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Evaluation of a Visible Light Responsive Photocatalytic Coating to Resist Microbial Contamination and Increase Indoor Air Quality

Clint M. Arnett and Rebekah C. Wilson

September 2023



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Evaluation of a Visible Light Responsive Photocatalytic Coating to Resist Microbial Contamination and Increase Indoor Air Quality

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Fungal Colonization and Increase Indoor Air Quality," MIPR 11605877

Abstract

To meet new Department of Defense (DoD) energy standards, buildings are being constructed, and existing buildings are being retrofitted with tighter envelopes. These new standards can reduce operational costs significantly but also limit fresh outdoor air coming into the built environments. This can result in the accumulation of harmful substances within buildings, which can have adverse effects on its occupants. New photocatalytic coatings may be a solution to this ever-increasing problem as they have the ability to destroy both chemical and biological toxins when activated with light. This work evaluated a novel indoor-light-reactive photocatalytic coating for its ability to eliminate or reduce microbial contamination under in situ test conditions. However, air and surface sampling revealed no reduction in either viable fungi and bacteria or total airborne mold spores. Additionally, no significant differentiation could be made in the composition of volatile organics between the treated and untreated areas. However, testing the photocatalytic activity of the coating with standardized test methods and increased illumination, revealed the coating did exhibit antimicrobial activity against mold, bacteria, and viruses. This suggested that there may be limited benefit to using the indoor-light-reactive photocatalytic coating to inhibit microbial contamination unless specific lighting conditions can be met.

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Preface

This study was conducted for the Office of the Assistant Chief of Staff for Installation Management (OACSIM), Installation Technology Transition Program, Washington, DC 20310-0600 under Project 474139, “Evaluation of a Photocatalytic Sol-Gel Coating to Resist Fungal Colonization and Increase Indoor Air Quality,” MIPR 11605877. The technical monitor was Ms. Natalie R. Myers, Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL).

The work was performed by the Material and Structures Branch of the Infrastructure Science and Engineering Division, US Army, ERDC-CERL. At the time of publication, Ms. Danielle Williams was acting branch chief, Mr. Timothy W. Shelton was division chief, and Dr. Justin B. Berman was the technical director for Infrastructure Science and Engineering. The deputy director of ERDC-CERL was Ms. Michelle J. Hanson, and the director was Dr. Andrew J. Nelson.

The commander of ERDC was COL Christian Patterson, and the director was Dr. David W. Pittman.

1 Introduction

1.1 Background

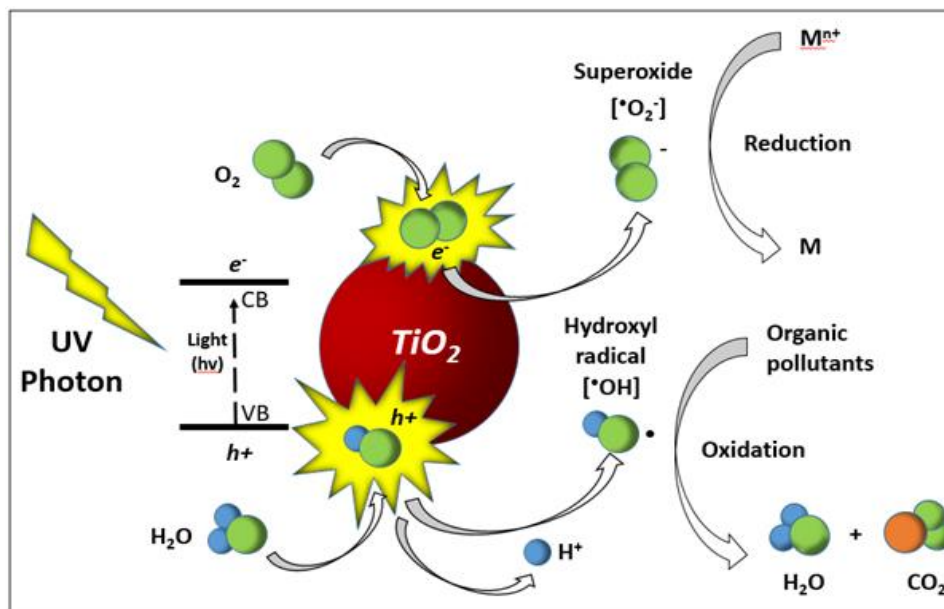
In an effort to reduce energy consumption on Army installations, buildings are being designed or retrofitted with tighter and more efficient envelopes. Although this lowers energy costs, it also has reduced the average ventilation standards significantly. Although this increases the structures' energy efficiency, the continued recirculation of indoor air and lack of fresh outdoor air has led to a significant decrease in indoor air quality according to the US Environmental Protection Agency (EPA 1991). The term sick building syndrome is used to describe a structure that exhibits acute health or comfort-related effects on its occupants, such as fatigue, headache, and respiratory and eye irritation (Ghaffarianhoseini et al. 2018; Joshi 2008). Spores, mycotoxins, and the volatile organic compounds (VOCs) released into the built environment by fungi (molds) can be major contributors to sick building syndrome (Straus 2009, 2011; Terr 2009). Fungal spores can cause mycoses and the volatile and nonvolatile compounds produced by molds can be toxic to humans either through cutaneous or respiratory exposure (Terr 2009; Bennet and Inamdar 2015). Buildup of these substances in the built environment is of great concern to the DoD as they can gravely affect building occupant health and ultimately threaten national security.

The US Environmental Protection Agency estimates that half of human illnesses can be attributed to poor indoor air quality (EPA 1991). It is estimated that up to \$70 billion is lost annually in the US due to occupant illness caused by sick building syndrome, and mold can contribute significantly to the problem (Bas et al. 2005; Nag 2019). Mold has also become a major issue in Army facilities. A recent inspection of all active-duty Army facilities has revealed that 2,100 have mold contamination that could affect soldier health and military readiness (Beynon 2023). The inspector general has stated the presence of mold within DoD facilities has placed the warfighter and their families at risk around the world (DoD OIG 2016). To ensure soldier quality of life, mold contamination at Army facilities must be addressed.

Commercial biocide-based treatments are available to treat and protect against mold proliferation. However, most commercially available

antimicrobial products are composed of harsh chemicals and require continual, labor-intensive reapplication to remain effective (Stephenson et al. 2011). Furthermore, they tend to off gas harmful toxins, which compromise indoor air quality and put both treatment personnel and building occupants at risk. To eliminate issues associated with traditional antifungal treatments, an innovative class of advanced catalytic coatings have been developed and commercialized in select foreign markets (Nanocoatings 2014). These next generation coatings are composed of catalytic titanium dioxide (TiO_2) and proprietary sol-gel formulations that are nontoxic, environmentally friendly, easy to apply, and remain active indefinitely. In the presence of water vapor, oxygen, and light, surfaces coated with TiO_2 formulations form strong oxidants, primarily hydroxyl and superoxide radicals, that can effectively destroy organic contaminants, including microorganisms and many classes of toxic VOCs, as shown in Figure 1 (Byrne et al. 2015; Desai and Kowshik 2009; Huang et al. 2016). The free radicals produced during the photocatalytic process can mineralize contaminants to carbon dioxide and water, effectively decontaminating and sterilizing the coated surface as well as destroying compounds that come in contact with them. Furthermore, sol-gels are superhydrophobic, rendering surfaces coated with them “self-cleaning” and extremely resistant to defacement. In fact, the primary use of photocatalytic sol-gel coatings in foreign markets is to protect building exteriors in urban settings from weathering with the added benefit of removing pollutants from the air. These coatings have been shown to be extremely effective at reducing the accumulation of soot and dirt (Green Millennium, “Links and Resources,” n.d.). These unique coating characteristics have great potential to significantly reduce facility maintenance costs while simultaneously increasing the quality of life on fixed installations and contingency basing environments.

Figure 1. Photocatalytic destruction of pollutants via titanium dioxide mediated oxidation-reduction reactions in the presence of light. Organic pollutants are mineralized to water and carbon dioxide by the free radicals produced (Image reproduced from Arnett et al. 2020. Public domain).



One such next generation photocatalytic nanocoating is TPX-HL, which is manufactured by Kon Corporation and distributed through a US-based manufacturing representative, Green Millennium (Pomona, California) (Figure 2). The coating is a nitrogen-doped solution composed of 0.85% TiO_2 anatase crystal that has photocatalytic properties as defined by ISO 10678, *Determination of Photocatalytic Activity of Surfaces in an Aqueous Medium by Degradation of Methylene Blue* (ISO 2010) and ISO 22197-1, *Test Method for Air-purification Performance of Semiconducting Photocatalytic Materials* (ISO 2016a).^{*} The active component, anatase, is the most commonly used photocatalyst in the world due to its reactivity and because it is inexpensive, very easy to produce, chemically and biologically inert, and nontoxic. The coating comes as a neutral solution that can be easily applied to wall coverings, tile, glass, metal, concrete, brick, and painted surfaces with a high-pressure, low-volume (HPLV) sprayer to create a thin, transparent, reactive coating. TPX-HL is super hydrophobic; has high coating applicability; and is durable, safe, and soil proof, making surfaces coated with it resistant to biotic and abiotic defacement. Traditionally, photocatalytic coating formulations require

^{*} For a full list of the spelled-out forms of the chemical elements used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 265, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

ultraviolet light (approximately 365 nm) for activity, but TPX-HL is truly unique in that the distributor claims it to be reactive under visible light from 510 nm and lower.* Therefore, the coating should be reactive under most indoor lighting sources (fluorescent, incandescent, or LED), and coated surfaces should act as purifiers capable of destroying microorganisms as well as VOCs. Furthermore, unlike other TiO₂-based catalytic coatings, TPX-HL can achieve highly photocatalytic activity and hardness after drying at room temperature. Other photocatalytic formulations require high heat (greater than 600°C) to achieve similar film hardness and photocatalytic activity. Therefore, TPX-HL can be applied in situ on almost any surface and environment.

Figure 2. Green Millennium supplied TPX-HL, an indoor-light-reactive photocatalytic coating.



TPX-HL has been tested for acute oral toxicity, mutagenicity, primary skin irritation, and toxicity as defined by the US Environmental Protection Agency and has been found to be safe. Links to all safety test reports can be found at <http://www.greenmillennium.com/tpx-hl>. The materials safety data sheet (SDS) for TPX-HL can be found in Appendix A. Additionally, TPX-HL is Leadership in Energy and Environmental Design certified by the US Green Building Council.

* For a full list of the spelled-out forms of the units of measure used in this document and their conversions, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52 and 345–47, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

1.2 Objective

Mold is found in almost all indoor environments and is quickly becoming the asbestos of the 21st century due to the adverse health effects it can cause. Fungi can proliferate on nearly any substrate, which can cause unsightly defacement and costly damage to infrastructure and contribute to poor indoor air quality (Arumala 2007). These are ever increasing problems for Army installations as maintenance costs increase and occupants are put at risk. Additionally, due to the austere nature associated with contingency basing, mold proliferation can be especially problematic, which can increase health risks to Soldiers, effecting readiness and ultimately the mission. One possible solution to this growing Army problem is to use novel formulations of catalytic coatings, which possess both antimicrobial and pollutant-destroying properties. These coatings have the unique ability to both resist fungal colonization as well as purify the air.

The objective of this demonstration was to conduct independent performance testing of one such novel photocatalytic coating, TPX-HL, to determine the coating's ability to resist microbial contamination as well as purify the air through the destruction of VOCs in a real-world environment. Results from this demonstration will help shape future guidance on the use of photoreactive coatings in an effort to mitigate microbial contamination in indoor environments and increase the quality of life on installations and contingency bases.

1.3 Approach

This demonstration evaluated a commercially available, indoor-light-responsive, photocatalytic coating for its ability to reduce microbial contamination, as well as eliminate VOCs in a restroom setting. Treated and untreated surfaces were sampled and examined for fungal and bacterial contamination using pour plate methods. Airborne contamination was evaluated by passive air sampling and analyzed for bacteria and mold based on the *Index of Microbial Air Contamination* (IMA) (Pasquarella et al. 2000). Airborne fungal spores were also collected using active air sampling with commercially available cassettes, and major classes of spores were identified and enumerated according to ASTM D7391-17, *Standard Test Method for Categorization and Quantification of Airborne Fungal Structures in an Inertial Impaction Sample by Optical Microscopy* (ASTM 2017a). Surfaces were also examined for fungal contamination via tape lift analysis and spores were identified via microscopic analysis using

ASTM D7658-17, *Standard Test Method for Direct Microscopy of Fungal Structures from Tape* (ASTM 2017b). Viable fungal and bacterial contamination on surfaces was determined by swabbing and plating as described by Public Health England (PHE) (PHE 2017). VOCs within the demonstration areas were quantitated by active collection of air samples followed by gas chromatograph–mass spectroscopy (GC-MS) analysis per US Environmental Protection Agency TO-15 test method, *Determination of Volatile Organic Compounds (VOCs) in Air* (EPA ORD 1999). The photocatalytic coating was further tested to determine its activity against mold spores, bacteria, and viruses using ISO-13125, *Test Method for Antifungal Activity of Semiconducting Photocatalytic Materials* (ISO 2013); ISO-17094, *Test Method for Antibacterial Activity of Semiconducting Photocatalytic Materials under Indoor Lighting Environment* (ISO 2014); and ISO-18071, *Determination of Antiviral Activity of Semiconducting Photocatalytic Materials under Indoor Lighting Environment* (ISO 2016b), respectively. Effectiveness of the indoor-light-reactive photocatalytic coating was compared to untreated surfaces to determine the coating's ability to control or eliminate microbial contamination and VOCs.

