Role of Persistent Disinfectants in Reducing Disease Transmission from Contaminated Surfaces

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The airline industry responded to the COVID-19 pandemic by adopting various disinfection methods to eliminate the SARS-CoV2 virus. Although the primary transmission of SARS-CoV-2 is airborne, transmission by surface contamination is a secondary threat. The uniqueness of the aircraft environment highlights the value of surface decontamination to minimize exposure. With guidance from Boeing, high-touch cabin surfaces are being thoroughly disinfected between flights, using disinfectants and protectants authorized by the United States Centers for Disease Control (CDC) and the United States Environmental Protection Agency (EPA) List N and approved by Boeing for aircraft cabin and cockpit use. To explore how in-flight safety might be further enhanced, disinfectant methods that provide active and continuous (or "persistent") disinfection, also called persistent disinfectants, were investigated. In particular, low touch point and high touch point interactions with prolonged contact in the flight environment showed differential benefit from persistent disinfectant methods. Therefore, these persistent disinfectant methods are promising for further reducing the risk of viral transmission during travel.

I. Background/Issue

The SARS-CoV-2 respiratory virus has caused over 1 million deaths worldwide within a year [1]. In response to this global spread, governments issued travel restrictions that contributed to a 60% reduction in air travel passengers for 2020 [2]. In the past 20 years, more than five virus pandemic threats emerged, two of which became pandemics. Most notably, these threats included SARS-1, H1N1, MERS, Ebola and SARS-CoV-2. Only SARS-1 and SARS-CoV-2 contributed to a global decrease in airline passenger demand [2]. As the world increases its reliance on global airline travel to conduct an increasingly interconnected system of trade, the occurrence of frequent virus-based pandemic threats compels the industry to develop clear mitigation strategies that will continue to ensure the safety of passengers regardless of future pandemics. Four of the five above listed viruses of pandemic potential spread through respiratory means, while Ebola spreads through contaminated fluids. This paper focuses on reducing the pathways for respiratory virus transmission onboard aircraft. Although bacteria are a risk to human health, modern medicine's ability to typically treat bacterial infections with antibiotics result in viruses being the primary pandemic threat [3], [4].

Viral Transmission

Viewing the current pandemic in broader context, the airline industry faces a particular challenge to demonstrate safety and reduce potential transmission risk for all pandemics. During a pandemic, travel is essential, and potential virus transmission during travel must be reduced by all available means. The generic pathway model of all respiratory viruses is shown in Figure 1. A person with COVID-19, or any respiratory virus, can transmit the virus through exhalation, talking, coughing, or mucus transfer. Exhalation, talking, and coughing result in aerosol suspension or airborne droplets of the virus. Droplets greater than 5 micrometers can be deposited on surfaces and cause contamination, also called surface fomite contamination. Infectious mucus can also be deposited on surfaces and objects via hands in particular. This results in two possible infection pathways, either by inhalation or by touching a contaminated surface followed by the eyes, nose, or mouth, also known as fomite transmission [4].

Interventions to reduce viral spread target both airborne and contaminated surface transmission pathways. Masks are known to be effective at intercepting both types of transmission at the mouth and nose, and thereby preventing both contaminated surfaces and airborne transmission. To reduce transmission via contaminated surfaces, six key intervention points are identified to work as multiple layers of defense, as shown in Figure 2. Respiratory viruses of current and future pandemics should be assumed to have transmission by all pathways [4].

While SARS-CoV-2 is thought to spread mainly by droplet and aerosol transmission, fomite transmission, or transmission through indirect touch, is thought to be significant. Academics differ on the risk of fomite transmission, and estimates attribute 10% to 45% of all COVID-19 infections to fomites [5]. Furthermore, the relative risk of aerosol versus droplet versus fomite transmission is likely context-specific and behavior-specific. The World Health Organization (WHO) maintains that fomite transmission should be considered a viable risk in procedural planning for SARS-CoV-2 [6] and, as of August 2020, recommends cleaning of high-touch surfaces in guest accommodation settings at least after each use, and preferably more often [7].

