Use of Bipolar Ionization for Disinfection within Airplanes

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Abstract

The 2020 worldwide spread of SARS-CoV-2 resulted in government issued travel restrictions and significant reductions in domestic and international passenger air travel. Global health multilateral organizations promptly began researching the novel virus to develop and determine methodologies to mitigate its spread and effect on humans.

Frequent disinfection of aircraft can be costly, time consuming, and can cause damage to materials and systems over time if not properly performed. The primary mode of transmission for SARS-CoV-2 is through respiratory droplets and it has been detected on surfaces for several hours[1,2] to multiple days after exposure.

Boeing formed the Confident Travel Initiative (CTI) to help minimize air travel risks during the COVID-19 pandemic. CTI is working across the industry to implement a coordinated approach with airline customers, airports, regulators, other industry stakeholders, infectious disease experts, and scientists. This represents an unprecedented international cooperation to address a global challenge.

Bipolar ionization was evaluated in various environments for antimicrobial effectiveness and safety, while keeping within the “turn” time parameter that an airplane may see on the ground in between revenue flights. Ions are commonly produced in nature and can occur at elevated levels near waterfalls, lightning strikes, and at higher elevations.

A multi-phased approach to evaluate the technology was developed to ensure a thorough assessment. This paper will delineate the methods used and findings of bipolar ionization.

- Antimicrobial effectiveness
- Byproduct production
- Safety for people
- Preliminary ground delivery process

Based on Boeing’s technical assessment, further study/development of air ionization by the industry is required before the technology can be incorporated for effective disinfection of airplanes in response to global pandemics caused by respiratory viruses such as SARS-CoV-2. The potential for utilization of air ionization for effective disinfection of microorganisms on

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surfaces and in air with no byproducts has been investigated by several external laboratories at higher flow velocities than an airplane cabin environment. Boeing's assessment of air ionization for airplanes determined that standardized test methods for antimicrobial effectiveness are required, provided mixed test results, and found very little external peer reviewed research in comparison to other traditional disinfection technologies.

List of Acronyms

- ATCC - American Type Culture Collection
- BBJ – Boeing Business Jet
- BSC – Boeing South Carolina (also referred to as Charleston, SC)
- BSL3 - Biosafety Level 3
- CTI – Confident Travel Initiative
- ECS – Environmental Control Systems
- EPA – Environmental Protection Agency (United States)
- HSV – Huntsville (Boeing Laboratory location)
- LPGC – Low Pressure Ground Connection
- NPBI – Needlepoint Bipolar Ionization
- NRC – National Research Council Canada
- PCA – Preconditioned Air (Ground Cart)
- STC – Supplementary Type Certificate
- TVOC – Total Volatile Organic Compounds

Introduction and Objectives

Air ionization devices produce positive (H+) and negative (OH-) ions by applying a high voltage to molecules present in the air, such as water, and can potentially produce other byproducts[3]. These charged ions attach and react to a large variety of compounds which they can neutralize and break down. Ions have been shown to inactivate airborne bacteria and viruses by breaking down their surface proteins, thus resulting in inactivation or lysis[2].

A multi-phased approach was developed which included laboratory analysis, ground based on-wing testing, flight testing with the technology equipped, and a set up for long term testing to ensure all parameters were considered and evaluated.

The objective of the statement of work was to quantitatively determine the antimicrobial efficacy of commercial ionization disinfection units against a variety of bacteria and viruses. Several tests were performed at various ion concentrations and relative humidity levels by Boeing and its research partners. The level of particulates, ozone, and potential byproducts were monitored both with and without ionization. This was to determine if a certain level of ions produced would be an effective disinfection method without impacting materials or human well-being.

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Background

Air ionization technology has been in use within the medical industry for decades and is a well-established technology that has recently seen incorporation into schools, airports, and business jets[4] in particular. Boeing evaluated both needlepoint bipolar ionization and corona discharge air ionization. Assessment of these technologies focused on the following:

- Laboratory antimicrobial effectiveness testing
- Ability to implement within preconditioned air units and passenger boarding bridge
- Ability to implement on aircraft
- Overall airplane antimicrobial effectiveness testing on surrogate viruses

Air ionization has been marketed to reduce pathogenic microorganisms, fungal allergens, odors, and volatile organics providing a healthier and cleaner environment.[5] Studies have claimed that air ionization technologies are effective against microbes such as Avian Influenza A virus subtype H5N1, *Mycobacterium tuberculosis*, Influenza H1N1 (swine flu), Polio Virus, *Escherichia coli*, Methicillin Resistant *Staphylococcus aureus* (MRSA), SARS, SARS-CoV-2, and fungal allergens.[5] Moreover, air ionization has been marketed to reduce airborne particles (dust, pet dander, pollen, etc.) through agglomeration or the buildup and collection of these particles.[5]

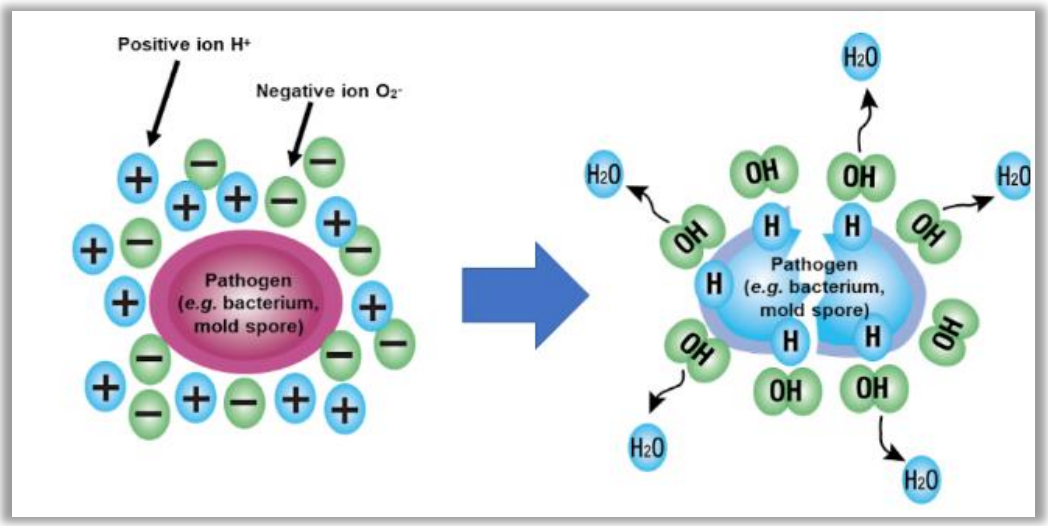

Figure 1. Air Ionization Cluster Formation[6]

Some other claimed benefits of this technology are energy consumption reduction, a decrease in carbon footprint, and passenger satisfaction. These claims were not evaluated by Boeing during assessment of the technology.