1.4 Scope

Fort Leonard Wood was initially identified as the demonstration location due to its proximity to the Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) and because of the relatively new three-Soldier-style barracks rooms that include bathrooms with toilets and showers. The relatively close location of Fort Leonard Wood to ERDC-CERL would minimize travel time and cost. The three-Soldier rooms would have provided identical test areas for each experimental condition as well as provided relatively equivalent patterns of use to ensure representative comparisons between the test areas are significant. However, due to COVID-19 travel restrictions, building maintenance, and troop scheduling conflicts, an alternate demonstration site had to be chosen. A second site was chosen at the Florida Avenue Residence Hall at the University of Illinois in Urbana, Illinois. However, approval to conduct the demonstration could not be granted in the relatively short window of accessibility to the housing facility for treatment, and a third demonstration site had to be identified. Ultimately the demonstration was conducted at ERDC-CERL in Champaign, Illinois, using new all-gender restrooms. The restrooms were chosen due to their relatively equivalent moderate use, identical layout (mirror images of one another), and use of

identical construction materials. Because travel to a demonstration site was no longer required, resources were leveraged to increase the number of sampling events in an effort to generate additional data points, which would be advantageous due to the relatively short demonstration period.

2 Materials and Methods

2.1 Demonstration location and photocatalytic coating treatment

Two near-identical, all-gender bathrooms located directly east of the Shaffer Auditorium on the ERDC-CERL campus were chosen to demonstrate TPX-HL (Figure 3). The restrooms were mirror images of one another and had dimensions of 2.41 m long by 2.26 m wide and 2.74 m tall. Each restroom had painted gypsum on the top one-third of the walls and ceramic tile (30.5×61 cm) on the lower two-thirds of the walls on the north, south, and east sides. The floors were concrete, covered with 30.5×61 cm ceramic tile. The ceilings were drop style with standard 61×61 cm ceiling tiles, and a single 61×122 cm florescent lighting fixture was in the center of the ceiling in each restroom. Each of the lighting fixtures housed two 122 cm 40W lightbulbs. Each restroom had a single toilet, sink, and mirror on the east wall and had one air supply vent (15×15 cm) in the ceiling, which originated from a unified source. Air hand driers were located in each restroom on the wall that divided the two areas. Inwall paper towel dispensers and trash receptacles were located adjacent to the entrances in the west wall. The doors were solid wood and swung inward toward the shared wall. The west walls were painted gypsum without tile.

Because TPX-HL is a neutral, water-type solution, surfaces were completely cleaned before application to remove dirt, grime, oils, water-repellant material, and any existing microbial colonization. Cleaning maximizes bonding to the surface and eliminates effects due to substrate impurities that can result in a loss of both material bonding and photocatalytic activity. Surface preparation and application of TPX-HL is shown in Figure 4. Treated surfaces as well as identical untreated surfaces were cleaned with a trisodium phosphate solution (TSP) (13 g L^{-1}) and rinsed thoroughly with clean water twice to remove all contaminants from the test surfaces. Cleaned surfaces were allowed to dry completely (greater than 48 hr) prior to treatment. Surfaces not to be coated were covered with tarps and masked off with painter's tape and plastic drop cloths. A Graco FinishPro HPLV 7.0 sprayer with a 0.8 mm spray tip (Minneapolis, Minnesota) was used to apply a thin film of TPX-HL at a distance of approximately 20 to 30 cm. To attain a uniform coating thickness of greater than $0.12 \mu\text{m}$, the spray rate recommended by the manufacture was used (see Appendix B). Coverage was estimated by the volume of TPX-HL sprayed m^2 of substrate covered. To ensure consistent coverage, a total of two coats were

applied in alternating directions. The painted gypsum, wall tiles, and ceiling tiles were coated with TPX-HL. The mirror, toilet, sink, door, and stainless-steel fixtures were not coated. Additionally, the floors were not coated because that would have required stripping of the surfaces and the durability of TXP-HL on a heavily trafficked surface was unknown. All treated materials were allowed to dry for 17 hr before use.

Figure 3. Indoor-light-responsive photocatalytic coating demonstration area located at the Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL), east of the Shaffer Auditorium. Dimensions and orientation of each all-gender restroom (top left), image of entrance (top right), the east wall of the north (bottom left), and the south (bottom right) restrooms.



Figure 4. Demonstration area surface preparation and treatment with TPX-HL. Surfaces in each restroom were cleaned with trisodium phosphate solution (TSP) (*top left*). Masking off of all surfaces not to be treated is shown in the *top middle* and *top right* images. Application of photocatalytic coating to walls and ceiling with a high-pressure, low-volume (HPLV) sprayer (*bottom left*) and area after application (*bottom middle and right*).



Temperature, humidity, and light were monitored with data tracking sensors every 60 seconds for 5–8-day intervals (depending on the data logger's battery life), five separate times throughout the duration of the demonstration in each bathroom to ensure environmental conditions were consistent between each of the areas being monitored. Room illumination was measured with a Reed SD-9300 data logger equipped with a lux probe (Wilmington, North Carolina), and relative humidity and temperature were measured using a Sper Scientific 800021 data logger with a combination temperature and humidity probe (Scottsdale, Arizona). The data loggers were placed in weatherproof boxes, and the combination temperature and humidity probes were mounted on the side of the box with the probe tips approximately 2.5 cm. below the base of the boxes to allow air to flow freely around the probes (Figure 5). The lux meters were attached to the front of the boxes vertically to measure the illumination

on the wall surfaces. Both meters were mounted in the same location above the entry door in each restroom in relation to the source of light, which was approximately 2.3 m above the floor in the center of the west walls in each restroom.

Figure 5. Humidity, temperature, and light data loggers in weatherproof case (left) and loggers mounted on the west wall above the entrance of the restroom (right).

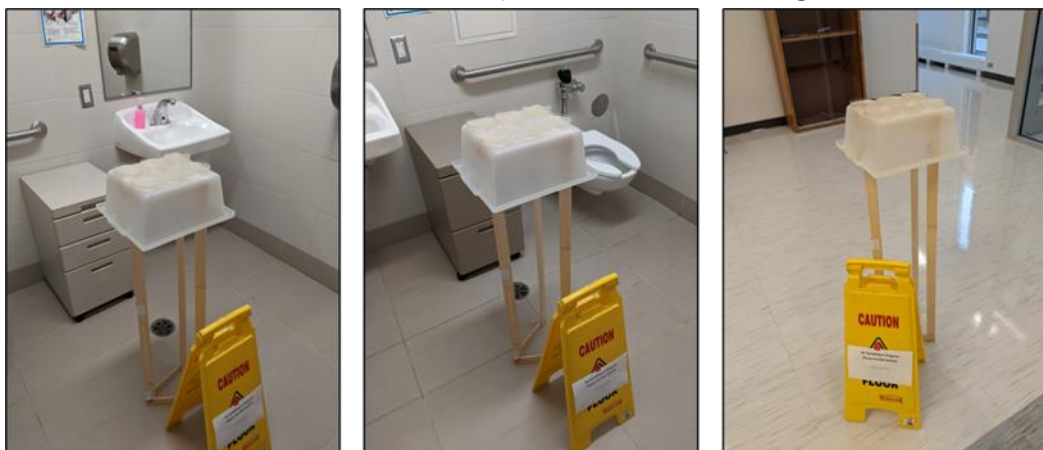


2.2 Air sampling for airborne fungal spores and bacteria

Passive air sampling for mold and bacteria were carried out 2 and 1 months prior to surface preparation and treatment then roughly biweekly after the coating application to determine its effect on the viability of airborne microorganisms. Passive sampling was performed to determine the IMA, which is the number of colony-forming units (CFUs) on a 9 cm petri dish containing an appropriate media (settle plates) 1 m above the floor and 1 m from walls, after a 1 hr exposure period (Napoli et al. 2012). Settle plates for enumerating viable airborne bacteria contained heterotrophic plate count agar (PCA) and plates for enumerating viable airborne fungi contained potato dextrose agar (PDA) with 0.1 g L⁻¹ chloramphenicol to suppress bacterial growth. Passive air sampling was performed prior to building occupant arrival (0600 to 0700) to minimize exogenous disturbances (Figure 6). Samples were taken in the treated and untreated restrooms as well as in the hallway approximately 11 m to the north outside the restrooms. Unexposed PCA and PDA plates served as negative controls to assess exogenous contamination. After exposure, heterotrophic plates were incubated inverted at 37°C for 48 hr, and CFUs were counted after 24 hr and 48 hr. Selective plates, containing antibiotic, were incubated upright at 25°C in the dark, and CFUs were counted after 5 days and 10 days.

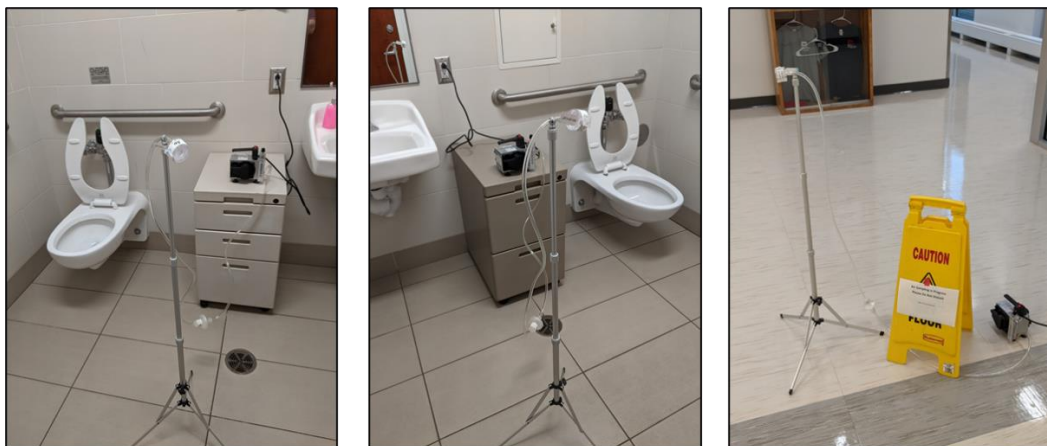
All sampling was performed in triplicate, and CFUs were averaged. The results for the settling bacteria and fungi were expressed in CFU m²-1 hr⁻¹ after 48 hr and 10 days of incubation, respectively.

Figure 6. Passive sampling for airborne bacteria and fungi with settle plates containing plate count agar (PCA) for enumerating bacteria and potato dextrose agar (PDA) for enumerating fungi. Plates were exposed for 1 hr suspended 1 m above the floor and greater than 1 m from all walls. Passive air sampling in the north restroom (left), south restroom (center), and control area in the hallway outside the restrooms (right).



Active air sampling for airborne fungal spores were carried out 2 months and 1 month prior to surface treatment. After coating with TPX-HL, active spore sampling of each restroom and the control area adjacent to the test areas were performed weekly from 0600 to 0630 over a course of 3 days. One sample in each area was taken each day over this period. Zefon Air-O-Cell air sampling cassettes (Ocala, Florida) were suspended 1 m above the floor and greater than 1 m from walls or any major obstacles (Figure 7). Air was pulled through the cassettes with a portable vacuum pump at a rate of 15 L min⁻¹ for 10 min (150 L total volume). An unexposed cassette served as a negative control. All samples collected were stored at 4°C until analysis. Samples were analyzed according to ASTM D7391-17, *Standard Test Method for Categorization and Quantification of Airborne Fungal Structures in an Inertial Impaction Sample by Optical Microscopy* (ASTM 2017a), and all major classes of mold spores were identified to the genus level and enumerated. Spore counts for each day of sampling were averaged, and the results expressed as the number of fungal spores m³-1.

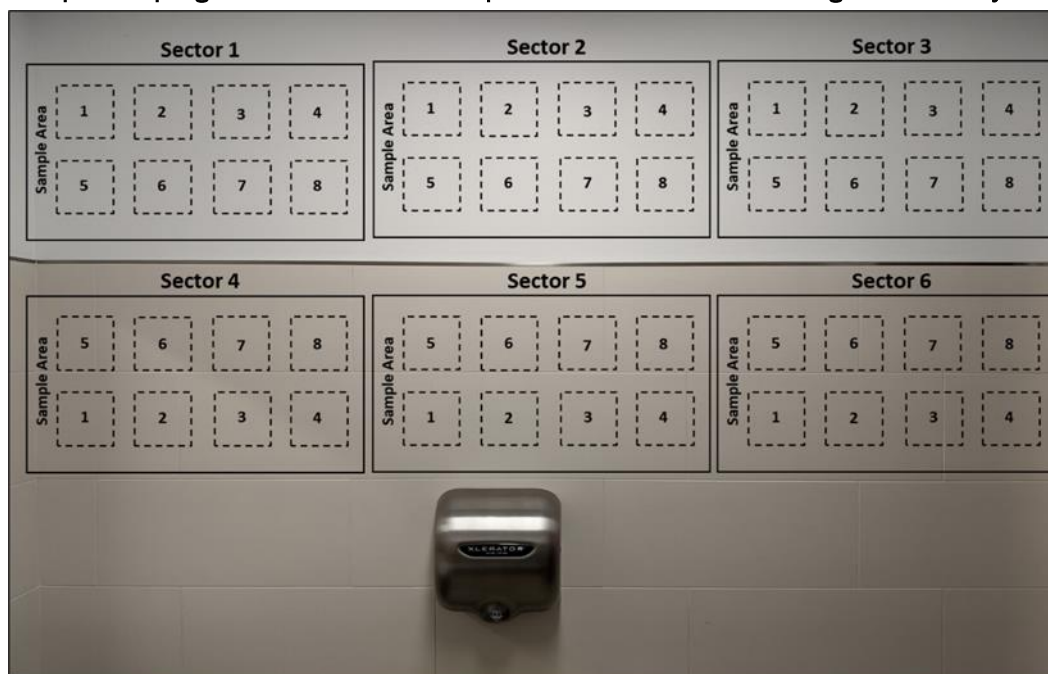
Figure 7. Active sampling for airborne fungal spores using Air-O-Cell sampling cassettes. Cassettes were positioned 1 m above the floor and greater than 1 m from all walls. Air samples were pulled through the cassettes for 10 min at a flow rate of 15 L min⁻¹. Active air sampling in the north restroom (left), south restroom (center), and control area in the hallway outside the restrooms (right).