Virus Transmission in an Airplane Cabin

Environmental factors, such as humidity, temperature, and air-exchange rate, can alter the likelihood of virus transmission to favor fomite transmission pathways. Airplane cabins have air exchange rates of 20-30 times per hour, reducing aerosol availability, and humidity below 15%, which may increase virus survival on surfaces [8]. A key, observational study of airplane cases surrounding norovirus, H1N1, and SARS-CoV-1 found that virus transmission via contaminated objects and surfaces was a substantial contributor for all three viruses. While H1N1 was spread primarily by close contact (70% of cases, 95% Confidence Interval (CI): 67%-72%) [7], both norovirus (85% of cases, 95% CI: 83%-87%) [9] and SARS-CoV-1 (50% of cases,95% CI: 48%-53%) [9] were primarily spread in the airplane environment by contaminated objects and surfaces. Since SARS-CoV-2 is known to be spread primarily by airborne routes [10], the higher air quality of the airplane cabin due to the frequent exchange of cabin air, the use of HEPA filters, and the cabin air flow from ceiling to floor results in a relatively safe space with regard to preventing airborne SARS-CoV-2 transmission. This makes the risk of fomite transmission a higher priority within the airplane cabin than in other environments.

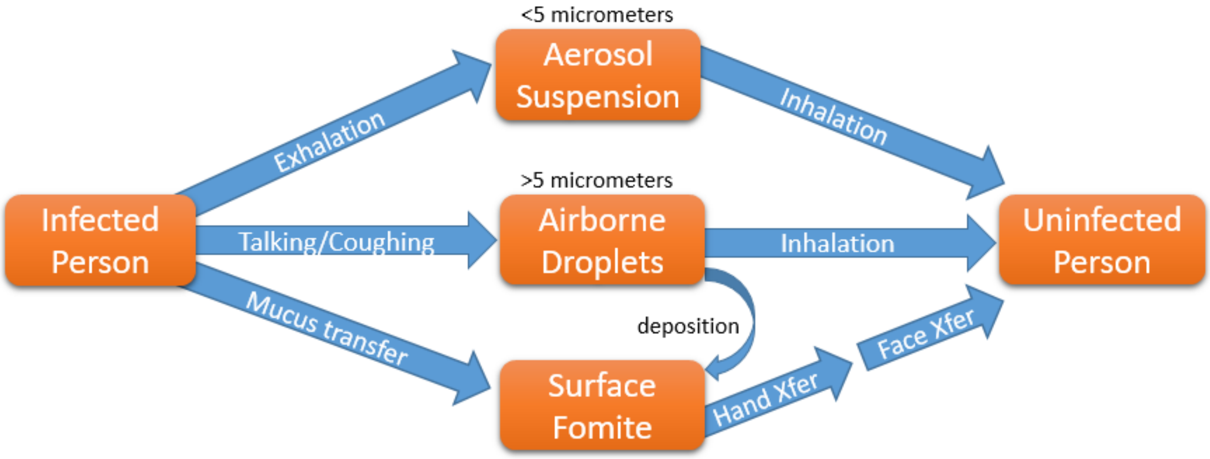


Figure 1: Transmission pathways for respiratory viruses

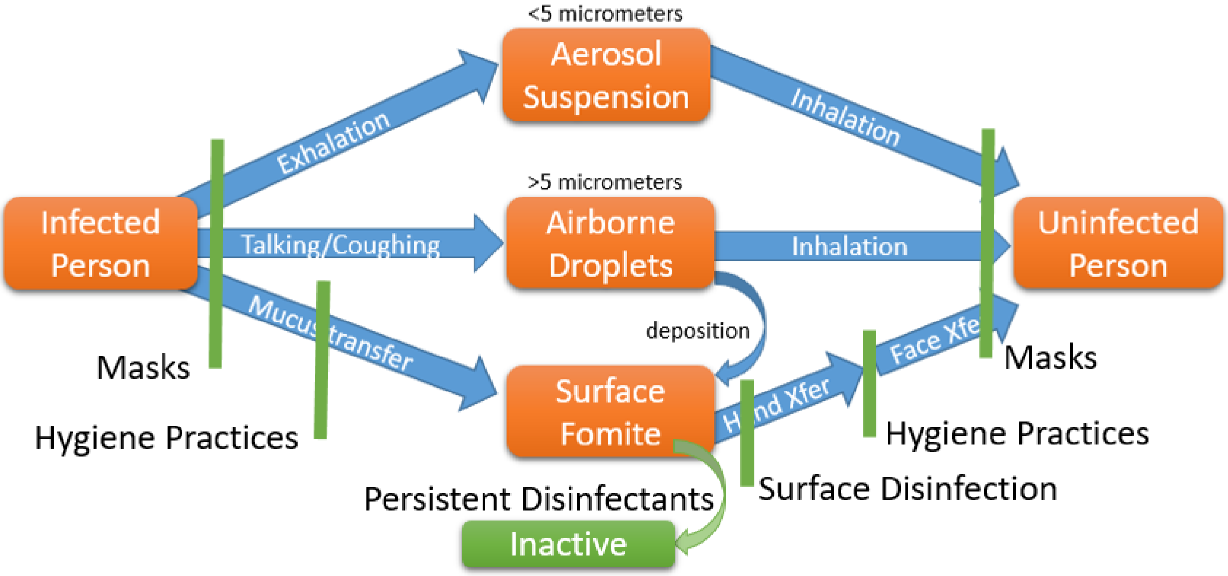


Figure 2: Intervention points for reduction of fomite transmission in contagious diseases.

Standard Surface Decontamination Methods

To mitigate the risk of virus transmission via contaminated objects and surfaces, both passengers and airlines can play active roles. As shown in Figure 2, passengers can mitigate the risk of virus transmission from contaminated surfaces by wearing masks and by employing personal hygiene practices such as increased hand washing, avoiding face touching, and the use of disinfection wipes [10]. For example, in a typical respiratory virus transmission, the simple intervention of hand washing has been shown experimentally to reduce diagnosis rates by 45% [11].