Based on literary research, most, if not all air ionization disinfection technologies revolve around the same chemical and physical concepts to inactivate viruses, bacteria, and fungi. Typical air ionization devices use high voltage (~10kV-20kV) to ionize the air and vapor molecules as shown in Figure 1 above. High voltage is applied across an anode and cathode (typically a

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small wire and/or plate combination). The electric field that develops breaks down air and vapor molecules, forming charged particles. These ionized molecules are unstable and short lived, and will seek out neutralizing molecules or surfaces due to the electrostatic force. This results in clustering around micro-particles and potentially harmful substances such as viruses, bacteria, fungi, odors, and allergens. Charged particles are then able to inactivate or kill viruses and bacteria by disrupting the outer layer of molecules.

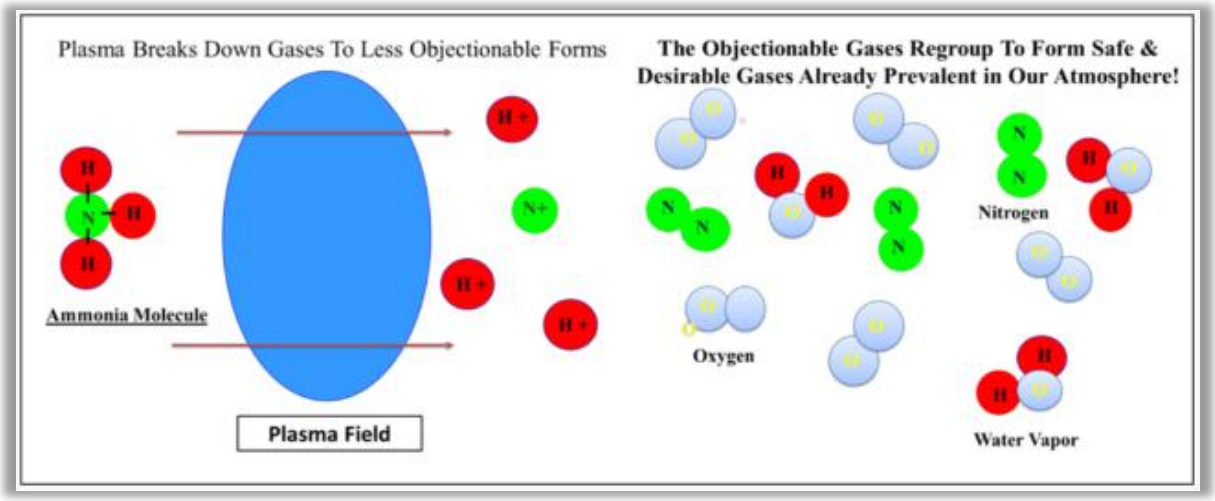

Figure 2. General Air Ionization Device Schematic[7]

Needlepoint Bipolar Ionization

Needlepoint bipolar ionization (NPBI) claims to generate comparable amounts of ions to that of other forms of air ionization with little to no ozone generation. It does not use a dielectric barrier and the power output is controlled to less than 12.07eV in order to prevent the formation of ozone, which can be hazardous in large quantities (greater than 100 ppb) [8] and an irritant at low quantities, while still generating ions from other gases and vapors, specifically water vapor.[5] The NPBI technology targets humidity water vapor which has an electron voltage potential of 1.23 eV.[5]

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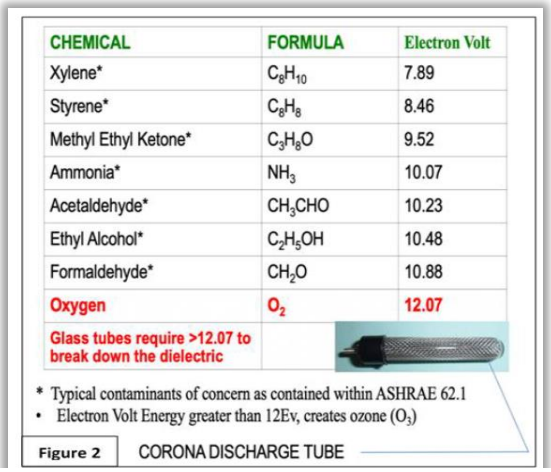

Figure 3: Electron Volt Potential for Common Gases[5]

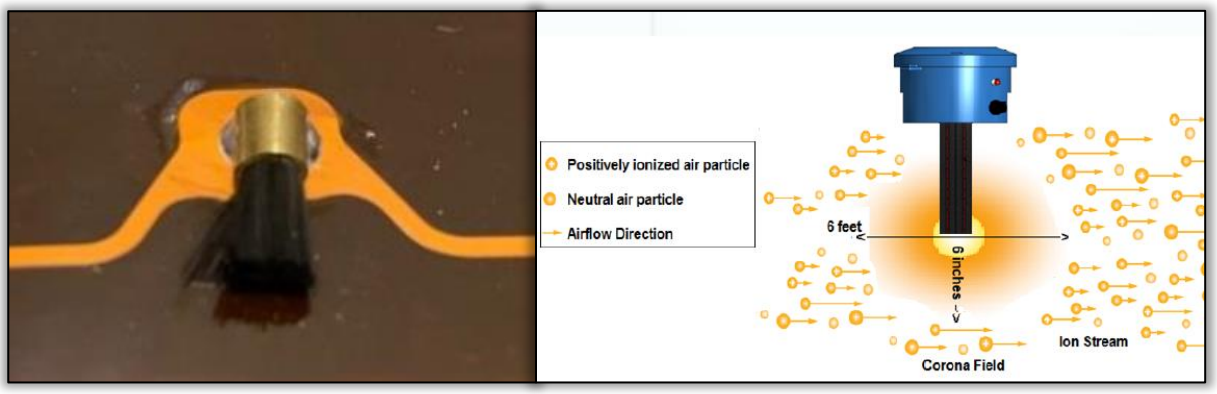

Figure 4: Needlepoint Bipolar Ionization[5, 9]