2.3 Surface sampling for mold spores and bacteria

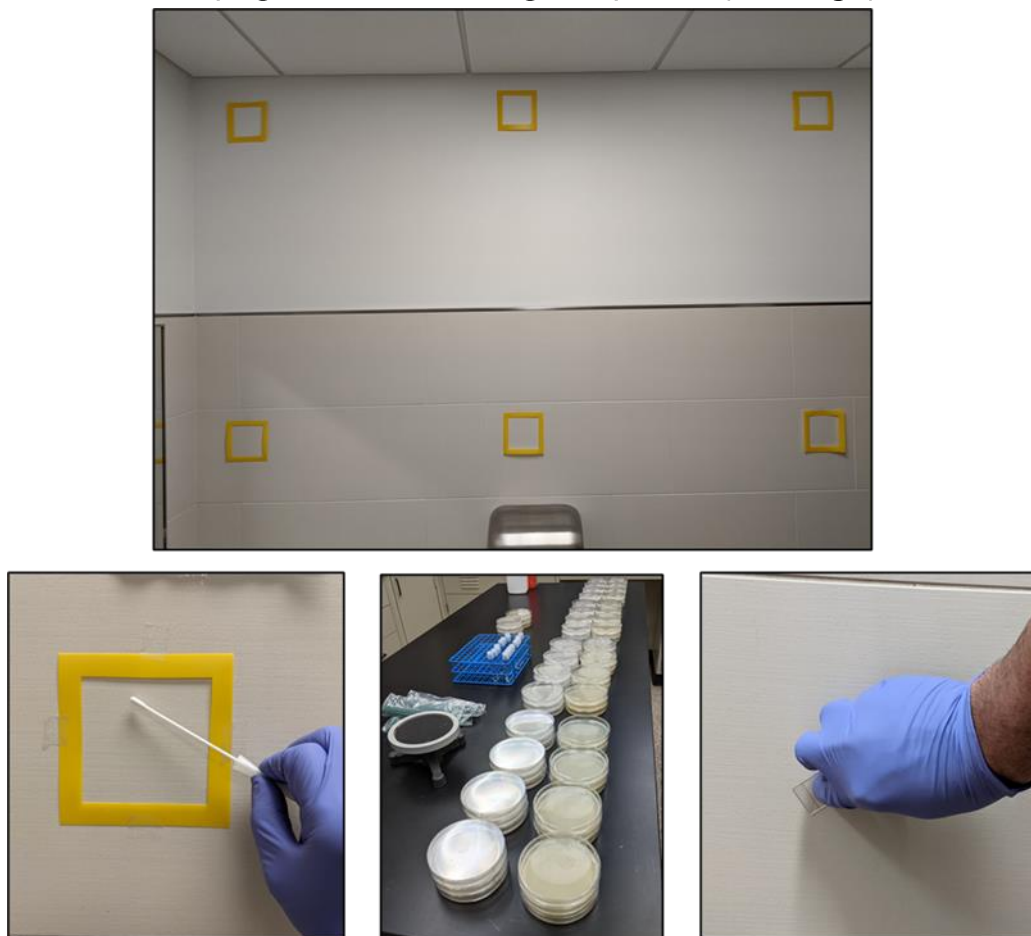
The presence of bacteria and fungi on the TPX-HL-treated and related untreated surfaces were determined by swab analysis based on the Public Health England's *Standard Method for Detection and Enumeration of Bacteria* (PHE 2017), and tape lift analysis as described by ASTM D7658-17, *Standard Test Method for Direct Microscopy of Fungal Structures from Tape* (ASTM 2017b). Areas in each restroom were sampled for surface bacteria and fungi as shown in Figure 8. The top two-thirds of the south wall in the north restroom and the top two-thirds of the north wall in the south restroom were divided into six equal sectors, which were further divided into eight sampling areas. Swab samples were taken eight times over the course of the study starting in the upper or lower left-hand corner of each of the six sectors total, three of which were painted gypsum and three were ceramic tile. Each sector was sampled eight times in a single sampling area and no area was sampled more than once.

Figure 8. Surface sampling areas for fungi and bacteria using swabs and lift tape. Walls being mirror images of one another were divided into six sectors, and each sector was further divided into eight sampling areas. Six swab and tape lift samples were taken in each restroom per sampling event. No area was sampled more than one time throughout the study.



Templates with a window measuring 10×10 cm were constructed out of 0.5 mm thick polypropylene and were used to swab a 100 cm^2 area as shown in (Figure 9). Swabbing templates were sterilized with 80% ethanol prior to use and held into place with clear tape. Aseptic swabbing of the surface was performed as described by ATSM D7789-12, *Standard Practice for Collection of Fungal Material from Surface by Swab* (ASTM 2012) and immediately placed into 5 mL of sterile maximum recovery dilutant consisting of 1 g of peptone and $8.5 \text{ g of NaCl L}^{-1}$. Swabs and dilutant were vortexed for 30 seconds, and $500 \mu\text{L}$ of the solution was plated on to either a PCA or PDA amended with $0.1 \text{ g of chloramphenicol L}^{-1}$ to enumerate viable bacteria and fungi, respectively. All areas swabbed were plated in triplicate, and unexposed swabs served as negative controls. Petri plates containing PCA were incubated inverted at 37°C for 48 hr, and then bacterial CFUs were counted. Plates containing PDA were incubated upright at room temperature for 14 days, and then fungal colonies on the plates were enumerated.

Figure 9. Surface sampling for fungi and bacteria using swabs and tape lift. A 100 cm² area was swabbed using aseptic techniques (*top* and *bottom left*) and plated on either PCA or PDA to enumerate the total viable bacteria and fungi on the surface (*bottom center*). Lift tape sampling of restroom walls using Bio-Tape Slides (*bottom right*).



Tape lift samples were taken weekly over the course of the study starting in the upper or lower left-hand corner of each of the six sectors outside the areas swabbed (Figure 9). Zefon Bio-Tape Slides were used, and six surface samples were taken weekly in areas representing mirror images in each restroom. No one area was sampled more than once throughout the evaluation. Samples were examined using optical microscopy, and the total fungal structures, both viable and nonviable, were identified and semiquantified down to the genus level as described by ASTM D7658-17. Unexposed slides served as negative controls. All samples collected were stored at 4°C until analysis.

2.4 Volatile organic compound analysis

On days the restrooms were actively air sampled, total VOCs were also monitored in real-time using a MiniRae 3000 handheld total VOC meter (RAE Systems, San Jose, California) calibrated with isobutene (Figure 10). Additionally, 74 specific VOCs were tested for in the restrooms by GC-MS analysis per US Environmental Protection Agency TO-15 test method *Determination of Volatile Organic Compounds (VOCs) in Air Collected in Specially Prepared Canisters and Analyzed by Gas Chromatography/Mass Spectrometry* (EPA ORD 1999). Compounds analyzed for in the restrooms using EPA TO-15 are listed in Appendix C. Air samples were collected in precleaned, negative-pressure (-102 kPa), 6 L stainless steel summa canisters equipped with 24 hr regulators (Figure 10). Samples were taken over a 24 hr period a total of eight times, distributed throughout the course of the study. The first air sampling took place prior to cleaning and treatment with TPX-HL to obtain background levels of VOCs present. The VOCs were identified and enumerated within the air samples per EPA TO-15 guidance using a Restek RTX-502.2 column (60 m, 0.25 ID, $1.4\ \mu\text{m}$) (Restek, Bellefonte, Pennsylvania). Concentrations of VOCs were reported as $\mu\text{g m}^{-3}$.

Figure 10. Air sampling for volatile organic compounds (VOCs) using a handheld meter in real time (*left*) and vacuum-pressurized summa canisters. Air samples of 6 L were collected over a 24 hr period. Air sampling in the north restroom (*center*) and south restroom (*right*).



2.5 Inactivation of mold spores, bacteria, and viruses

Two remnant ceramic tiles measuring 30.5 cm wide, 61 cm long, and 8 mm thick, leftover in the construction of the restrooms, were used to fabricate coupons to test the fungal spore, bacteria, and virus inactivation by TPX-HL, according to select ISO photocatalytic test methods.

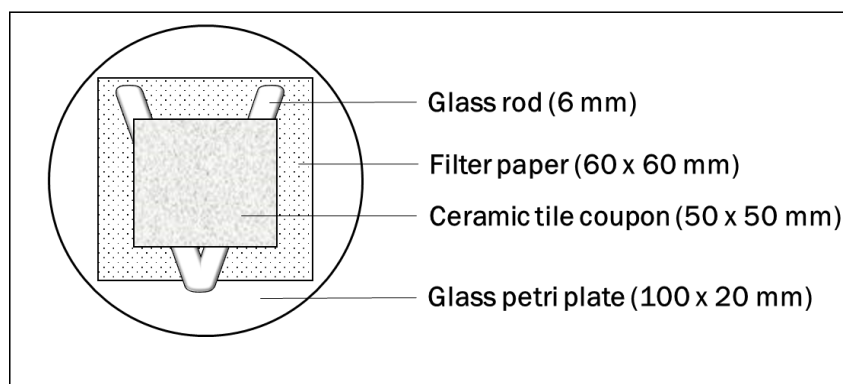
Both tiles were cleaned with TSP solution and allowed to dry for 48 hr before coating one tile with TPX-HL under the conditions described above. Both tiles were cut into 5×5 cm squares using a wet saw equipped with a diamond cutting blade (Figure 11). Tiles were allowed to air dry for 2 weeks before use. All microbial and viral species used in the coating testing were purchased from the American Type Culture Collection (ATCC) (Manassas, Virginia).

Figure 11. Fabrication of ceramic test coupons used to evaluate the antimicrobial activity of TPX-HL. Remnant restroom tiles being cut with a wet saw (left) and finished 5×5 cm coupons (right).



A modified ISO 13125, *Test Method for Antifungal Activity of Semiconducting Photocatalytic Materials*, was used to assess fungal resistance to tiles coated with TPX-HL (ISO 2013). *Aspergillus niger* (ATTC #9142) and *Penicillium citrinum* (ATTC #9849) were grown, and spores were harvested as described in ISO 13125. Spores obtained from each species were combined, and the total spore concentration was determined microscopically using a hemocytometer. The resulting spore stock was diluted to a final concentration of 5.0×10^5 spores mL^{-1} . One hundred μL of the spore stock was spotted on the surface of each test coupon, resulting in approximately 5.0×10^4 spores on each coupon surface. The test specimens were placed in light-transmissible glass test vessels (100×20 mm) containing approximately 5 mL of deionized water dispensed onto filter paper to prevent the inoculum from drying out during incubation (Figure 12).

Figure 12. Diagram of test vessel used to evaluate the photocatalytic antimicrobial activity of TPX-HL via three ISO photocatalytic test methods.



All components of the test vessels were sterilized by autoclaving at 120°C for 20 minutes before use. Mold spores from one set of uncoated tile coupons were immediately recovered, which served as the baseline for spore extraction efficiency from the coupon surface and spore stock viability. The remaining test vessels were either incubated in the dark at 25°C for 17 hr or illuminated with florescent lighting at approximately 1,000 lux for 17 hr at 25°C. Light intensity was monitored with a Reed SD 9300 data logger equipped with a lux probe. After incubation, the spores were recovered from the test coupons as described in ISO-13125, and viability was assessed by serially diluting the recovery solution and pour plating with PDA in triplicate. Colonies were counted and the percentage of viable mold spores recovered was calculated. Antifungal activity of the photocatalytic coating was expressed as the percentage of surviving spores relative to the total number of spores inoculated onto the surface of the coupons.

Test method ISO 17094, *Test Method for Antibacterial Activity of Semiconducting Photocatalytic Materials under Indoor Lighting Environment*, was used to assess bacterial resistance to tiles coated with TPX-HL (ISO 2014). *Escherichia coli* (ATTC #8739) and *Staphylococcus aureus* (ATTC #6538P) were grown as recommended by the culture collection, and the number of CFUs were determined by serial diluting the cultures and plating onto ATCC-recommended media in triplicate. Both bacteria were combined in a 1 to 1 ratio based on cell densities, and the total cell concentration was diluted to a final concentration of 1.0×10^6 cells mL⁻¹ with 1/500 nutrient broth. One hundred fifty µL of the bacterial suspension was spotted on the surface of each test coupon, resulting in approximately 1.5×10^5 bacterial cells on each tile. The test specimens were placed in sterile, light-transmissible glass test vessels as described previously.

Bacteria from a set of uncoated tile coupons were immediately recovered, which served as the baseline for cell extraction efficiency from the coupon surface and bacteria stock viability. The remaining test vessels were either incubated in the dark at 25°C for 17 hr or illuminated with florescent lighting at 1,000 lux for 17 hr at 25°C. Light intensity was monitored with a Reed SD 9300 data logger equipped with a lux probe. After incubation, the bacteria were recovered from the test coupons as described in ISO-17094, and viability was assessed by serially diluting the recovery solution and pour plating with nutrient agar in triplicate. Plates were incubated at 37°C for 24 hr before CFUs were counted and the percentage of viable bacteria recovered from the coupon surface was calculated. Antibacterial activity of TPX-HL was expressed as the percentage of surviving bacteria relative to the number of bacteria spotted onto the coupon surfaces.