Airlines can add a layer of protection by disinfecting high-touch cabin surfaces between flights. Surface disinfection, as defined by the CDC, is a process that eliminates many or all pathogenic microorganisms, except bacterial spores. Factors contributing to the effectiveness of disinfection include: 1) prior cleaning of the object; 2) organic and inorganic contaminants present; 3) type and level of microbial contamination; 4) concentration of and exposure time to the disinfectant 5) physical nature of the object (e.g., crevices, hinges, and lumens); 6) presence of biofilms; 7) temperature and pH of the disinfection process; and 8) in some cases, relative humidity [12]. Disinfection that provides a 99.99% reduction in possible disease-related pathogens can be achieved by a broad range of methods, including many chemicals that are applied as sprays, mists or hand-wipes [13]. Standard disinfectants are designed to kill microbes in minutes and only while wet. The toxicity of standard disinfectants toward microbes is improved by the presence of liquid water and molecular mobility, both of which improve bioavailability of the active ingredient. The amount of time a standard disinfectant must remain in wet contact with a surface to attain a desired disinfection level is called “dwell time”.

On an airplane, in high-touch locations such as a handle or seat head rest, viable microbes on a surface transfer readily, so that after initial contamination, the next two to three touches could possibly transmit an infectious dose [14], [15]. For this reason, the WHO recommends that high-touch locations be cleaned after every use [7].

While cleaning high-touch locations between each landing of the aircraft may protect the next set of passengers, it does not prevent the transmission from low-touch surfaces. In considering transmission from low-touch surfaces or between passengers on the same flight, it is important to understand that with viral contamination, microbes cannot survive indefinitely without a host. Viruses further fall into two classifications: those enveloped by a lipid membrane (e.g., H1N1, HSV-1, and SARS-CoV-2) and those that are non-enveloped (e.g. norovirus, rhinovirus, poliovirus). While non-enveloped viruses are hardier than enveloped viruses, both become inactive during desiccation after initial exposure of the surface [16]. Therefore, the probability of viral transmission decreases over time, and the initial surface touches within the first few hours after contamination are the highest threat. This is in contrast to bacterial contamination, where the bacteria may multiply on a surface, making the initial exposure less dangerous than future exposures occurring after a period of time.

