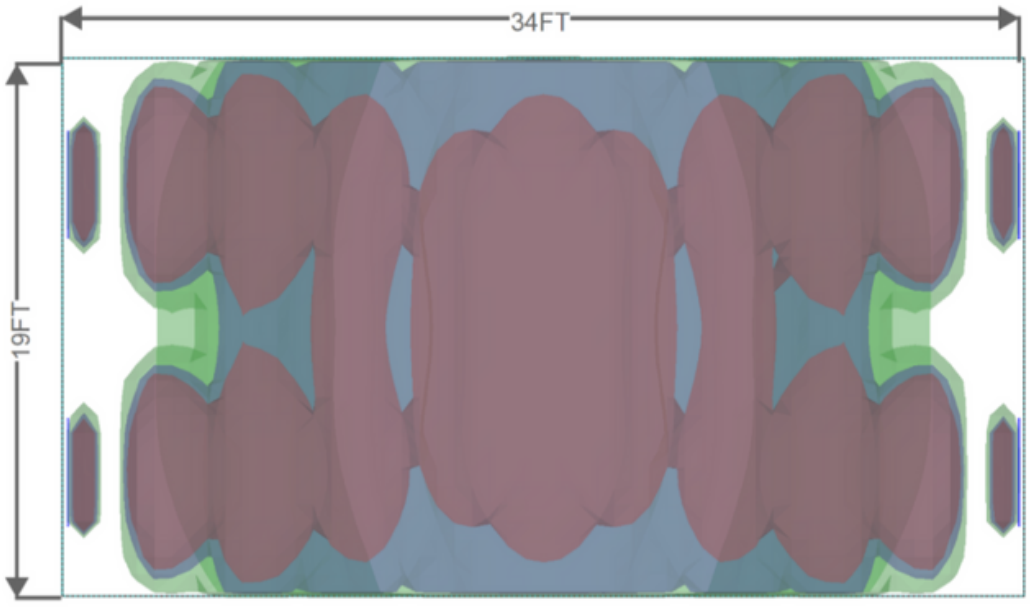


Figure 19: Plan view showing 10 (green), 30 (blue) and 50 (red) µW/cm^2 fluence rate distribution in the group cycling space.

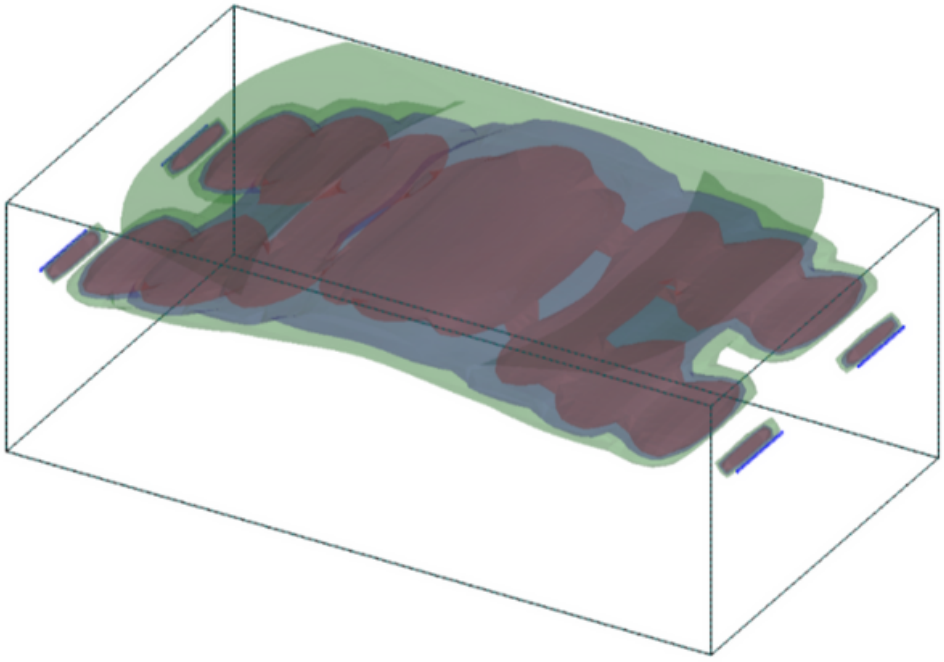


Figure 20: Isometric view of fluence rate distribution in the group cycling space.