Antiviral activity of coupons coated with TPX-HL were determined using test method ISO 18071, *Determination of Antiviral Activity of Semiconducting photocatalytic Materials under Indoor Lighting Environment*, (ISO 2016b). *Escherichia coli* (Migula) Castellani and Chambers (ATTC #23631) and *E. coli* bacteriophage Q-β (ATTC #23631-B1) were propagated and enumerated, and phage titer was determined per ATCC recommendations. Bacteriophages were diluted to a final concentration of 2.05×10^7 plaque-forming units (PFUs) mL⁻¹ with 1/500 nutrient broth. One hundred fifty µL of the bacteriophage suspension was spotted on the surface of each test coupon resulting in approximately 3.08×10^6 phage on each coupon surface. The test specimens were placed in sterile test vessels as described above. Bacteriophage from uncoated coupons were immediately recovered, which served as the baseline for phage extraction efficiency from the tile surface and viability of the phage stock. The remaining coupons were either incubated in the dark at 25°C for 17 hr or illuminated with florescent lighting at roughly 1,000 lux for 17 hr at 25°C. Light intensity was monitored with a Reed SD 9300 data logger equipped with a lux probe. After incubation, the bacteriophages were recovered from the test coupons as described in ISO-18071 and PFUs were determined by serially diluting the recovery solution and pour plating with tryptone agar and the *E. coli* host strain in triplicate. Plates were incubated at 37°C for 24 hr before PFUs were counted and the percentage of viable bacteriophage recovered from the coupon surface was calculated. Antiviral activity of the photocatalytic coating was expressed as the percentage of surviving bacteriophage, as determined by plaque formation, relative to the total number of bacteriophage placed onto the coupon surfaces.

3 Results and Discussion

3.1 Demonstration site location and coating application

The all-gender restrooms were chosen for this demonstration because of their relatively high and equal use during the COVID-19 pandemic when personnel access to the ERDC-CERL campus was limited. Initial considerations were developed through discussions with the local Department of Public Works staff that stated the restrooms receive fairly high usage as measured by consumables used (paper towels and toilet paper). Larger male restrooms, one being located in building 1 and the other in building 2, which had equal size, build materials, and accommodations (number of sinks, toilets, and urinals), were also considered. However, during the partial shutdown and slow return of personnel back to the ERDC-CERL site, it was determined that the building 1 restroom received greater use due to the proximity to the security staff and essential laboratory personnel during the shutdown. Additionally, each of the restrooms were on separate and independent air-handling systems, which would likely have a significant effect on the air quality in each area and the overall results of the study. The all-gender restrooms were adjacent to one another and on the same air-handling unit; therefore, it was assumed air quality in each area would be near identical and any differentiation in the presence of microorganisms and or VOC could be attributed to treatment with the photocatalytic coating.

After cleaning each restroom and allowing them to completely dry, the walls and the ceiling of the north restroom was coated with TPX-HL using a HPLV sprayer at the coating manufacture's recommended application rate. After allowing the photocatalytic coating to completely dry (approximately 17 hr), it became an insoluble hard film and was ready for regular use. Although TPX-HL has a light-yellow tint when in liquid form, if applied at the correct rate, it dries completely transparent with no discernable sheen or texture. No differentiation between the treated and untreated gypsum and tile surfaces could be visualized with the naked eye. Using the coverage chart in Appendix B and knowing the volume of TPX-HL used during the application process, it was estimated that greater than a 0.12 μm coating thickness was achieved, which was the manufacture's minimum specification for effective catalytic surface sterilization and air purification.

Usage of the restrooms over the course of the demonstration was determined by data loggers that tracked lux, as each restroom was equipped with motion-sensing lights. Thus, when occupied, the lights turn on and the lux can be recorded, which in turn gives an indication of the amount of use of each restroom. More than 6,000 lux data points were collected for each restroom over the course of the study. Based on the lux data logger information, the TPX-HL-treated and untreated restrooms were illuminated an average of 5.6 ± 1.0 and 5.9 ± 1.1 hr per day, respectively. The average lux readings over the test period were 428.5 ± 12.4 and 415.2 ± 8.9 for the treated and untreated restrooms, respectively. Based on the number of hours of light exposure caused by the occupancy sensors, it was determined that each restroom was used nearly equally over the course of the study and the average illumination was equal as well.

The relative humidity and temperature were also tracked in each restroom during the study. Each parameter was read on 1-minute intervals, and over 36,000 data points were collected for each restroom over the course of the demonstration. The treated restroom had an average relative humidity of $51.2\% \pm 5.1\%$ and an average temperature of $22.0^{\circ}\text{C} \pm 0.4^{\circ}\text{C}$. The untreated restroom had an average relative humidity of $50.2\% \pm 4.9\%$ and an average temperature of $22.5^{\circ}\text{C} \pm 0.4^{\circ}\text{C}$. The values indicated proper indoor air humidity and temperature levels throughout the demonstration as defined by American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standards for maintaining comfort and reducing the risk of fungal growth (ASHRAE 2021). These data indicate that both restrooms had rather consistent temperature and humidity levels throughout the study and that there was no observable difference between the two restrooms that would cause a variation in indoor air quality.

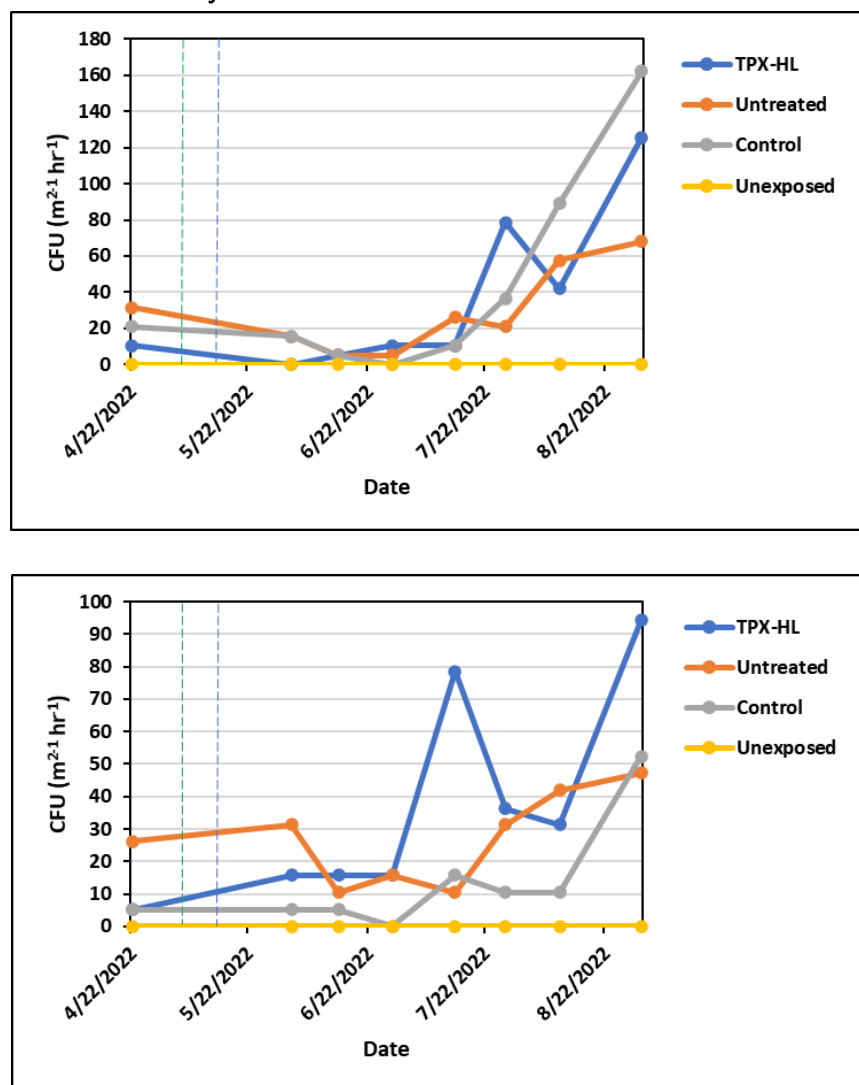
3.2 Passive air sampling for viable bacteria and fungi

To determine the number of viable airborne fungi and bacteria in the test areas that were settling on surfaces, passive air sampling was performed in both restrooms and compared to a control area located in the hallway outside each restroom (Figure 13). The unexposed controls for both bacteria and fungi showed no CFUs throughout the study, which demonstrated that colonies formed on the exposed plates were due to settling microorganisms from the air and not exogenous contamination. Note that all passive air sampling was performed from 0600 to 0700 and areas were closed to minimize disturbances around the settling points. By mid-July, all areas

sampled had equal average numbers of fungi settling onto the test plates ($5.2 \text{ CFUs m}^{-2} \text{ hr}^{-1}$) that slowly increased over the course of the study. This observation was expected because fungi proliferate and spread their spores in the warmer and more humid conditions of summer (Shelton et al. 2002). By the end of the study, the control area outside the restrooms had the highest number of settling fungi at $162.4 \text{ m}^{-2} \text{ hr}^{-1}$, and the treated restroom had the second highest number of fungi ($125.7 \text{ m}^{-2} \text{ hr}^{-1}$). The untreated area had the least number of settling fungi at $68.1 \text{ m}^{-2} \text{ hr}^{-1}$, which was a 48% decrease compared to the treated restroom. This suggests that treatment with TPX-HL likely had no effect on mold proliferation on the treated surfaces and, in turn, lowering the number of airborne mold spores settling on the PDA plates.

A similar trend was observed with settling airborne bacteria. As with the fungi, the average number of airborne bacteria settling onto agar plates increased over the summer months in all areas tested (Figure 13). Concentrations of bacteria were not reduced in the TPX-HL-treated area as the study progressed. In mid-July, the average settling rate of bacteria in the treated restroom was $78.6 \text{ m}^{-2} \text{ hr}^{-1}$, whereas it was 10.5 and $15.7 \text{ m}^{-2} \text{ hr}^{-1}$ in the untreated restroom and control area, respectively. By the end of the study, the settling rate of bacteria in the treated area increased to $94.3 \text{ m}^{-2} \text{ hr}^{-1}$, and the untreated and control area settling rates increased to 47.2 and $52.3 \text{ m}^{-2} \text{ hr}^{-1}$, respectively. The near 2-fold increase in bacteria settling rate in the treated restroom compared to the untreated and control area suggests that TPX-HL likely had little or no effect at reducing bacterial concentrations in the area.

Figure 13. Average settling of viable airborne microorganisms as determined by passive air sampling. Fungal (upper) and bacterial (lower) colony-forming units (CFUs) per sampling event. The *green-dashed line* indicates the day the demonstration areas were cleaned with TSP. The *blue-dashed line* indicates the day of the TPX-HL treatment in the north restroom.

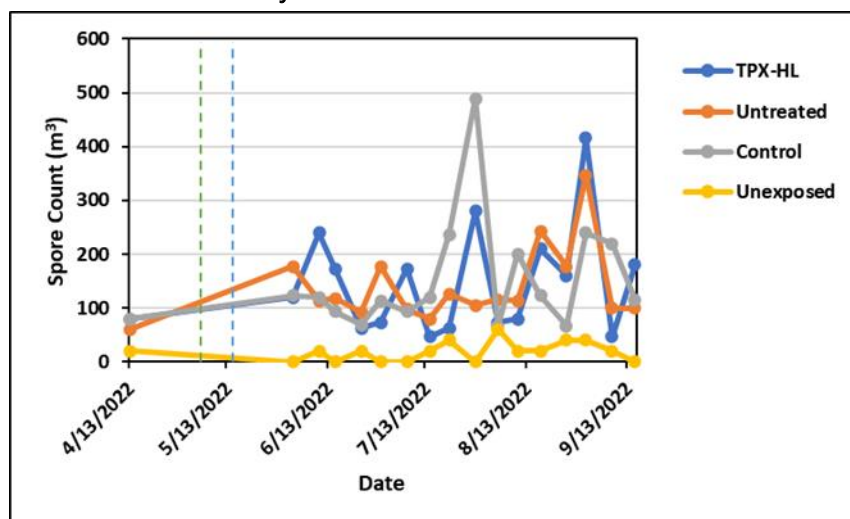


3.3 Active air sampling for total fungal spores

To determine the number of total airborne fungi (both viable and nonviable) in the test areas, active air sampling was performed in both restrooms and compared to a control area located in the hallway outside each restroom (Figure 14). As with the passive air sampling, all samples were performed in the morning from 0600 to 0700 and areas were closed to access to minimize disturbances around the spore traps during sampling. Although mold spores were identified down to the genus level via microscopic analysis, no trend could be determined between the areas sampled. For

example, no area was found to have significantly increased or decreased levels of any particular genus. Consequently, all fungal genera were combined, and the total number of mold spores were compared between the three areas to determine TPX-HL antifungal effectiveness with the assumption that reducing fungal proliferation would lower total airborne spores both viable and nonviable. The unexposed control cassettes did periodically have several mold spores on the cassette capture surfaces throughout the study, which was likely due to cross contamination during the analysis process. However, spore numbers remained low and therefore were not considered to significantly affect the overall outcome of the spore trap analysis. After cleaning and treatment, the total spore counts ranged from 60 to 347 spores m^{-3} in the untreated area, and in the treated area from 47 to 416 spores m^{-3} . Airborne mold spores in the control area located in the hallway ranged from 67 to 489 m^{-3} over the course of the study. Overall, other than the June 28 sampling, the untreated and treated restrooms followed similar trends in total airborne fungal spores present and no clear benefit to treating with TPX-HL could be made by analyzing airborne spore concentrations.