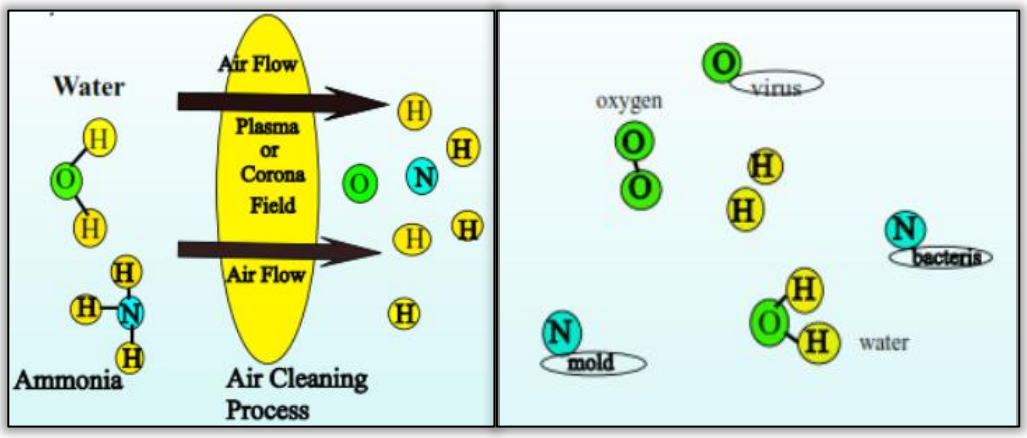

Figure 5. Air Ionization Eradication Methodology[9]

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The kill mechanism of the NPBI process is the stealing of hydrogen from pathogen surface molecules. This occurs due to the charged nature of ions which are produced through NPBI. The removal or neutralization of hydrogen from the pathogen surface molecule (whether, viral, bacterial, or fungal) leads to inactivation. The formation of cluster ions also can assist with coagulation of particulates in the air and lead to settling and de-suspension.

Prior testing has claimed significant kill or inactivation rates through the use of NPBI as shown in Table 1. This test data was provided by a potential supplier for air ionization in aircraft and conducted through 3rd party laboratories.

Table 1. NBPI Proposed Kill Rate from NPBI Technology Supplier[5]

Pathogen	Time in Chamber	Kill Rate	Test Agency
Mycobacterium tuberculosis	60 minutes	69.09%	EMSL
Clostridioides difficile	30 minutes	86.87%	EMSL
Norovirus	30 minutes	93.50%	ATS Labs
Methicillin-resistant Staphylococcus aureus	30 minutes	96.24%	EMSL
Staphylococcus aureus	30 minutes	96.24%	EMSL
Mold spores	24 hours	99.50%	GCA
Escherichia coli	15 minutes	99.68%	EMSL
Legionella pneumophila	30 minutes	99.71%	EMSL

Currently, NPBI is the only form of air ionization that has been approved to operate in certain type of aircraft, via supplemental type certificate (STC). In particular, this technology has been implemented in specific models such as the Boeing Business Jet (BBJ) as well as in competitor airplanes of similar scale.

Corona Discharge Air Ionization

Corona discharge air ionization systems work by neutralizing air pollutants and microorganisms by means of oxidation with ‘activated oxygen’. This is a generalized term for reactive oxygen compounds, which include ozone. For this technology, tubes are typically used that contain a dielectric barrier discharge which results in these activated oxygen particles. The process involves the application of a high voltage between two electrodes separated by the dielectric material (glass as an example) to force electric discharge. This electric discharge is captured by surrounding oxygen and water molecules as seen in Figure 6.

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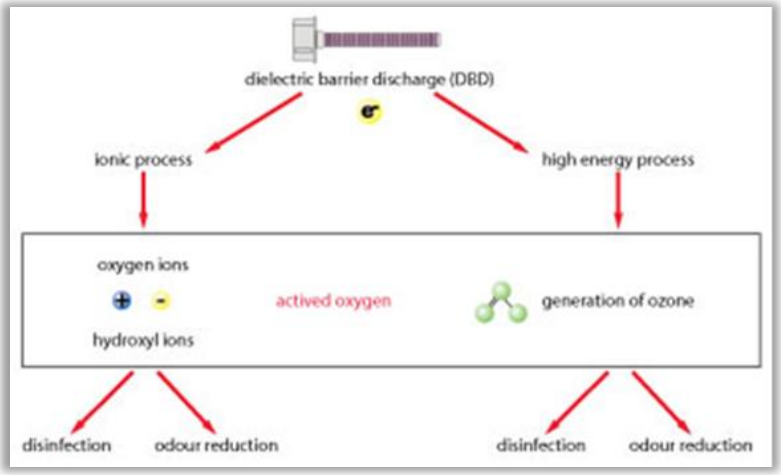

Figure 6. Air Ionization Corona Discharge Process[10]

Neutral air molecules are negatively or positively charged as they pass over an ionization discharge barrier. This results in formation of oxygen ions, reactive oxygen species, superoxides, peroxides, and hydroxyls. The combination of the oxygen ions (both positive and negative), as well as the listed radicals is referred to as “activated oxygen”. This cannot only generate ozone, but can also form reactive byproducts such as ultrafine particulates and short chain aldehydes. This suggests that utilization of high ventilation rates are pertinent to limit the impact upon any occupant that may be present.

Materials and Methods

Multiple tests were conducted, in conjunction with Boeing’s research partners and potential suppliers in order to determine the applicability and prospect of air ionization. This section provides a high level overview of the test methodologies utilized for a total of four forms of testing: (1) Huntsville Laboratory Testing (HSV); (2) University of Arizona Laboratory Testing; (3) National Research Council Canada (NRC) 737-200 Ground Testing; (4) Boeing Charleston 787-10 Ground Cart Testing (BSC).

Air Ionization Antimicrobial Effectiveness Testing - Huntsville Laboratory

Testing of NBPI was performed by Boeing Huntsville Laboratory in a 15’10” x 12’ x 7’9” stainless steel grounded room with static air flow as shown in Figure 7. The NBPI device tested included both air ionization and an installed fan to distribute ionized air into the room. Known concentrations of bacteria and bacteriophage were applied to surfaces using a modified approach to that of ASTM E1153-12 and JIS Z 2801. Negative ion counts were measured using AlphaLab Inc. AIC2 Ion Count Meters.