Low-touch locations may retain the virus for several hours, or in some cases, days, yet are unlikely to be touched. These low-touch locations are a more likely source of virus transmission during a pandemic, owing to the social training for hand washing after contact with high-touch locations. Hospital-based studies early in the CoViD-19 pandemic using pre-pandemic cleaning methods in rooms with infected patients have supported this model by showing clinically insignificant differences between the contamination levels of high-touch versus low-touch locations [17]. Yet after enhanced cleaning procedures were implemented, a similar study in a hospital in Wuhan, China, continued to find similar incidence of high severity fomite doses on low-touch surfaces (4.5% of samples) as high-touch surfaces (5.7% of samples) [18].

Between-trip interventions reduce an already low level of risk of transmission and will cause transmission between a plane’s flights to be diminishingly rare; however, additional measures are required to reduce same-flight transmission. While same-flight transmission remains rare, a study of SARS-CoV-2 surface transmission on a public bus in China, where masks were not worn, demonstrates the difference between same-trip and next-trip transmission. During the shared bus ride, the index patient spread the virus to seven other passengers. On the return bus trip, without the index patient but with contaminated surfaces, only one additional passenger became infected, and that person was seated very close to the seat of the original index patient [19].

Therefore, both low-touch surfaces and same-flight transmission represent potential areas for focusing risk mitigation efforts. A unique approach to systematically improve safety by actively and continuously removing virus contaminants involves a class of materials known as persistent disinfectants or antimicrobials. The US EPA requires materials that make legal claims regarding antimicrobial behavior to cause a 99.9% reduction within two hours after exposure to a virus on any surfaces coated with the persistent disinfectants [20]. The US EPA also requires that the disinfection occur in the absence of any added energy source or method, though regulations vary internationally. The coating's active ingredient must accomplish the destruction of the microbe on its own. The remainder of this paper focuses on persistent disinfection options and possible transmission models when these persistent disinfection options are applied.

II. Persistent Disinfectant Coatings

As stated previously, persistent disinfectants, or antimicrobials, provide active and continuous decontamination of a surface. The four most typical methods include: (1) antimicrobial coatings applied post production, (2) built-in antimicrobial treatments, (3) persistent antimicrobial lighting, (4) persistent antimicrobial aerosols or ions. However, this paper will focus only on antimicrobial coatings applied post production and built-in treatments.

Antimicrobial Coatings

In contrast with standard disinfectants, antimicrobial coatings work in a dry environment. These coatings cause longer-term disinfection that is bound on the surface for sustained activity[i]. Without liquid water and molecular mobility, antimicrobial coatings tend to disinfect more slowly, with most on the market taking hours to achieve 99.9% microbial neutralization. Next-generation antimicrobials are aimed at virus destruction in the low minutes range.

Many nations lack protocols for the use of antimicrobial coatings, and authorization and classification methods also vary. In some cases, classifications have been limited to 1) disinfectants or 2) objects with antimicrobial properties. While the chemicals used for antimicrobial coatings have been approved for public use for several decades, their durability and effectiveness at disinfecting are often unverified, owing to the lack of consistent policy. As a result, claims and standardized testing methods vary between jurisdictions. The US EPA recently created a new classification for persistent disinfectants that allows for antibacterial or antiviral claims of up to 28 days [20].

While many novel methods of surface disinfection and persistent disinfection are in development, the US EPA has granted antimicrobial designations to two mechanisms by which microbes are commonly destroyed using antimicrobial coatings. The first category outlined here is metallic ion oxidization. The second is mechanical disruption.

Silver and copper ions have long been used for disinfection owing to their high electron affinity (125.6 kJ/mol & 118.4 kJ/mol, respectively) making them the top two stable and widely available metals for this purpose. When exposed to hydroxyl (OH) groups on organic matter, copper and silver ions rapidly oxidize, breaking the oxygen off the host organism, and slowly destroying or deactivating the organism. In coating formulations, these systems can be found as nanoparticles designed for slow release into organic materials, or as solid metallic coatings with variable particle size. An example product, Viroblock®, has been shown to achieve disinfection within 30 minutes [21].