Figure 14. Total airborne fungal spore counts both viable and nonviable in the treated and untreated restrooms. The *green-dashed line* indicates the day the demonstration areas were cleaned with TSP. The *blue-dashed line* indicates the day of TPX-HL treatment in the north restroom.



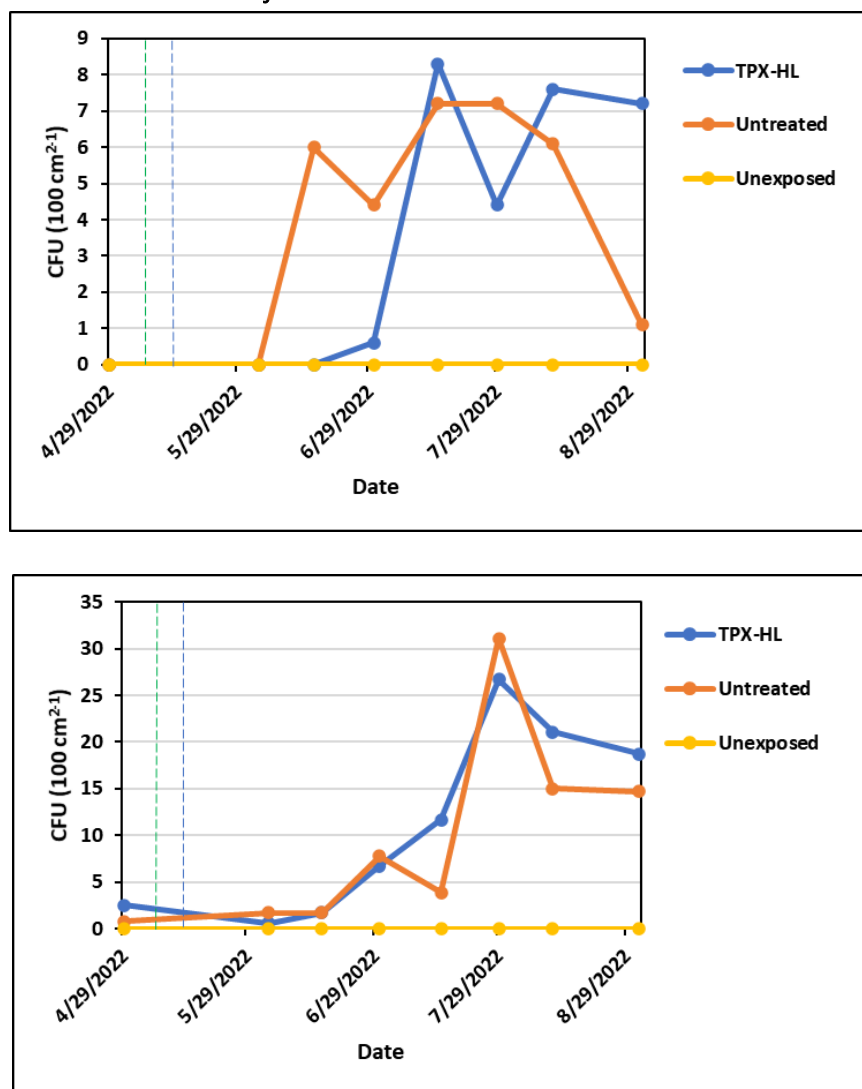
3.4 Surface sampling for viable bacteria and fungi via swabbing

To determine the average number of viable microorganisms (both bacterial and fungal) on the surfaces of each restroom, surfaces were swabbed periodically and plated onto selective media, and fungal and bacterial

colonies were counted (Figure 15). The same areas were swabbed in each restroom relative to the position of the fixtures present to represent as equivalent sampling area as possible. Six areas were swabbed in each restroom during each sampling event (one in each sector). The CFUs reported are the average of each of the six swabbed areas, representing three areas on the painted gypsum and three areas on the ceramic tile. No fungal colonies were detected on the swab control plates throughout the study, which indicated that the CFUs detected were from the wall swabs and not contamination. Viable fungal counts on the walls in both restrooms were low until late spring and early summer, which correlated to passive and active air sampling. This was expected, and the study was planned, as best as possible, to take place over the summer months when fungi are known to readily proliferate due to the warm, moist conditions in the Midwest. Viable fungi were detected in the untreated area by mid-June at 6.0 CFUs 100 cm²⁻¹. In late June, the average viable spore count in the untreated area was 4.4 CFUs 100 cm²⁻¹, whereas the concentration in the TPX-HL-treated area was 0.6 100 cm²⁻¹. This suggests that the photocatalytic coating may have had an effect in preventing mold proliferation in the spring months; however, by mid-July, viable fungal spore concentrations on the walls of the treated and untreated restrooms peaked at 7.2 and 8.3 CFU 100 cm²⁻¹, respectively. Towards the end of the study, fungal concentrations on the wall in the treated area remained roughly the same at 7.2 to 7.6 CFUs 100 cm²⁻¹. However, in the untreated area, the spore concentration steadily decreased from 7.2 to 1.1 CFUs 100 cm²⁻¹ by the end of the study. Collectively, these data suggest that TPX-HL treatment has little detectable long-term effect at minimizing fungal proliferation on the surface of the restroom wall.

Similar to fungi, viable bacterial counts remained low until the summer months. Concentrations of bacteria gradually increased in the untreated and treated areas from 1.7 CFUs cm²⁻¹ each in mid-June to 31.1 CFUs cm²⁻¹ and 26.7 CFUs cm²⁻¹ in late July, respectively. Viable bacteria on the walls then decreased to 14.7 CFUs cm²⁻¹ in the untreated area and 18.7 CFUs cm²⁻¹ in the treated area. No bacterial colonies were detected on the control agar plates throughout the study, which again indicated that colonies detected were from the wall swabs and not exogenous contamination. These data suggest that coating the wall with TPX-HL had no detectable effect on reducing the number of viable bacteria on the wall over the course of the study.

Figure 15. Average viable surface microorganisms as determined by swabbing and plating onto selective media. Fungal (*upper*) and bacterial (*lower*) CFUs per sampling event. The *green-dashed line* indicates the day the demonstration areas were cleaned with TSP. The *blue-dashed line* indicates the day of the TPX-HL treatment in the north restroom.



Tape lift samples were collected in an effort to identify any fungi in close proximity to where the swab samples were taken by microscopic examination. Although classes of fungi were identified down to the genus level from the tape lifts, as with the cassette analysis, no clear distribution of a particular genus could be distinguished between either restroom.

The number of viable fungi and bacteria prior to cleaning the restrooms with TSP was lower than expected. This was believed to be due to the cold temperatures and low humidity during the winter months in the Midwest and also to the reduce occupancy on the ERDC-CERL campus. Site

restrictions due to COVID-19 were in place through the spring of 2022, which limited the use of the areas and, likely, the overall microbial exposure. Additionally, swab analysis can be inherently biased due to sampling size and number, the swabbing technique used, and the microbial recovery efficiency from the swab (Griffith 2016). Therefore, viable fungi and bacteria on the wall surfaces may have been higher than shown. However, the trends in the concentrations of bacteria and fungi should have remained the consistent because the same number of samples (in roughly identical areas) were taken using the same technique by the same sampler.

3.5 Volatile organic compounds present in air samples

A handheld photoionization VOC meter was used to measure total VOCs prior to each active air sampling event on three separate days. The meter is capable of detecting more than 200 unique VOCs in seconds and has a detection range from 100 ppb to 15,000 ppm. However, no VOCs were detected in the restrooms or control area throughout the study on any given sampling day. This indicated that VOCs were either not present during the time the measurements were taken, or they were in concentrations below 100 ppb. Subsequent GC-MS analysis of air samples taken with summa canisters would suggest the latter, that VOCs were most likely below the detection limit of the handheld detector.

Of the 74 specific VOCs that were analyzed for in the samples taken from the restrooms by GC-MS via EPA TO-15, a total of 14 were detected at various times throughout the study. Table 1 lists the VOCs detected along with their molecular weights and Chemical Abstract Service (CAS) registry numbers. A list of all VOCs analyzed for by EPA Method TO-15 is included in Appendix C, which includes the compounds' CAS numbers and molecular weights. These VOCs are a subset of 189 VOCs listed as hazardous air pollutants (HAPs) by Title III of the Clean Air Act amendments of 1990 (EPA ORD 1999). These compounds represent common volatile organics that are found in indoor environments, which can derive from biotic and abiotic sources. These served as a suitable set of VOCs to monitor to evaluate any reduction in the TPX-HL-treated restroom. Figure 16 shows 14 of the VOCs detected and their concentrations at each air sampling event over the course of the coating evaluation.

Table 1. Fourteen VOCs detected by Environmental Protection Agency (EPA) TO-15 in 6 L air samples taken over the course of the photocatalytic coating evaluation. The Chemical Abstract Service (CAS) registry numbers and molecular weights are listed.

VOCs Detected	CAS#	Molecular Weight (MW)
Dichlorodifluoromethane	75-71-8	120.9
Chloromethane	74-87-3	50.49
<i>n</i> -Butane	106-97-8	58.12
Ethanol	64-17-5	46.07
Trichlorofluoromethane	75-69-4	137.4
2-Propanol	67-63-0	60.09
Acetone	67-64-1	58.08
<i>n</i> -Hexane	110-54-3	86.18
2-Butanone	78-93-3	72.11
<i>cis</i> -1,2-Dichloroethene	156-59-2	96.94
Ethyl acetate	141-78-6	88.11
4-Methyl-2-pentanone	108-10-1	100.2
Toluene	108-88-3	92.14
1,4-Dichlorobenzene	106-46-7	147

Dichlorodifluoromethane, also known as Freon 12, was detected in the TPX-HL-treated restroom in the first air samples taken after the restroom was cleaned and treated and not detected again until late July. Both restrooms had roughly equal concentrations of dichlorodifluoromethane from this time point to the end of the study, which ranged from 2.8 $\mu\text{g m}^{-3}$ to 3.5 $\mu\text{g m}^{-3}$. This suggests that treating the surfaces of the restroom seemingly had no observable effect on lowering the concentration of dichlorodifluoromethane in the area. *n*-Butane was detected throughout the study in both restrooms, and the concentration peaked in the untreated area at over 90 $\mu\text{g m}^{-3}$ in late July. At this same time point, the *n*-butane concentration in the TPX-HL-treated area was 27 $\mu\text{g m}^{-3}$, which may indicate some effectiveness towards the destruction of this volatile compound. Chloromethane was also detected in both restrooms throughout most of the evaluation at low levels ranging from 1.0 $\mu\text{g m}^{-3}$ to 1.5 $\mu\text{g m}^{-3}$. No chloromethane was detected in the treated area at the end of the study and 1.1 $\mu\text{g m}^{-3}$ was detected in the untreated area. This may suggest the destruction of chloromethane by TPX-HL, but it should be noted that the concentrations were at the lower limit of detection for the method

used. Ethanol was also detected throughout the evaluation period in both areas sampled. Prior to cleaning each test area, roughly $200 \mu\text{g m}^{-3}$ and $34 \mu\text{g m}^{-3}$ of ethanol was detected in the untreated and to-be-treated restrooms, respectively. Ethanol concentrations after cleaning in the TPX-HL-treated area ranged from $33 \mu\text{g m}^{-3}$ to $88 \mu\text{g m}^{-3}$. After cleaning, the ethanol concentration in the untreated restroom peaked at $190 \mu\text{g m}^{-3}$, and concentrations in the TPX-HL-treated restroom were $73 \mu\text{g m}^{-3}$ at this same sampling point. All other ethanol concentrations at the remaining sampling points were relatively equal between the two areas. Although the level of ethanol was lower in the early-July sampling, the elevated ethanol concentration in the untreated area before cleaning precludes attributing this observation to TPX-HL treatment. Likely, an external source of ethanol was responsible for the concentration spikes, such as sanitizing products being used in the area. Trichlorofluoromethane was detected in both areas at near equal concentrations at one sampling point only, and therefore, treatment with TPX-HL has no apparent effect at reducing its concentration. 2-Propanol was also observed in both restrooms throughout the study in concentrations ranging from $17 \mu\text{g m}^{-3}$ to $77 \mu\text{g m}^{-3}$. The concentration of 2-propanol peaked in late July at $77 \mu\text{g m}^{-3}$ in the untreated restroom and was $58 \mu\text{g m}^{-3}$ in the treated restroom. However, all other 2-propanol concentrations were relatively equal between the two areas, which suggests that TPX-HL likely has little effect at reducing the concentration of the compound. Acetone was detected in both restrooms at concentrations of roughly $20 \mu\text{g m}^{-3}$ except in late July when the concentration rose to $170 \mu\text{g m}^{-3}$ in the untreated area. Seemingly, TPX-HL may have had an effect on the acetone concentration in the treated area at this time point. Similarly, *n*-heptane and 4-methyl-2-pentanone were only detected in the untreated area at a single time point, and therefore, the lack of these compounds in the treated area may be due to TPX-HL but more likely due to an independent exogenous event in the untreated area while sampling and not due to photocatalysis. More data points would be needed to determine the effects of treatment on these three volatile compounds.

Figure 16. Concentrations of 14 VOCs detected by the EPA TO-15 test method from 6 L air samples in the treated and untreated restrooms per sampling event.