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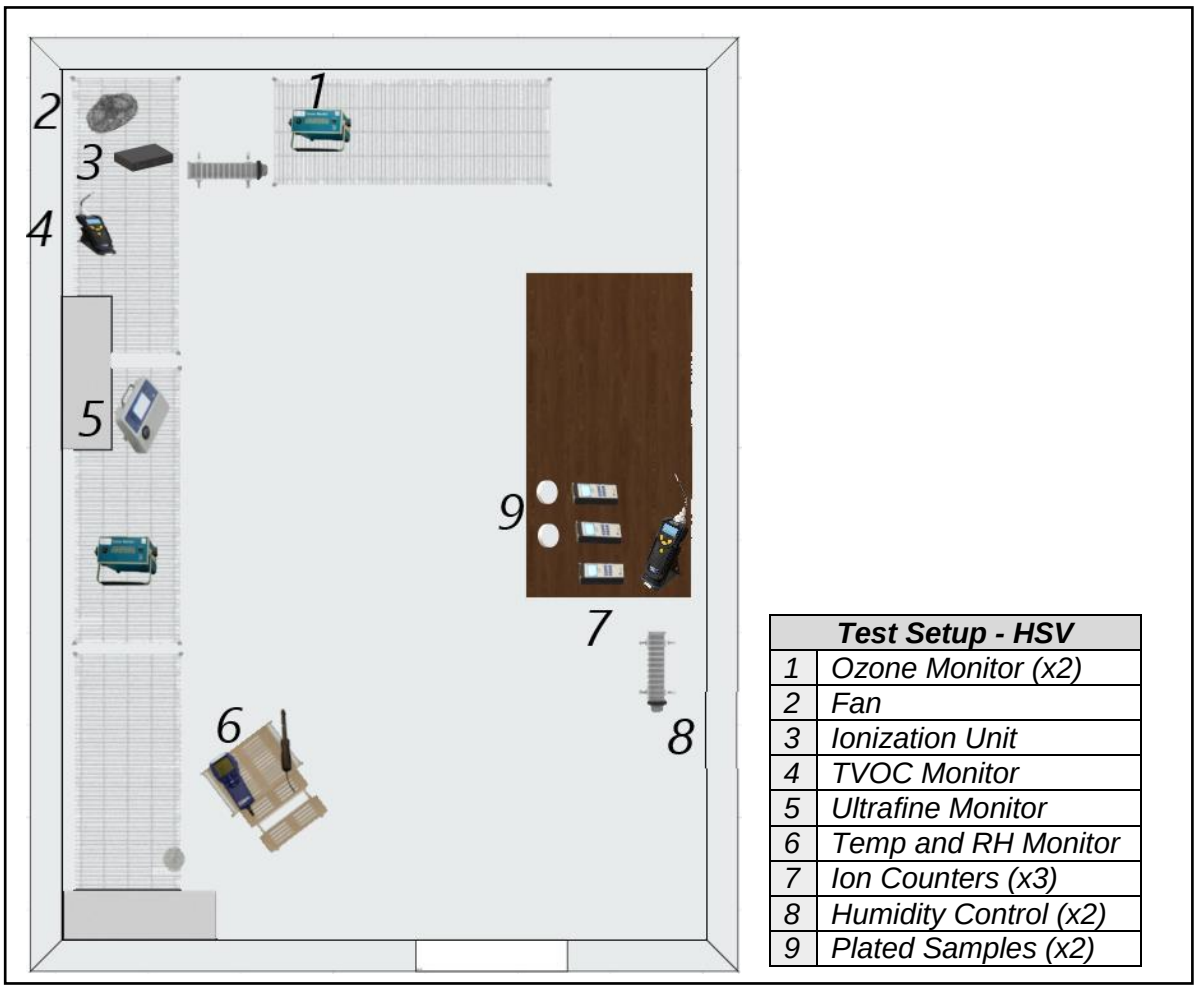

Test Setup - HSV	
1	Ozone Monitor (x2)
2	Fan
3	Ionization Unit
4	TVOC Monitor
5	Ultrafine Monitor
6	Temp and RH Monitor
7	Ion Counters (x3)
8	Humidity Control (x2)
9	Plated Samples (x2)

Figure 7: Test Setup

The two ionization units were turned on and moved to different locations within the area to see if the ion counts were consistent throughout. The ionization levels varied when modifications to the test conditions were made (units placed at different heights, varying distances, and whether there was additional airflow in the room by means of a portable fan). It was observed that both the airflow and direction of the ionization unit were important when trying to increase and maintain ion counts. The ion count significantly dropped when two ionization devices were pointed towards each other.

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Figure 8: Air Ionization Element[11]

For the efficacy testing, concentrated stocks of microorganisms (Table 2) were dried onto duplicate glass slides, and were placed sample-side up on a sterile surface in the room with exposure to various ion concentrations. Control samples were placed in a sterile biosafety cabinet with air flow to compare ion-treated and untreated samples. Ion counters were placed as close as possible to the sample slides while ensuring the flow of ionized air to the samples was undisturbed. Samples were exposed to ion concentrations ranging from 5,000 to >30,000 ions/cm^3 for 30 to 90 minutes. Enumeration of bacteria was performed by serial dilutions and cultivation by the pour plate method per Standard Methods for the Examination of Water and Wastewater. The enumeration of bacteriophage was performed by a plaque forming assay per the American Type Culture Collection.

The microbial enumeration data from a countable dilution at each exposure duration is used to calculate the percent reduction in counts due to an antimicrobial treated coupons as follows:

$$Percent\ Reduction = \frac{(A - B) * 100}{A}$$

Where A is the number of viable microorganisms on the control coupon at a specific exposure duration and B is the number of viable microorganisms on the antimicrobial treated coupons at the same exposure duration. This methodology accounts for the loss and viability or activity of microorganisms due to desiccation at each exposure duration and provides the antimicrobial activity of the treated surface.

The log reduction is calculated in CFU/ml, PFU/ml, or 50% $TCID_{50}$/ml due to antimicrobial treated coupons at each exposure duration as follows:

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$$Log\ Reduction = log10(\frac{A}{B})$$

Where A is the counts/ml on the control coupon at a specified interval and B is the counts/ml on the antimicrobial treated coupons at the same exposure duration.