Mechanical disruption of the virus involves electrostatic attack on the virus that results in separation of the virus' body or outer shell. These approaches typically involve a group with a positive charge that attracts the negatively charged microbes onto a dipole-aligned methyl chain that mechanically pierces the virus. Example CAS numbers for this method include CAS 27668-52-6, CAS 199111-50-7, and CAS 68424-85-1. As with other systems, bioavailability of the system is critical to effectiveness. Testing data obtained by Boeing has shown substantial differences in disinfection speed when using the same active ingredient. This is understood to be related to the available surface area of active ingredient on the surface versus other non-sterilizing components. One of these systems has obtained the EPA claim of 99.9% effective on coronaviruses within 2 hours after exposure [22]. Boeing testing has found that similar materials typically disinfect 99.9% of SARS-CoV-2 in 1 to 3 hours on enveloped viruses and longer than 4 hours for non-enveloped viruses.

Built-in Treatments

Additives such as copper, silver, polymers, or ceramics can be included in various materials, giving the materials disinfectant properties through metallic ion oxidation and compound-derived oxidation.

EOS^{CU}, or Cupron, is a copper oxide-based antimicrobial that can be incorporated within polymers to provide the antimicrobial activity of copper. EOS^{CU} is a synthetic, hard surface preventative antimicrobial that is EPA-registered for public-health claims against several strains of bacteria [ii], though the process for anti-viral claims remains in development with the EPA [23].

Agion® by Sciessant, which is a proprietary mixture of silver and copper, releases small amounts of antimicrobial ions in the presence of bacteria and viruses. Agion® has been shown to inactivate viruses by 99.99% in five minutes. Agion® has been cleared by the FDA for incorporation into N95 masks, along with many other products listed by the FDA for emergency use in N95 masks[24].

LuminOre® CopperTouch Antimicrobial Surfaces is an EPA registered antimicrobial product that can be included on virtually any surface. The durable LuminOre® coating has shown a 2-log (99%) reduction of SARS-CoV-2 and a 3-log (99.9%) reduction of Ebola and Marburg viruses in a promising pre-print paper [25].

III. Virus Transmission Models

Transmission Model

In response to the COVID-19 pandemic, The Boeing Company developed a computational simulation model to increase knowledge of virus transmission in cabin interiors. The simulation aims to describe the transmission of viral particles through surface contamination during a typical aircraft flight, assuming a six-wide seating configuration. Boeing's simulation uses data assumptions such as virus survival time on surfaces, typical viral load transmission to and from hands, frequency of face touches, and trips to the lavatory, the goal being to combine agent-based and discrete event modeling with human factors (varying from person to person) and epidemiological considerations. In many key data areas, empirical values are not available and relative scores are assumed. These areas for assumption include viral load required for infection, virus shed rates, and viral survival rates during transfer. Due to these limitations, the simulation cannot determine absolute risk of infection caused by transmission from contaminated surfaces. However, the results provide meaningful relative values for comparing multiple scenarios, and are indicative of likely viral transmission from contaminated surfaces at large.

Coating Effectiveness over Time Study

To model the effectiveness of antimicrobial coatings on reducing disease transmission, four scenarios were simulated, in which only the speed of persistent disinfection was changed. The simulation's default values were used for all factors except the exponential surface decay rate, or the rate at which the virus decays on the surface, which was set to four durations and aligned with each scenario:

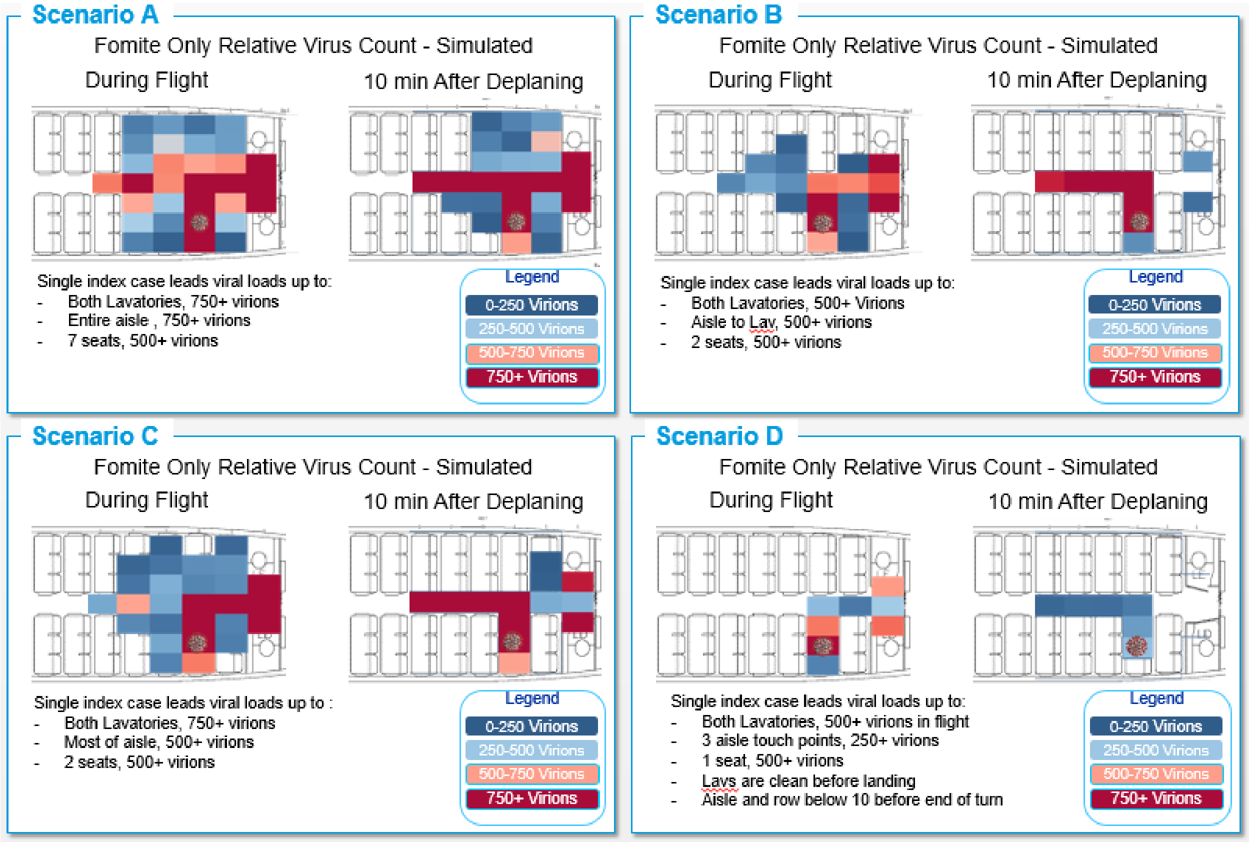
1. Scenario A represents an aircraft without any persistent disinfectants applied, though fully disinfected between flights, assumes 8-hour surface decay rate.

2. Scenario B represents an aircraft where all surfaces have been coated by a persistent disinfectant for which the effectiveness on viruses does not meet EPA required claims, assumes 4-hour disinfection to achieve 99.9% viral reduction.
3. Scenario C represents an aircraft where all surfaces have been coated by a persistent disinfectant for which the effectiveness on viruses meets EPA claims, assumes 2-hour disinfection to achieve 99.9% viral reduction.
4. Scenario D represents a coating that substantially exceeds EPA claim requirements, and assumes 20-minute disinfection to achieve 99.9% viral reduction. Note that to our knowledge, no coating exists that meets the requirements of scenario D and can be widely applied within the aircraft cabin.

In all four scenarios, four rows of the airplane are modeled with all seats occupied, and two open lavatories. The aircraft is assumed to be fully sanitized immediately prior to the flight, representing the best practices for surface cleaning, and individuals are presumed to not have any contamination when boarding the aircraft. A single contaminated passenger was seated in the middle seat, left side, third row. Each seat location and aisle location is classified as one voxel, or single block, for simulation, comprising the highly touched surfaces in that zone. For example, aisle-way voxels transfer fomites for scenarios such as stow bin access and headrest contact.