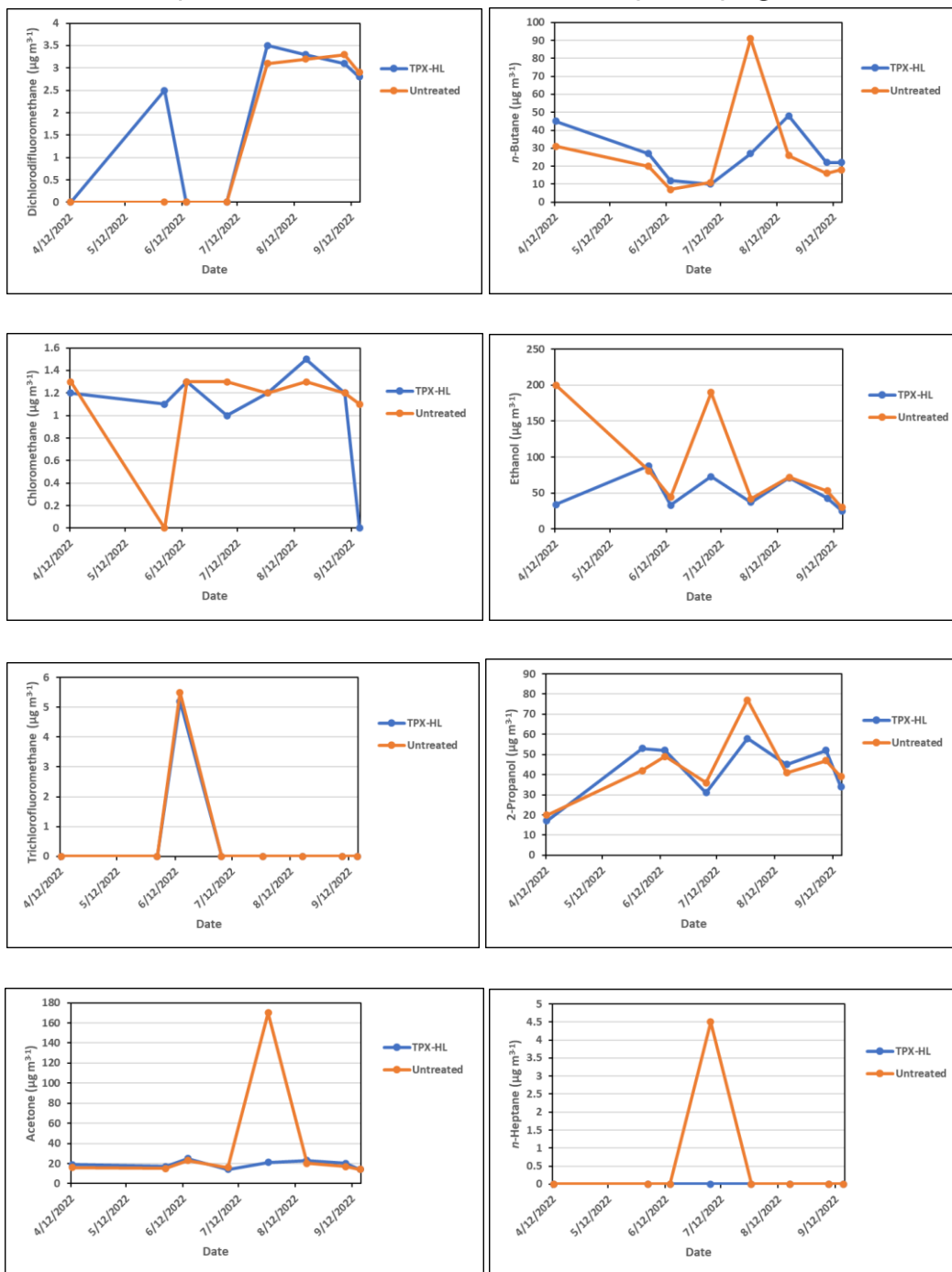
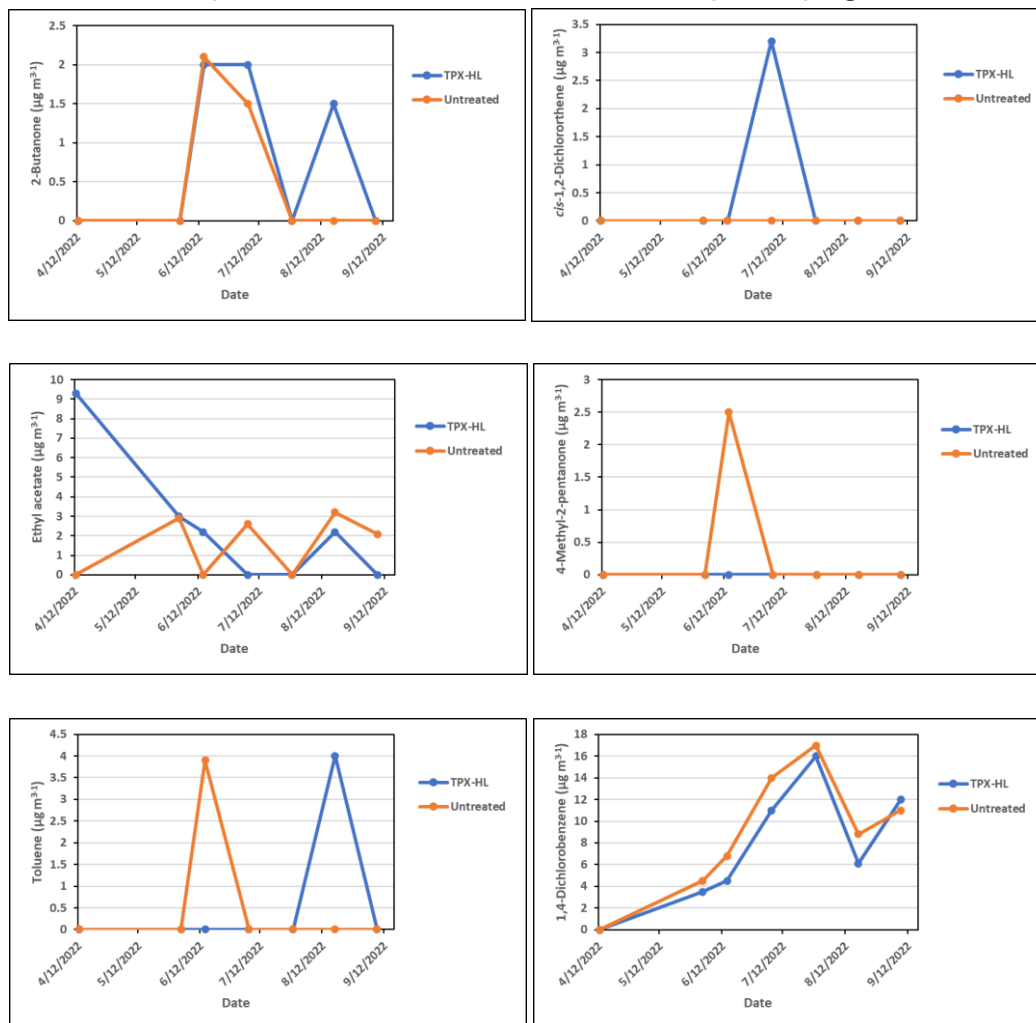


Figure 16 (cont.). Concentrations of 14 VOCs detected by the EPA TO-15 test method from 6 L air samples in the treated and untreated restrooms per sampling event.



2-Butanone was detected in both restrooms starting in mid-June through late July, ranging from $1.5 \mu\text{g m}^{-3}$ to $2.1 \mu\text{g m}^{-3}$. A small amount of 2-butanone ($1.5 \mu\text{g m}^{-3}$) was again detected in mid-August but only in the TPX-HL-treated area; thus, it is likely that TPX-HL has no effect on 2-butanone concentrations. *cis*-1,2-Dichloroethene was only detected at one time point in the treated area, and thus, no attribution to TPX-HL can be made. Ethyl acetate was observed in both restrooms during the evaluation. The first sampling after cleaning and treatment revealed equal concentrations of ethyl acetate ($3.0 \mu\text{g m}^{-3}$). The concentration decreased to zero in the treated area over the subsequent two sampling time points. The concentration of ethyl acetate in the untreated area fluctuated from $0.0 \mu\text{g m}^{-3}$ to $3.2 \mu\text{g m}^{-3}$. At the end of the study the concentration of ethyl acetate was $2.1 \mu\text{g m}^{-3}$ in the untreated area and zero in the treated area. This suggests that TPX-HL may have had some effect on lowering

the ethyl acetate concentrations. Toluene was also detected in each restroom at near equal concentrations but at different sampling time points, and no conclusion on the effect of TPX-HL can be made. Last, 1,4-dichlorobenzene was detected in both restrooms starting in early June. At each sampling point, the concentration of 1,4-dichlorobenzene was 1 $\mu\text{g m}^{-3}$ to 3 $\mu\text{g m}^{-3}$ lower in the treated restroom except the last sampling point, where the concentration in the treated area was 12 $\mu\text{g m}^{-3}$ and in the untreated area it was 11 $\mu\text{g m}^{-3}$. Although concentrations of 1,4-dichlorobenzene were lower in the treated area at all time points (except mid-August), the similar concentrations throughout the study suggest that TPX-HL likely has limited or no effect at reducing this VOC. Collectively, the GC-MS data indicate that TPX-HL may have reduced the levels of select VOCs in the treated area, but a more in-depth study with a greater number of sampling points and replication would be required to determine this conclusively.

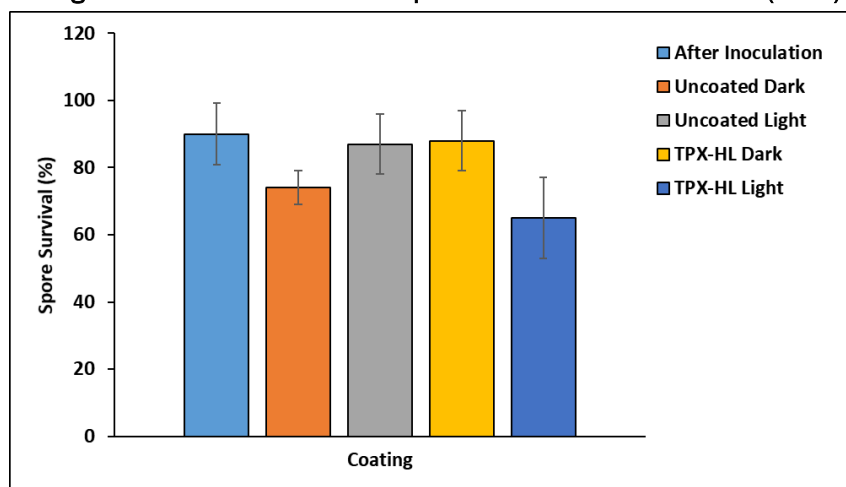
3.6 Assessment of photocatalytic coating antimicrobial activity

The ISO-13125 standard test method was used to better assess the antifungal activity of the photocatalytic coatings. Test coupons constructed out of remnant ceramic tile were coated with TPX-HL and spotted with a mixture of *A. niger* and *P. citrinum* spores, then irradiated with light or incubated in the dark for 17 hr (Figure 17). After the incubation period, the mold spores were recovered from the surfaces of the coupons and pour plated in selective PDA, fungal colonies were counted, and spore survival was calculated (Figure 18).

Figure 17. Uncoated and photocatalyst-coated ceramic coupons being irradiated with approximately 1,000 lux florescent light for 17 hr: (a) uncoated, (b) TPX-HL coated, and test specimens incubated in the dark under a black plastic bag (bottom).



Figure 18. Fungal spore survival on uncoated ceramic coupons and coupons coated with TPX-HL incubated in the dark or exposed to approximately 1,000 lux light for 17 hr. The error bars represent the standard deviation ($n = 3$).

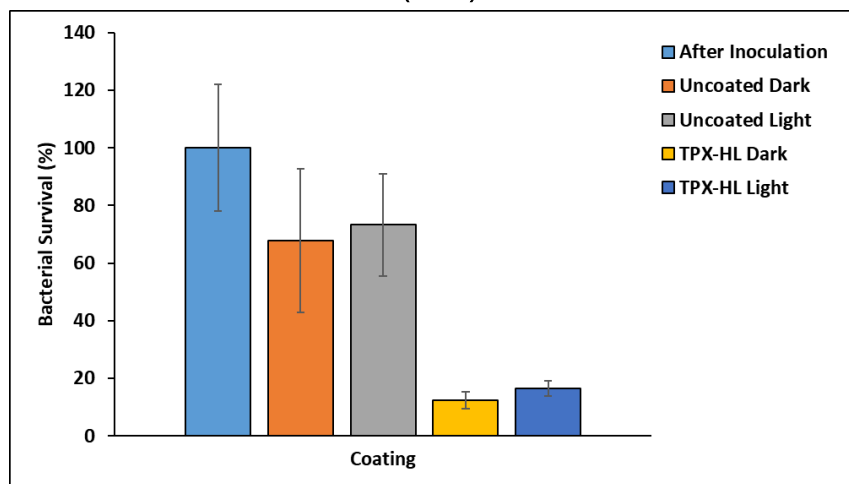


Fungal spore survival was assessed immediately after inoculation and was found to be $90\% \pm 9\%$ based on the target number of spores spotted on the coupons. This served as the baseline for spore recovery and viability for

the experiment and was used to assess the photocatalytic coating. Spore survival on the uncoated coupons incubated in the dark was $74\% \pm 5\%$ and on the coupons incubated under the light was $87\% \pm 9\%$, which demonstrated an efficient spore recovery and viability and that light exposure alone had no negative effect on spore viability. A small but significant difference was found when comparing spore survivability on coupons coated with TPX-HL incubated either in the dark or under florescent light. Spore survival when incubated in the dark was $88\% \pm 9\%$ and when incubated under light was $65\% \pm 12\%$. The percentage of survival for each test condition suggests that mold spores were both effectively recovered from the coated surface and that the coating had a slight antifungal activity under the test conditions used. Although TPX-HL did apparently demonstrate antifungal activity, 17 hr of constant light exposure at roughly 1,000 lux was required. Although it is unknown how this exposure level would relate to a particular in-situ application such as this study, it may make it impractical for most interior applications to control fungal proliferation. This may be the reason no apparent antifungal effects were observed during the demonstration as the restrooms used for the evaluation were on motion-sensing lighting systems and only received on average 5.6 hr of light at approximately 429 lux day^{-1} . Therefore, in order for the coating to be effective against fungal spores, it may be necessary to have greater light exposure or exposure to higher-intensity light, such as sunlight through a window. With ever-increasing DoD energy conservation requirements, application of TPX-HL may not be effective in controlling fungal proliferation unless illumination is carefully evaluated.