Table 2: Microorganisms Selected for Huntsville Testing

Organism	ATCC® Number	Notes
Escherichia coli	8739™	Gram-negative bacteria used commonly used for antimicrobial testing
Staphylococcus aureus	6538P™	Gram-negative bacteria used commonly used for antimicrobial testing
Pseudomonas aeruginosa	27853™	Biofilm-producing gram-negative bacteria
Enterococcus faecalis	29212™	Gram-positive bacteria associated with human clinical environments
Enterobacter cloacae	13047™	Gram-negative bacteria associated with human clinical environments
Escherichia coli Bacteriophage MS2	15597-B1™	Norovirus surrogate

An example of the test setup and colonies of Staphylococcus aureus on agar plates are shown in Figure 9.

Figure 9: LEFT - Setup of Sample Slides and Ion Counters. RIGHT – Cultivated *S. aureus* Plates With and Without Ion Treatment

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Additional parameters were tested to better understand their effects on ion disinfection, including:

- Media used to prepare and dry microbial cultures onto the glass sample slides, such as phosphate-buffered saline, 10% peptone, or nutrient broth
- Glass slides placed in sterile plastic petri dishes or onto sterile foil to test its effect on repelling or attracting ions
- Test setup in the stainless steel test chamber or in a closed laboratory space with standard drywall walls

Air Ionization Disinfection – University of Arizona Laboratory Testing

Boeing partnered with the University of Arizona for a variety of CTI work due to their capabilities and Biosafety Level 3 (BSL3) laboratory status which allowed for the potential of aerosolized laboratory virus testing as well as surface testing. Currently, there are no standard procedures for testing air ionization technology. MS2 Bacteriophage (validation of the Boeing Huntsville Laboratory testing) and Coronavirus 229E (common cold), as a surrogate for SARS CoV-2, were tested with 5% fetal calf serum as a soil simulant. The inoculum was placed on stainless steel coupons and allowed to dry. Samples were exposed to ionization after the inoculum dried on the surface. Testing occurred in a mock hospital room (15’ x 15’ x 10’) with test locations per the United States Environmental Protection Agency (EPA) protocols. Both the supply and return air were blocked off within the room.

For MS2 Bacteriophage, ion counters were placed with the test samples on shelves of two, four, and six feet in height and between seven and a half to eight and a half feet away from the ionization unit, which was placed in the middle of the room. Measured ion concentrations were approximately 500,000 ions/cm^3 for 60 and 120 minutes of exposure.

Coronavirus 229E had two different test runs, one with bipolar ionization and the other with the positive ions attenuated, producing a greater percentage of negative ions. The ion counters were placed with the test samples on shelves of approximately 1, 3, and 6.5 feet in height. For the first experiment, the samples were between 7.5 to 8.5 feet away from the ionization unit, in the middle of the room. Measured ion concentrations were approximately 86,000 ions/cm^3 for exposure durations of 15, 30, and 60 minutes. For the second experiment, the samples were between 2.75 to 6 feet away from the ionization unit, in the middle of the room. Measured ion concentrations were approximately 56,000 ions/cm^3 for exposure durations of 15, 30, and 60 minutes.

Air Ionization Disinfection – NRC 737-200 Ground Testing

National Research Council Canada (NRC) conducted tests with their Boeing 737-200 airframe in December of 2020, simulating the same airflow conditions when ventilated by a preconditioned air cart (PCA) at an airport gate, as shown in Figure 10. Boeing and the NRC collaborated to conduct baseline and antimicrobial effectiveness tests. The objective of the statement of work was to quantitatively determine the logarithmic level of reduction of bacteria

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and bacteriophage from various exposure times to positive and negative ions produced by Boeing procured needlepoint ionization units. NRC conducted several tests:

- Baseline tests to understand the delivery of ions by a PCA unit through the environmental control systems (ECS) air distribution ducting into the cabin, and also free flow by placing the PCA hose assembly directly into the cabin.
- Antimicrobial effectiveness tests via supplying ion through ECS ducting systems
- Antimicrobial effectiveness tests via supplying ions directly into the cabin

Figure 10: NRCC Test Setup for 737-200

Carrier inoculum was prepared by mixing 35 µL 5% tryptone, 25 µL of 5% bovine serum albumin, and 100 µl of 0.4% bovine mucin (type 1) with 340 µl I*Staphylococcus epidermidis*. Disks (1 cm in diameter) of brushed stainless steel (AISI #304) were used as archetypical hard, non-porous, high-touch environmental surfaces (HITES). The disks were washed and sterilized by autoclaving and each disk received 10 µL of the microbial suspension with an added tripartite soil load. The inoculated carriers were dried for one hour under ambient conditions. Six locations in the aircraft were chosen for carrier placement: seat back tray, top of seat, overhead luggage compartment door, flight deck, lavatory and forward galley work surface (Figure 11). The samples were exposed to ionization for 1, 2, and 4 hours. This was to understand the impact of various ion concentrations for effectiveness as well as whether the units produced byproducts such as ozone or total volatile organic compounds (TVOCs). Ambient environmental parameters such as temperature, relative humidity, and flow rates were captured at multiple locations within the cabin, both with and without ionization, to gain an understanding of the cabin environment.

The NRC conducted multiple baseline tests (before microbial testing) with different PCA hose assembly layouts, placing the unit at different locations within the hose assembly. They also tested two delivery methods: 1) delivering ions to the cabin through ECS ducting systems, and 2) free flow method via of placing the hose assembly outlet directly in the cabin.

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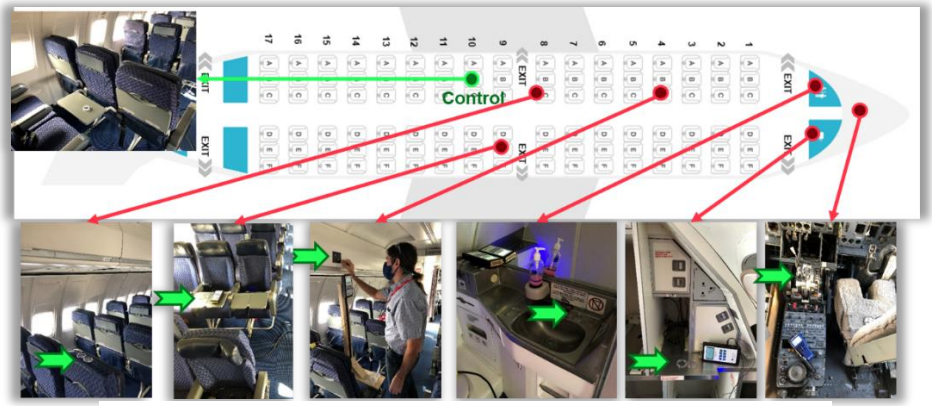

Figure 11. Sample Locations throughout the Cabin

Air Ionization Disinfection – New 787-10 Ground Testing

A double aisle airplane (787-10) was used to evaluate two external ground based ionization technologies. While the aircraft sits on the ground, conditioned air is usually supplied via the low pressure ground connections which are located on the belly of the airplane. Ionized air was produced prior to entry into the aircraft and carried with conditioned air provided from a preconditioned air (PCA) cart as shown in Figure 12.