Group fitness is one of the many aspects of life that people are eager to get back to. The nature of the activities, however, are very conducive to spreading airborne pathogens. The increased respiratory level means that any infected person in the room outputs more infectious particles than they would in a situation where they were at rest. In this example we show a 650 square foot fitness studio with 16 participants in addition to an instructor; ASHRAE guidelines would estimate 3.7 ACH for such a space. If a participant in the class were infected with COVID-19, then they would pose a 4% risk of infection to everyone in the class. With four fixtures laid out as shown in Figures 19 and 20, the risk of infection would be reduced to 1%. If the instructor were infected, since they are talking loudly to the class, this would pose a 20% chance of infection to the class that would be reduced by 75% with Luminii's UVGI system. The four fixtures create an additional 19 eACH that helps keep the classes safe while enjoying fitness together. Looking beyond the pandemic, the flu can spread in group fitness classes. The class has a 50% chance of infection from an infected instructor, and a 10% chance of infection from an infected participant. These risks get reduced by 45% with the UVGI system in place.

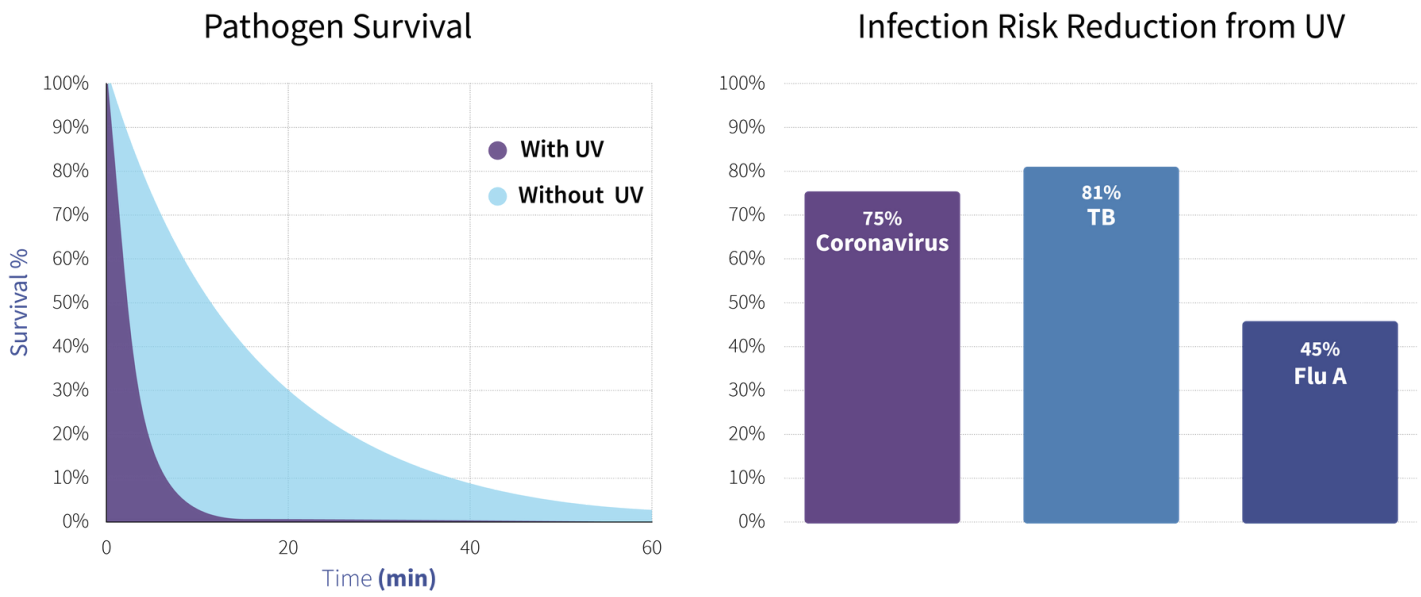


Figure 21: Comparison of pathogen survival and infection risk reduction in a fitness class. Left shows the pathogen decay over time for SARS-CoV-2; right shows the infection risk reduction caused by the UVGI system for various airborne infections.