Boeing's simulation results were compiled by selecting the 99th percentile highest transmission case for each scenario, to determine the relative impact of the coating in reducing super-spreading events. A threshold was set based upon a viral load of 500 virions (virus particles) per seat or per person. As previously described, though, the model has not been validated against true transmission, as the human infective doses for many microbes, including SARS-CoV-2, remain unknown for fomite transmission. Rather, the purpose of the simulation is to compare the relative performance of the four scenarios, for which absolute estimates are not necessary. Average load during the three hour flight was determined and shown by seat voxel in Figure 3. The simulation continued beyond de-boarding by 10 minutes to approximate the contamination conditions that may be faced by the cleaning crew.

These results indicate a direct relationship between disinfection speed and spread of the virions through the airplane. There is also an impact, though to a lesser degree, between the coating disinfection speed and passenger virion count. We observe a non-linear decrease in passenger contamination on the timescale shown in Figure 4, when the time to reach disinfection is less than two hours, indicating substantial value in higher timescales. What is also evident is the reduced total viral content on the aircraft under all scenarios for the cleaning crew. This emphasizes the role of persistent disinfectant coatings as a backstop for cleaning procedures that may serve to substantially reduce the risk of cleaning gaps between flights. It is evident, though, that even at disinfection timeframes of two hours for 99.9% reduction, the main aisle way, lavatories and immediate vicinity of the contaminated passenger retain viral load after deplaning that calls for cleaning between flights. The viral particle counts shown in Figure 4 do not take into account personal hygiene practices such as hand washing or reduced face touching.



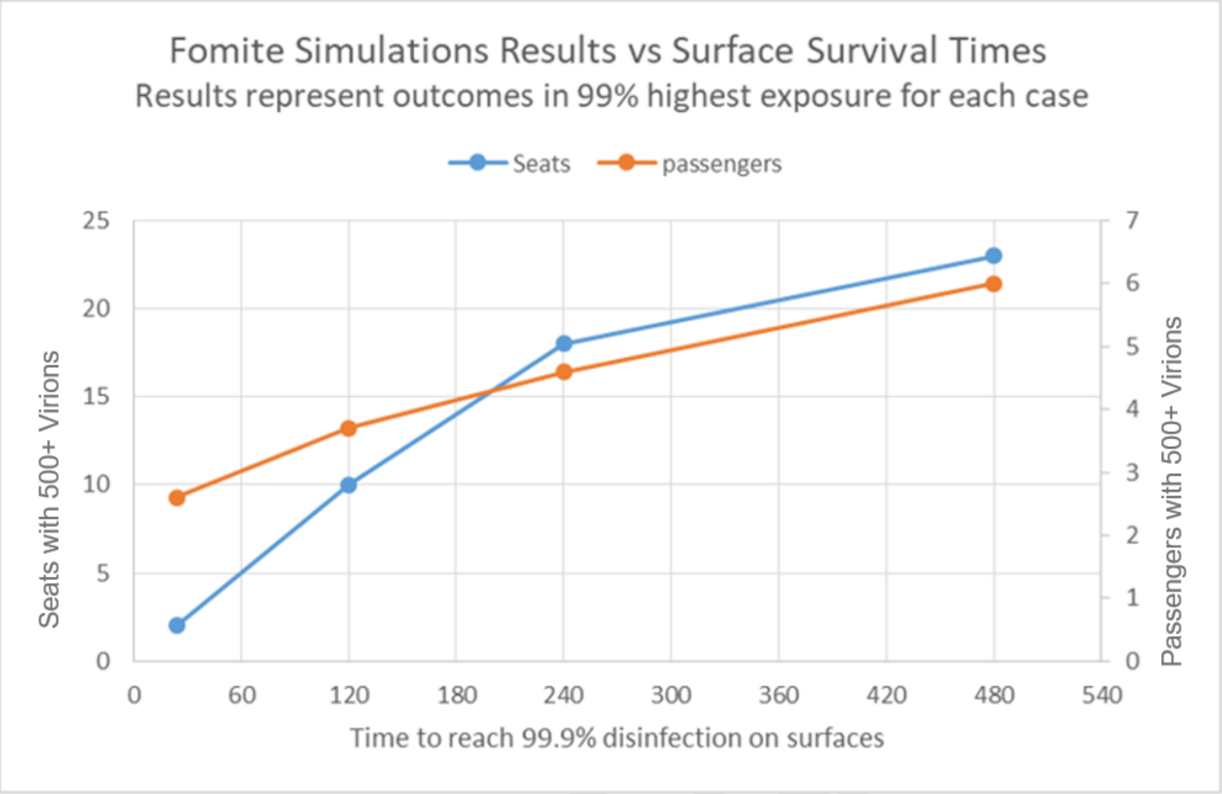
Single index case leads viral loads up to:
- Both Lavatories, 750+ virions
- Entire aisle , 750+ virions
- 7 seats, 500+ virions