Figure 12: Test Setup for 787-10

Background levels of ozone, ions, and TVOCs were slightly higher when one LPGC was connected rather than two. Since most applications use two LPGC when providing air to the aircraft, efficacy testing was performed using both. Ion concentration, ozone, TVOC, temperature, relative humidity, and flow rates were captured at multiple locations within the aircraft cabin, both with and without ionization, to gain an understanding of the cabin environment.

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Two locations were selected to perform efficacy testing. For both technologies tested, the Flight Deck and Row 40 in the economy section were selected as shown in Figure 13. The difference in these ion levels was not significant and varied throughout testing**.**

Figure 13: Testing Locations (Row 40 and Flight Deck)

Glass slides were inoculated with *Escherichia coli* in 10% peptone or *MS2 Bacteriophage* in ATCC 271 broth and exposed to the ionized cabin for 90 and 180 minutes, as well as a non-ionized area held in an adjacent building (control sample). Microbial samples were placed in duplicate near Row 40 in economy and also in the flight deck. Measurements were captured periodically to enable documentation of any possible anomalies from external sources or identify if a unit had failed (from ion levels decreasing). The ion levels in the cabin were much lower than what had been previously witnessed in a laboratory setting.

Based on the relatively low cabin ion concentrations provided through the low pressure ground connects, ionized air was also supplied directly into the cabin to see if ion counts improved by circumventing the ECS system. Plastic factory air socks were used by attaching the sock to the ionization unit and routing the air through a rear cabin door. Ion levels were found to be significantly higher, and an efficacy test was run for 60 minutes using both *Escherichia coli* and *MS2 Bacteriophage*. This layout is exhibited in Figure 14 and Figure 15. Figure 16 displays the differences of a typical air distribution with a PCA cart versus air supplied through the rear door.

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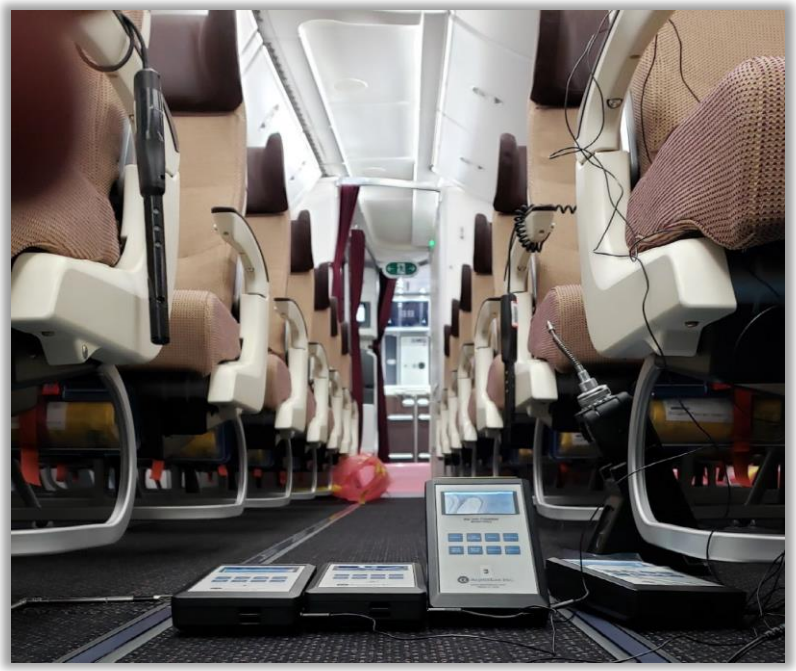