APPLICATION EXAMPLE 4- COMMON AREA OF A SENIOR LIVING FACILITY

Figure 22: Purifii AER W installed in the common area of a senior living facility.

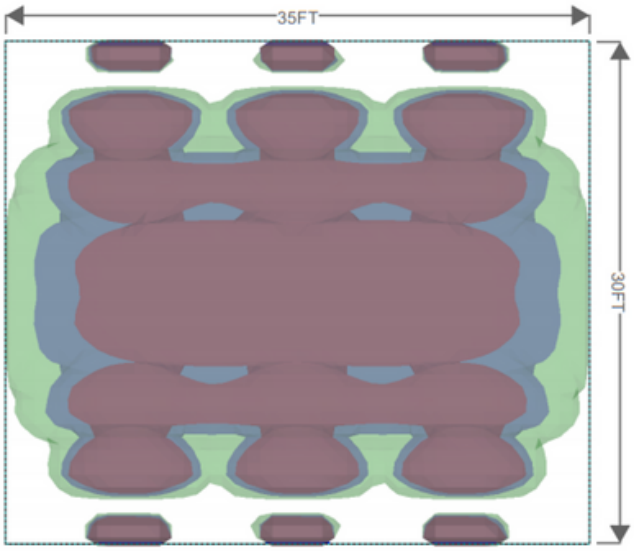


Figure 23: Plan view showing 10 (green), 30 (blue) and 50 (red) µW/cm^2 fluence rate distribution in the common area.

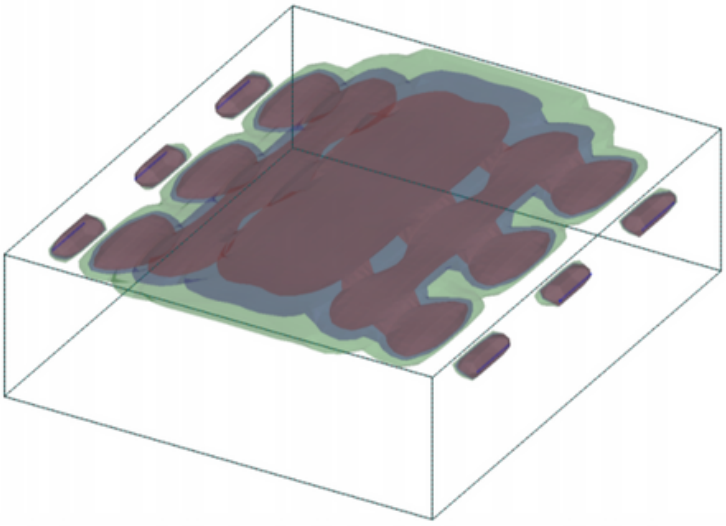


Figure 24: Isometric view of fluence rate distribution in the common area.

Common areas at senior living facilities provide families with spaces to spend time with their elderly relatives, but, as has been seen during the pandemic, can also create a dangerous situation for residents who are highly vulnerable to airborne infections. Installing six UVGI fixtures in a typical 1000 square foot common area as shown in Figures 23 and 24 provides a simple way to increase the safety of social gatherings at senior living facilities. This 1000 square foot space has an expected ACH of 1.2 based on ASHRAE standards. If we consider a group of 15 people in the common area talking with each other for an hour, one person infected with COVID-19 would pose a 1% chance of infection to the other occupants. That risk goes down to 0.1% with Luminii's UVGI system. In the proposed layout, the system creates an additional 49.5 eACH, keeping those at the highest risk for serious complications much safer from coronavirus infection. Likewise, if there was someone infected with the flu, they would pose a 4% risk of infection to anyone in the room, compared to a 0.7% risk of infection with the UVGI system in place.