To better assess the antibacterial activity of TPX-HL, the ISO-17094 standard test method was used. Coupons constructed out of remnant ceramic tile were coated with TPX-HL and spotted with a mixture of *E. coli* and *S. aureus*, then illuminated with light or incubated in the dark for 17 hr as described previously. After the incubation period, the bacteria were recovered from the surfaces of the coupons, the bacteria were pour plated in nutrient agar, bacterial colonies were counted, and bacteria survival was calculated (Figure 19).

Figure 19. Bacteria survival on uncoated ceramic coupons and coupons coated with TPX-HL incubated in the dark or exposed to approximately 1,000 lux light for 17 hr. The error bars represent the standard deviation ($n = 3$).

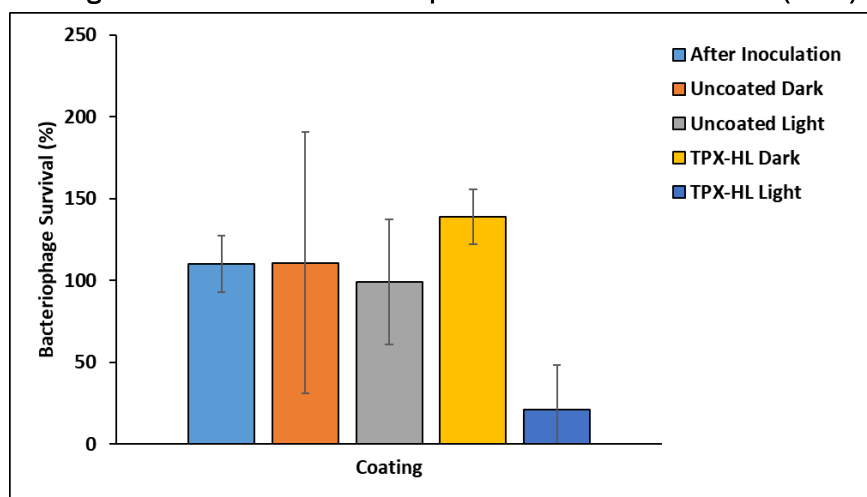


As with the fungal spores, survival of bacteria spotted onto the uncoated coupons was assessed immediately after inoculation, and cell recovery was found to be $100\% \pm 22\%$ based on the total number of cells placed on the ceramic coupons. This indicates that cell recovery and viability for the experiment was effective and efficient. Furthermore, after plating the recovery buffer, the two species of bacteria could clearly be distinguished from one another and were found to be roughly in a 1 to 1 ratio as mixed prior to inoculation. Bacteria survival on the uncoated coupons incubated in the dark was $78\% \pm 25\%$ and on the coupons incubated under light was $73\% \pm 18\%$. There was no statistically significant loss of bacteria between the untreated coupons, whether they were incubated in the dark or in the light. Nor was there a difference in the number of viable cells compared to cells recovered immediately after inoculation. This demonstrated that the cells remained viable over the course of the study and exposure to light had no apparent effect on the viability. When compared to the uncoated coupons, a significant difference in bacterial survival was found when comparing coupons coated with TPX-HL incubated in the dark and under florescent lighting. Bacteria survival when incubated in the dark was $12\% \pm 3\%$ and when incubated under light was $16\% \pm 3\%$. A 66% reduction in viable cells was observed on coupons incubated in the dark, and a 57% reduction was observed in coupons incubated under light when compared to the corresponding uncoated coupons. Coating the coupons with TPX-HL clearly had an effect on bacterial viability. However, bacterial survivability could not be attributed to photocatalytic activity of the coating as viable cell numbers were nearly equal between illuminated and

nonilluminated coupons. This suggests the coating exhibited antibacterial properties that may not be related to the infused photocatalyst.

In addition to antifungal and antibacterial activities of TPX-HL, antiviral properties were also evaluated using ISO-18071, *Determination of Antiviral Activity of Semiconducting Photocatalytic Materials under Indoor Lighting Environment* (ISO 2016b). Test coupons constructed out of ceramic tile were coated with TPX-HL and spotted with *E. coli* bacteriophage Q- β , then irradiated with light or incubated in the dark for 17 hr (Figure 20). After the overnight incubation period, the phages were recovered from the surfaces of the coupon, pour plated in tryptone agar inoculated with the host *E. coli* strain, PFUs were counted, and bacteriophage survival was calculated (Figure 20).

Figure 20. Bacteriophage survival on uncoated ceramic coupons and coupons coated with TPX-HL incubated in the dark or exposed to approximately 1,000 lux light for 17 hr. The error bars represent the standard deviation ($n = 3$).



Survival of bacteriophage spotted onto the uncoated coupons was assessed directly after inoculation, and phage recovery was found to be $110\% \pm 17\%$ based on the total number of bacteriophages spotted on the test coupons. This indicates that phage recovery and viability for the experiment was effective. On the untreated coupons incubated in the dark, phage survival was $111\% \pm 80\%$ and on coupons illuminated with light was $99\% \pm 38\%$. There was no statistically significant loss of bacteriophage viability between the uncoated coupons, whether they were incubated in the dark or under the light. Nor was there a difference in the number of viable bacteriophages compared to phages recovered immediately after coupon surface inoculation. As with the other test methods used, this indicates that the

phages remained viable over the 17 hr incubation period and exposure to light had no apparent effect on phage survivability. However, a significant difference in bacteriophage survival was observed when comparing the TPX-HL-treated coupons either incubated in the dark or under florescent lighting. Phage survival when incubated in the dark was $139\% \pm 17\%$, and when incubated under light, the survival rate dropped to $21\% \pm 27\%$. These data clearly demonstrate that the coating had an inhibitory effect on the *E. coli* bacteriophage and that it was due to photocatalytic activity.

4 Conclusions

As building efficiencies become more stringent due to ever-increasing DoD standards, air exchanges are being reduced to save energy. Although this practice increases efficiencies, indoor air quality is generally sacrificed as the same air is increasingly recirculated. Although these practices lower operational costs and save resources, they can also lead to sick building syndrome. Microorganisms, particularly mold, can contribute significantly to a decrease in indoor air quality as well as threaten building infrastructure, which has recently become a major issue for Army installations. Photocatalytic coatings could be a solution to this ever-increasing problem. They have the capability to destroy harmful microorganisms such as mold and the toxic chemicals they produce. This work evaluated a novel indoor-light-reactive, next-generation photocatalytic coating, TPX-HL, for its ability to reduce microbial contamination under in-situ test conditions. The light-reactive coating was evaluated in two near-identical restrooms, and surface and airborne microbial contamination was monitored. Additionally, TPX-HL was tested for its ability to inactivate mold spores, bacteria, and viruses using standard test methods.

No reduction in viable airborne bacteria and fungi or total mold spores (viable and nonviable) could be detected over the course of the study in the restroom treated with TPX-HL. Treatment may have delayed the colonization of fungi on the walls of the restroom; however, by the end of the study more mold was detected in the treated area compared to the untreated area. No differentiation in the number of viable bacteria on the surface of the walls could be made between the two restrooms. Additionally, no significant difference in VOCs in each area could be determined. However, testing the photocatalytic activity of the coating with standardized test methods and increased illumination, revealed the coating did exhibit antimicrobial activity against fungi, bacteria, and viruses. Collectively, these findings suggest that there may be limited benefit to using the indoor-light-responsive photocatalytic coating to inhibit microbial contamination and reduce indoor air pollutants unless specific lighting conditions can be met. However, due to the restraints placed by the global pandemic and the short nature of the project, extended testing periods (e.g., greater than one year) and higher building occupancy and illumination may be needed to better evaluate the coating's effectiveness. Extended testing under real-world conditions may be needed to better assess the photocatalytic coating

for its long-term resistance to fungal contamination and ability to destroy VOCs for appropriate Army applicability.

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Appendix A: Safety Data Sheet for TPX-HL

The next five pages show the safety data sheet for the photocatalytic coating TPX-HL.

SAFETY DATA SHEET <TPX-HL>

1 / 5 pg.

Date of revision: Jan 16, 2015

1. Identification of the substance / preparation and of the company / undertaking

Product name: TPX-HL
 Applications Recommended: Photocatalytic coating agent
 Manufacturer: Kon Corporation
 Address: 22646, Matsunokihara, Miyano, Yamauchi-cho, Takeo-City,
 Saga-prefecture, Japan
 Tel: +81-954-20-7115
 Fax: +81-954-20-7116
 Manager: Takaharu Fujii
 In case of emergency contact: Quality control department
 Tel: +81-954-20-7115

2. Hazards identification

[GHS classification]

Physical hazards	Flammable liquid	Not classified
	Pyrophoric liquid	Not classified
	Self-heating liquid	Not classified
	Water-reactive flammable chemicals	Not classified
	Oxidizing liquid	Not classified
	Metal corrosive substance	Unclassifiable
Health hazards	Acute toxicity(Oral)	Not classified
	Acute toxicity(Transdermal)	Not classified
	Acute toxicity(Inhalation: Steam)	Unclassifiable
	Acute toxicity(Inhalation: Dust, Mist)	Not classified
	Skin corrosivity / Irritative	Not classified
	Damaging Serious / irritation to the eye	Not classified
	Respiratory sensitization	Unclassifiable
	Skin sensitization	Unclassifiable
	Germ cell mutagenicity	Not classified
	Carcinogenic	Unclassifiable
	Specific target organ toxicity(single exposure)	Unclassifiable
	Specific target organ toxicity(repeated exposure)	Unclassifiable
Environmental hazards	Aquatic environmental hazards(Acute)	Unclassifiable
	Aquatic environmental hazards(Chronic)	Unclassifiable
	Harmful effect on the ozone layer	Unclassifiable

※Hazard information not mentioned above, are "Not a classification target" or "Unclassifiable".

3. Composition / Information on ingredients

Distinction of single product or mixture : Mixture (Aqueous dispersion)

Component name	Content	Chemical formula	CAS No.
Titanium oxide (IV)	0.8~0.9wt%	TiO ₂	13463-67-7
Peroxititanium acid		Ti ₂ O ₃ (OH) _x (x≥2)	905310-10-3
Water	99.1~99.2wt%	H ₂ O	7732-18-5

4. First aid measures

Inhalation	Remove to fresh air, and take a rest in the easy style of breathes. Get medical attention/advice if you feel unwell.
Ingestion	Wash out mouth. Receive medical attention, the allowance. Get medical attention/advice if you feel unwell.
Skin contact	Wash the affected area with plenty of water. If skin irritation or rash occurs, get medical advice/attention.

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Eye contact	Rinse cautiously with clean water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing. If eyes irritation persists, get medical advice/attention.
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5. Fire-fighting measures

For the product itself does not burn, if this product is involved in a fire, never to be taken into account especially for firefighting.

6. Accidental release measures

Personal precaution	Wear proper protective equipment.
Environment precautions	Prevent from flowing out into sewer, watercourse or river.
Methods and materials for containment and cleaning up	Collect in a container empty. Wipe off residual spill by using absorbing water paper or cloth, and collect in plastic bag.
Measures to prevent secondary disaster	The product which was remained on the floor are risk of slipping, collect carefully, and wipe enough.

7. Handling and storage

Handling	Wear proper protective equipment to avoid contact and inhalation. Use only outdoors or in a well-ventilated area.
Storage conditions	Store the product in a cool and dark space of 5 ~ 25 °C (No freezing).
Incompatible materials	No information
Packaging materials	Metal containers should be avoided because of the potential for corrosion by water. Be placed in sealable containers for quality maintenance.

8. Exposure controls / Personal protection

Allowable concentration		(temporary) 0.3 mg./m ³ (TiO ₂ : Titanium dioxide nanoparticle) <Japan Society for Occupational Health(2013)>
Engineering measures		Placing local or whole exhaust ventilation.
Protective equipment	Respiratory protection	Wear dust mask or an appropriate respiratory protective equipment.
	Hand protection	Wear appropriate protective gloves.
	Eye protection	Wear appropriate protective glasses.
	Skin and body protection	Wear the appropriate protective clothing.
Hygiene measures		When using this product, do not eat, drink or smoke. Wash your hands clean after handling.