Figure 14: Ideal Test Configuration Setup

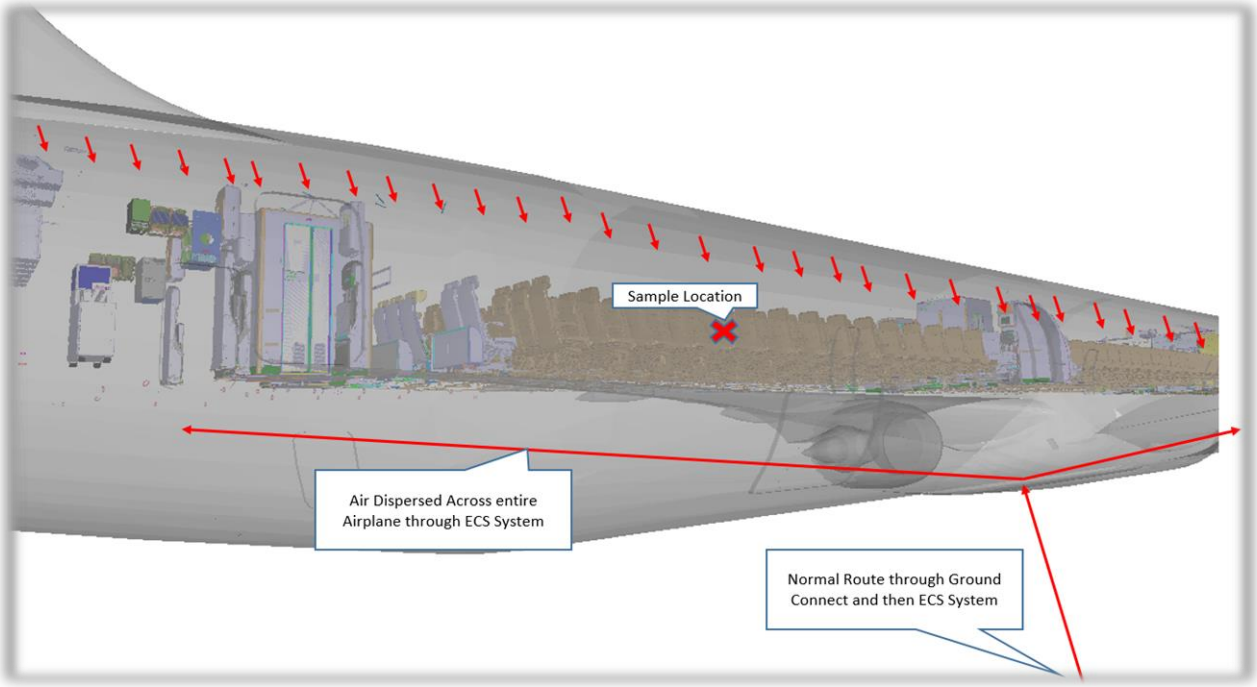

Figure 15: Original Test Configuration Setup through ECS routing

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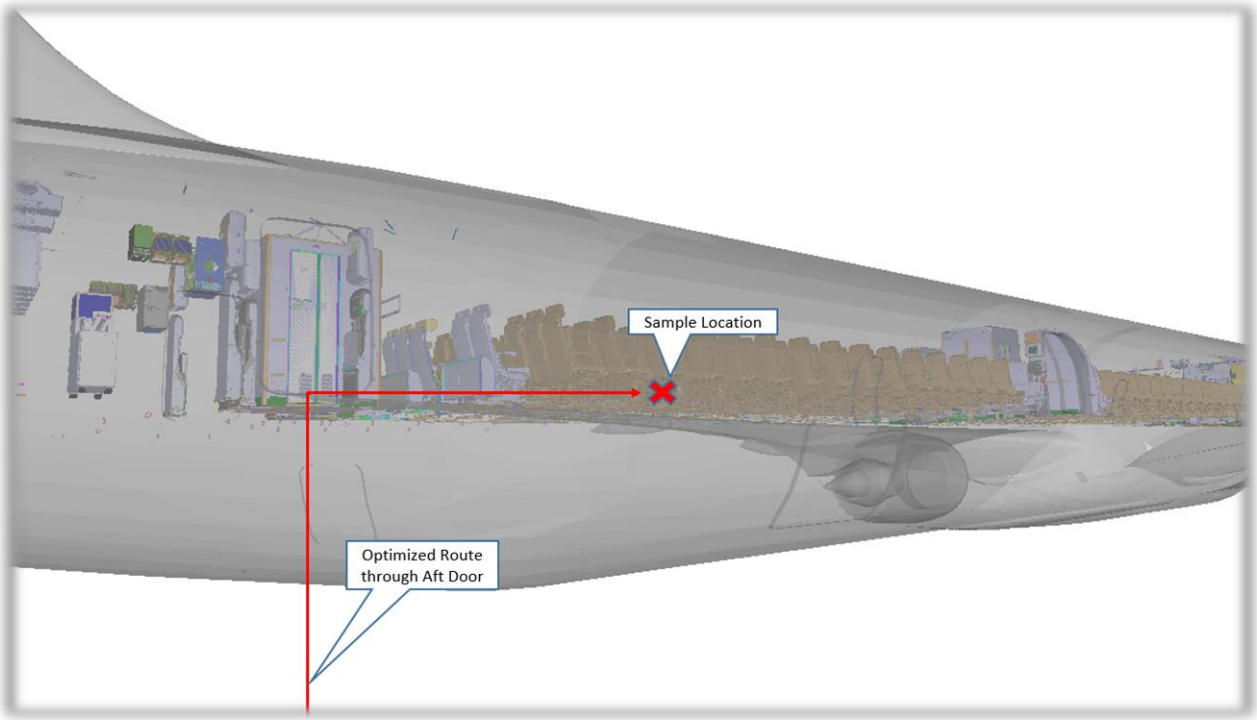

Figure 16: Test Configuration Setup of ECS Circumvention

Results

Air Ionization Disinfection - Huntsville Laboratory Testing

Testing in Huntsville detected no ozone production from the NPBI unit. Initial results have shown minimal reductions in viral inactivation. The norovirus surrogate *MS2 Bacteriophage* bared no observable reduction (<20.6% or <0.1-$\log_{10}$) over a 60 minute interval. It should be noted that noroviruses are more difficult to kill than enveloped viruses, such as coronaviruses.

There were minimal reductions in surface bacteria viability by bipolar ionization. There were no reductions in *Staphylococcus aureus, Pseudomonas* aeruginosa, *Enterococcus faecalis, and Enterobacter cloacae* with <20.6% or <0.1 $\log_{10}$ reduction over a 60 minute exposure duration. *Escherichia coli* did not perform well in tests when suspended and dried in phosphate buffered saline, but had better survivability in 0.1% peptone. Subsequent trials utilizing the 0.1% peptone mixture resulted in no observable reduction in viability (<20.6% or <0.1 $\log_{10}$) over a 60 minute exposure duration.

None of the additional parameter changes had an observable effect on the antimicrobial efficacy of air ionization, including what the glass slides were placed on (plastic petri dishes or aluminum foil) and testing the ionizers outside of the stainless steel test chamber.

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Table 3: Huntsville Laboratory Testing Results

Organism	Ions/cm^3	Duration	Results
Pseudomonas aeruginosa	>30k*	60 min	<0.1 log kill (<20.6% reduction)
Staphylococcus aureus	>30k*	60 min	<0.1 log kill (<20.6% reduction)
MS2 bacteriophage	>30k*	60 min	<0.1 log kill (<20.6% reduction)
Enterococcus faecalis	>30k*	60 min	<0.1 log kill (<20.6% reduction)
Enterobacter cloacae	>30k*	60 min	<0.1 log kill (<20.6% reduction)
Escherichia coli	>30k*	30, 60, & 90 min	<0.1 log kill (<20.6% reduction)

*Range closer to 40-75k

Air Ionization Disinfection – University of Arizona Laboratory Testing

Test results were not conclusive. As highlighted by the University of Arizona, “Generally, to be considered a disinfectant, a 3 to 5 log reduction in target organism is necessary to be considered effective. Microbial assays are highly variable and usually a 90% reduction is desired to be confident that a product is having any significant anti-microbial effect. Under the test conditions of this study none of the viruses achieved this level of reduction.”