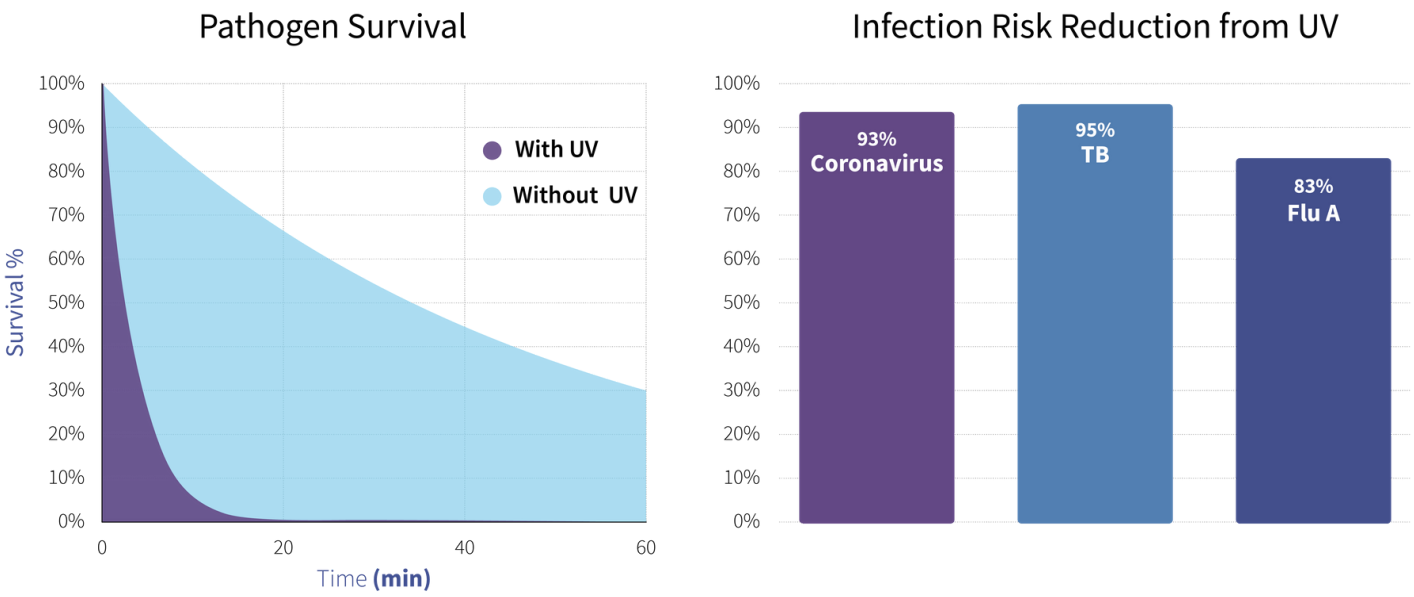


Figure 25: Comparison of pathogen survival and infection risk reduction in a senior living common area. Left shows the pathogen decay over time for SARS-CoV-2; right shows the infection risk reduction caused by the UVGI system for various airborne infections.

7. CONCLUSION

By creating a safe, effective and aesthetically pleasing upper air UVGI solution, Luminii has contributed a useful addition to existing toolkits for airborne infection control. This tool can be useful in combating the ongoing COVID-19 pandemic, and looking forward, the slim, architecturally integrated nature of the fixture opens opportunities for adoption by a much wider array of end users as compared to larger, more industrial looking fixtures. Additionally, the elimination of toxic mercury supports the environmental goals of end users and should also play a role in accelerated adoption. Proven efficacy against SARS-CoV-2 in the lab serves to vet this tool for immediate use on the front lines of the COVID-19 pandemic and existing studies on the efficacy of UV-C against numerous pathogens paint a path forward for the control of various known and novel airborne pathogens in the future.

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10. DISCLAIMERS

1. All risk reduction and effectiveness modeling described in this paper is presented for illustrative purposes only. Results are based on mathematical models employing typical and average values for many parameters. Performance in the real world will vary based on numerous factors. These results are not indicative of real-world performance and are for comparison purposes only.

2. Luminii's products are not medical devices and are not intended to diagnose, treat, cure or prevent any disease.