9. Physical and chemical properties

Appearance	White yellow opaque liquid
Smell	None
pH	7~9
Melting point / freezing point	No data
Boiling point	100°C (Water)
Flash point	Noncombustibility
Explosive range	Non-explosive
Vapor pressure	3.2kPa/25°C (Water)
Vapor density	No data
Specific gravity (relative density)	1.00 (25°C)

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<TPX-HL>

Solubility in water	Dispersion
Octanol / water partition coefficient	No data
Decomposition temperature	No data
Viscosity	< 12 mPa·s

10. Stability and reactivity		
Stability		Stable in normal handling conditions
Possibility of a hazardous reactions		No information
Conditions to avoid	Incompatible materials	Material was prohibited from mixing with water
	Hazardous decomposition products	No information

11. Toxicological information		
Acute toxicity	Oral	【Titanium oxide (IV)】LD ₅₀ >10,000 mg/kg (IUCILID (2000));rat From the above, classified as "Not classified".
	Transdermal	【Titanium oxide (IV)】approxLD ₅₀ >10,000 mg/kg (IUCILID (2000));rabbit From the above, classified as "Not classified".
	Dust / mist inhalation	【Titanium oxide (IV)】LC ₅₀ >6.82 mg/L/4h (IUCILID (2000));rat From the above, classified as "Not classified".
Skin corrosion / irritation		【Titanium oxide (IV)】0.5g/24h= Mild irritation, 0.1g/24h=None (IUCILID (2000));rabbit From the above, classified as "Not classified".
Serious eye damage / eye irritation		【Titanium oxide (IV)】 There is a result of that there is mild irritation, but as a result of that there is no irritating in (was washed in 5 minutes after application) Another test is obtained. (IUCILID (2000));rabbit However, because titanium oxide (IV) concentration of this product is less than 10%, classified as "Not classified".
Respiratory sensitization / skin sensitization		【Titanium oxide (IV)】 No data From the above, classified as "Unclassifiable".
Germ cell mutagenicity		【Titanium oxide (IV)】 Negative in the bone marrow cell micronucleus test / chromosome aberration test was carried out under the condition that the belly vaginal administration of mouse. (NTPDB(2005)) From the above, classified as "Not classified".
Carcinogenic		【Titanium oxide (IV)】 In IARC, it is classified into groups 2B. However, the occurrence of tumors in inhalation exposure test to the lung to rats and mice and hamsters, observed only for rats of high-dose administration. Moreover, similar trend was observed the tests for rats using other inert poorly soluble particles. It is considered that the rat-peculiar immune system acted. In epidemiological population studies on human made in Europe and North America, the causal relationship of titanium oxide and carcinogenicity did not show.(March 2012 dated 25 issue; Japan titanium oxide Industry Association of opinion) From the above, classified as "Unclassifiable"
Reproductive toxicity		【Titanium oxide (IV)】 No data From the above, classified as "Unclassifiable".
Specific target organ toxicity (single exposure)		【Titanium oxide (IV)】 Lethal dose by oral administration in rats is 10,000 mg / kg or more. In addition, the ingestion of this substance in humans is regarded substantially harmless. Moreover "oral" is classified as "Not classified". However, the data in the other path is insufficient. From the above, classified as "Unclassifiable".

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Specific target organ toxicity (repeated exposure)	【Titanium oxide (IV)】 In any of the tests on rats and mice, it is no influence caused by exposure at a dose of 1,250 mg/kg/day more than the upper limit guidance. On the other hand, there is a description that the pneumoconiosis changes for few worker of occupational exposure more than 20 years were revealed. The epidemiological studies that main purpose is whether titanium oxide has fibrosis effect have been often performed. However, the most of the studies are negative for the causal relationship. The hard evidence of association between titanium oxide and pulmonary fibrosis has not found. In case of inhalation exposure to rats for 2 years exceeding the guidance concentration upper limit of 250 mg/m³ (5days/week, 6h/day: dust), serious effect was not observed. However, there is no data of percutaneous exposure the other. From the above, classified as "Unclassifiable".
Aspiration hazard	No data

12. Ecological information		
Aquatic environment acute hazard		No data
Aquatic environment chronic hazard		No data
Biological toxicity	Fish toxicity	No data
Persistence / degradability	Bioaccumulation	No data
	Mobility in the soil	No data

13. Disposal considerations	
Residual waste	Avoid release to the environment. Disposal of contents and container must be in accordance with the criteria of the relevant laws and regulations.

14. Transport information		
International regulation	Maritime Regulatory Information	Non-hazardous materials
	Aviation regulatory information	Non-hazardous materials
National regulations (Japan)	Land regulatory information	Not applicable
	Maritime Regulatory Information	Non-hazardous materials
	Aviation regulatory information	Non-hazardous materials
Special safety measures	In case of stowing, give no damage. Reliably prevent collapse of cargo. Please make sure that there is nothing of any leaked liquid upon transportation. Be placed in a cool, dark place.	

15. Regulatory information	
Follow all regulations in your country.	
【In Japan】	
Chemical Substances Control Law	
Act on Prevention of Marine Pollution and Maritime Disaster	

16. Other information
Data that has been described here are based on the latest knowledge and experience. The purpose of the safety data sheet is intended to provide information of how to use safely this product. Data that has been described here, does not guarantee any performance of the product. Notes are intended for normal using. In the case of special using, should be considered this point. In addition, this product has been containing water. Therefore, if you have long-term storage in a metal container, please note that there is a possibility that the container is corroded.

SAFETY DATA SHEET

5 / 5 pg.

<TPX-HL>

【References】

1. GHS data-base (NITE: National Institute of Technology and Evaluation)
2. SANGYO CHUDOKU-BINRAN (Written in Japanese) (SIKAYAKUSYUPPAN Co., Ltd)
3. Handbook of Danger and Harmful Chemical Substances
(JISHA: Japan Industrial Safety and Health Association)
4. JIS Z 7253
5. Applicable laws and regulations
6. Other available data

Appendix B: Coverage Chart for TPX-HL

This page shows the amount of air purifying photocatalytic coating need to properly cover both porous and nonporous surfaces.

Components	Purpose:	AIR PURIFICATION / STERILIZATION / DEODORIZATION		
	Products:	PTA	TPX-HL	
		Painted or Organic	Porous	Non-Porous
	Type of Surfaces:	Plastic, acrylic, all organic painted substrates, etc.	Cement, Concrete, Stucco, Stone, Porous Tile, etc.	Metal, sealed granite, non-porous tile, etc.
	Min. Micron-Thickness:	0.10	0.17	0.12
	Coverage (ft ²) / Liter:	600	350	500

Coverage Chart / Notes	Coverage Chart			
	Square feet	Qty Needed (Liter)	Qty Needed (Liter)	Qty Needed (Liter)
	100	0.17	0.29	0.21
	200	0.34	0.58	0.41
	300	0.51	0.87	0.61
	400	0.68	1.16	0.82
	500	0.85	1.45	1.02
	600	1.02	1.74	1.23
	700	1.19	2.03	1.43
	800	1.36	2.32	1.64
	900	1.54	2.61	1.84
	1,000	1.71	2.90	2.05
	1,100	1.88	3.19	2.25
	1,200	2.05	3.48	2.46
	1,300	2.22	3.77	2.66
	1,400	2.39	4.06	2.86
	1,500	2.56	4.35	3.07
	1,600	2.73	4.64	3.27
	1,700	2.90	4.93	3.48
	1,800	3.07	5.22	3.68
	1,900	3.24	5.51	3.89
	2,000	3.41	5.80	4.09
	Notes:			
	1. Wasting amount of solution by air is not measured. Generally, it is said that the wasting percentage is lower when you coat the solution inside of building than outside.			
	2. For organic or painted substrates, PTA is required as the primer.			

Tools	Recommended Tools:			
	1. 0.8 ~ 0.5mm HVLP Spray gun			
	2. Compressor			
	3. Mask / Goggle			
	4. Gloves			

Optional	Optional Tools:			
	1. VOC sensor			
	2. UV Sensor			
	3. TSP			
	4. UV Sensor			

Appendix C: List of Target Volatile Organic Compounds Analyzed for by EPA Method TO-15

Compound	CAS#	Molecular Weight (MW)
Acetone	67-64-1	58.08
Acetonitrile	75-05-8	41
Acrylonitrile	107-13-1	53
3-Chloropropene (Allyl chloride)	107-05-1	76.53
Benzene	71-43-2	78.11
Benzyl chloride	100-44-7	126
Bromodichloromethane	75-27-4	163.8
Bromoethane (Ethyl bromide)	74-96-4	108
Bromoform	75-25-2	252.8
Bromomethane	74-83-9	94.94
1,3-Butadiene	106-99-0	54.09
<i>n</i> -Butane	106-97-8	58.12
Chlorobenzene	108-90-7	112.6
Chloroethane	75-00-3	64.52
Chloroform	67-66-3	119.4
Chloromethane	74-87-3	50.49
Carbon disulfide	75-15-0	76.14
Carbon tetrachloride	56-23-5	153.8
2-Chlorotoluene	95-49-8	126.6
Cyclohexane	110-82-7	84.16
Dibromochloromethane	124-48-1	208.3
1,2-Dibromoethane	106-93-4	187.8
1,2-Dichlorobenzene	95-50-1	147
1,3Dichlorobenzene	541-73-1	147
1,4-Dichlorobenzene	106-46-7	147
Freon 12 (Dichlorodifluoromethane)	75-71-8	120.9
1,1-Dichloroethane	75-34-3	98.96
1,2-Dichloroethane	107-06-2	98.96
1,1-Dichloroethene	75-35-4	96.94
1,2-Dichloroethene (cis)	156-59-2	96.94
1,2-Dichloroethene (trans)	156-60-65	96.94
1,2-Dichloropropane	78-87-5	113
1,3Dichloropropane (cis)	542-75-6	111
1,3Dichloropropane (trans)	10061-02-6	111
Freon 114 (1,2-Dichlorotetrafluoroethane)	76-14-2	170.9

Compound	CAS#	Molecular Weight (MW)
1,4-Dioxane	123-91-1	88.12
Ethyl acetate	141-78-6	88.1
Ethanol	64-17-5	46.07
Ethylbenzene	100-41-4	106.2
4-Ethyltoluene	622-96-8	120.2
<i>n</i> -Heptane	142-82-5	100.2
Hexachloro-1,3-butadiene	87-68-3	260.8
<i>n</i> -Hexane	110-54-3	86.17
Isopropyl alcohol (2-Propanol)	67-30-0	60.1
Isopropylbenzene (Cumene)	98-82-8	120.19
Methylene chloride	75-09-2	84.94
2-Hexanone (MBK)	591-78-6	100.1
2-Butanone (MEK)	78-93-3	72.1
4-Methyl-2-pentanone (MIBK)	108-10-1	100.2
Methyl methacrylate	80-62-6	100.12
Methyl-tert-butyl ether (MTBE)	1634-04-4	88.15
Naphthalene	91-20-3	128.17
Propylene	115-07-1	58.08
Styrene	100-42-5	104.1
Tertiary butyl alcohol (TBA)	75-65-0	74.12
1,1,2,2-Tetrachloroethane	79-34-5	167.9
Tetrachloroethene	127-18-4	165.8
Tetrahydrofuran	109-99-9	72.11
Toluene	108-88-3	92.14
1,2,4-Trichlorobenzene	120-82-1	181.5
1,1,1-Trichloroethane	71-55-6	133.4
1,1,2-Trichloroethane	79-00-5	133.4
Trichloroethene	79-01-6	131.4
Freon 11 (Trichlorofluoromethane)	75-69-4	137.4
Freon 113 (1,1,2-Trichloro-1,1,2-trifluoroethane)	76-13-1	187.4
1,2,4-Trimethylbenzene	95-63-6	120.2
1,3,5-Trimethylbenzene	108-67-8	120.2
2,2,4-Trimethylpentane (Isooctane)	540-81-1	114.2
Vinyl acetate	108-05-4	86
Bromoethene (Vinyl bromide)	593-60-2	106.9
Vinyl chloride	75-01-4	62.5
Xylene (para & meta)	1330-20-7	106.2
Xylene (ortho)	95-47-6	106.2

Abbreviations

ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ATCC	American Type Culture Collection
ATSM	American Society for Testing and Materials
CAS	Chemical Abstract Service
CERL	Construction Engineering Research Laboratory
CFU	Colony-forming unit
EPA	Environmental Protection Agency
EPA ORD	Environmental Protection Agency, Office of Research and Development
ERDC	Engineer Research and Development Center
GC-MS	Gas chromatograph–mass spectroscopy
HAP	Hazardous air pollutant
HPLV	high-pressure, low-volume
IMA	<i>Index of Microbial Air Contamination</i>
MBK	2-Hexanone
MEK	2-Butanone
MIBK	4-Methyl-2-pentanone
MTBE	Methyl-tert-butyl ether
MW	Molecular weight
OACSIM	Office of the Assistant Chief of Staff for Installation Management
OIG	Office of the Inspector General

PCA	Plate count agar
PDA	Potato dextrose agar
PFU	Plaque-forming unit
PHE	Public Health England
SDS	Safety data sheet
TBA	Tertiary butyl alcohol
TSP	Trisodium phosphate
VOC	Volatile organic compound

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14. ABSTRACT To meet new Department of Defense (DoD) energy standards, buildings are being constructed, and existing buildings are being retrofitted with tighter envelopes. These new standards can reduce operational costs significantly but also limit fresh outdoor air coming into the built environments. This can result in the accumulation of harmful substances within buildings, which can have adverse effects on its occupants. New photocatalytic coatings may be a solution to this ever-increasing problem as they have the ability to destroy both chemical and biological toxins when activated with light. This work evaluated a novel indoor-light-reactive photocatalytic coating for its ability to eliminate or reduce microbial contamination under in situ test conditions. However, air and surface sampling revealed no reduction in either viable fungi and bacteria or total air-borne mold spores. Additionally, no significant differentiation could be made in the composition of volatile organics between the treated and untreated areas. However, testing the photocatalytic activity of the coating with standardized test methods and increased illumination, revealed the coating did exhibit antimicrobial activity against mold, bacteria, and viruses. This suggested that there may be limited benefit to using the indoor-light-reactive photocatalytic coating to inhibit microbial contamination unless specific lighting conditions can be met.			
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