Single index case leads viral loads up to:
- Both Lavatories, 500+ Virions
- Aisle to Lav, 500+ virions
- 2 seats, 500+ virions

Single index case leads viral loads up to :
- Both Lavatories, 750+ virions
- Most of aisle, 500+ virions
- 2 seats, 500+ virions

Single index case leads viral loads up to:
- Both Lavatories, 500+ virions in flight
- 3 aisle touch points, 250+ virions
- 1 seat, 500+ virions
- Lavs are clean before landing
- Aisle and row below 10 before end of turn

Figure 3: Simulation results for four scenarios of surface viral survival times from the Boeing model. Scenario A "Untreated" assumed 480 minutes virus survival on surfaces, B – 240 minutes, C – 120 minutes, D – 20 minutes.



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IV. Discussion and Operational Implications

Decontamination Practices

Persistent disinfectant coatings within the aircraft provide two areas of operational benefit: a potential reduction in cleaning for low-touch surfaces, and insurance against missed areas during disinfection. If persistent disinfectants are able to achieve disinfection within 20 minutes, our analysis demonstrates that many areas of the cabin, such as lavatories and galleys, may require cleaning service only, without disinfection. The use of antimicrobials that exceed the current EPA requirements would support a cleaning strategy on only high-touch points; the low-touch points would be disinfected by the time the plane lands. Any antimicrobial coating, particularly those with speeds at or below 120 minutes, will provide insurance against missed or poorly cleaned areas during the cleaning between flights by significantly reducing the fomite exposure risk.

Customer Benefits

In our simulation, a middle seat was occupied by a contaminated passenger to estimate the risk of transmission associated with travel in a fully loaded aircraft. While the heat map (Figure 3) shows the potential for fomite contamination, human infective doses for a number of microbes, including SARS-CoV-2, are yet to be quantified in relation to surfaces. However, the simulation data confirms that passengers located adjacent to the contaminated passenger or along the aisle way are exposed to moderate or high levels of fomites. In the presence of antimicrobial coatings, the transmission toward aisle-way passengers is substantially reduced below the 500-virion threshold in the 99th percentile scenario. We observe, in agreement with field observations ([19], [26]), that it is not seating location that primarily determines total exposure. Passengers are more likely to pick up virions from aisle-way and lavatory activities. Additional hygiene practices – such as reduced face contact, hand washing, and use of disinfectant wipes – as shown in Figure 2 may further reduce this risk. As previously described, though, the model has not been validated against true transmission.

V. Conclusion

Persistent disinfectant coatings within the cabin can provide significant customer benefits by reducing fomite exposure risk in combination with standard disinfection methodologies and personal hygiene. Our analysis shows that the industry should strive for antimicrobial coatings with increased disinfection speed, to reduce the viral load for cleaning crews and passengers. The ultimate use of any of these effective antimicrobial coatings requires further analysis, regulatory approval, evaluation and testing for application, efficacy, material compatibility and flammability, toxicity, impacts on environmental control systems, and required removal capability for use in an aircraft. The use of persistent disinfectant coatings can reduce the impact of future pandemics upon the airline industry, enabling safer travel and reduced viral spread.

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