In the configurations tested, surface efficacy testing with the University of Arizona showed a 66.7% inactivation of Coronavirus 229E (enveloped virus that causes the common cold) at 60 minute exposure to a range of 50,000 to 62,000 ions/cm^3 with positive ions attenuated. These were deemed statistically significant. Statistical significance could be impacted by the number of samples tested. In addition, a longer exposure with negative ions may result in a greater reduction of Coronavirus 229E. Due to the potential for air ionization as a disinfection methodology, but lack of experimental confirmation, the tests results were deemed inconclusive by Boeing Technical Experts.

Air Ionization Disinfection – NRC 737-200 Ground Testing

The microbial efficacy tests were conducted and exposed to positive and negative ions from 1 hour to 4 hours. Microbial samples were prepared and then exposed to the ionized cabin (Figure 11), based on two configurations:

1. Ion delivery via ECS ducting system (Figure 17)
2. Free flow ion delivery to the cabin (Figure 18)

Figure 19 shows the variance between the two delivery methods.

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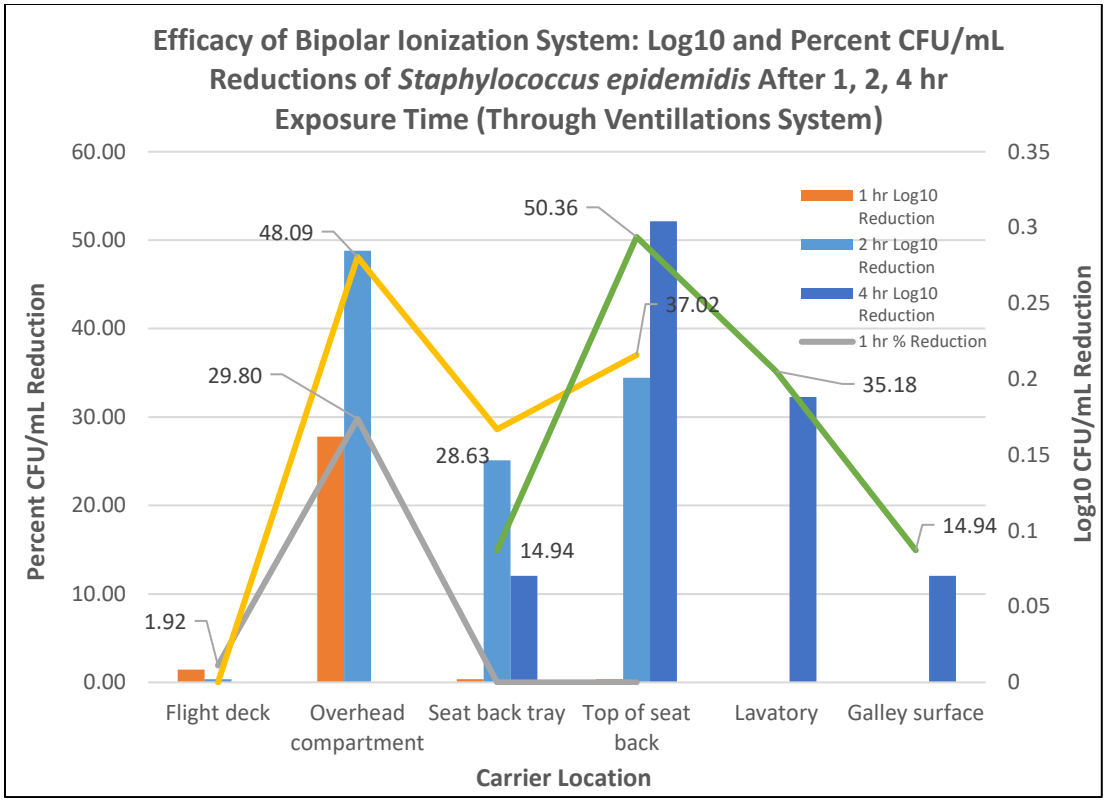

Figure 17: Bacteria Log Reductions Between 1-4 hours via ECS Ducting system

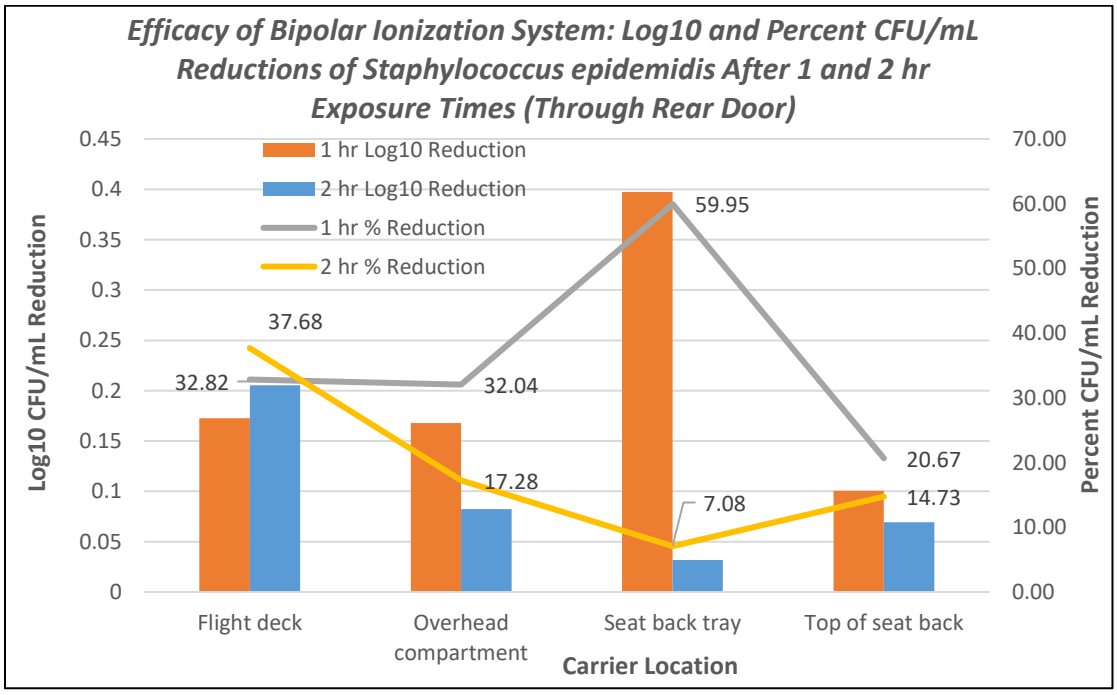

Figure 18. Bacteria Log Reductions 1-2 Hours via Free Flow

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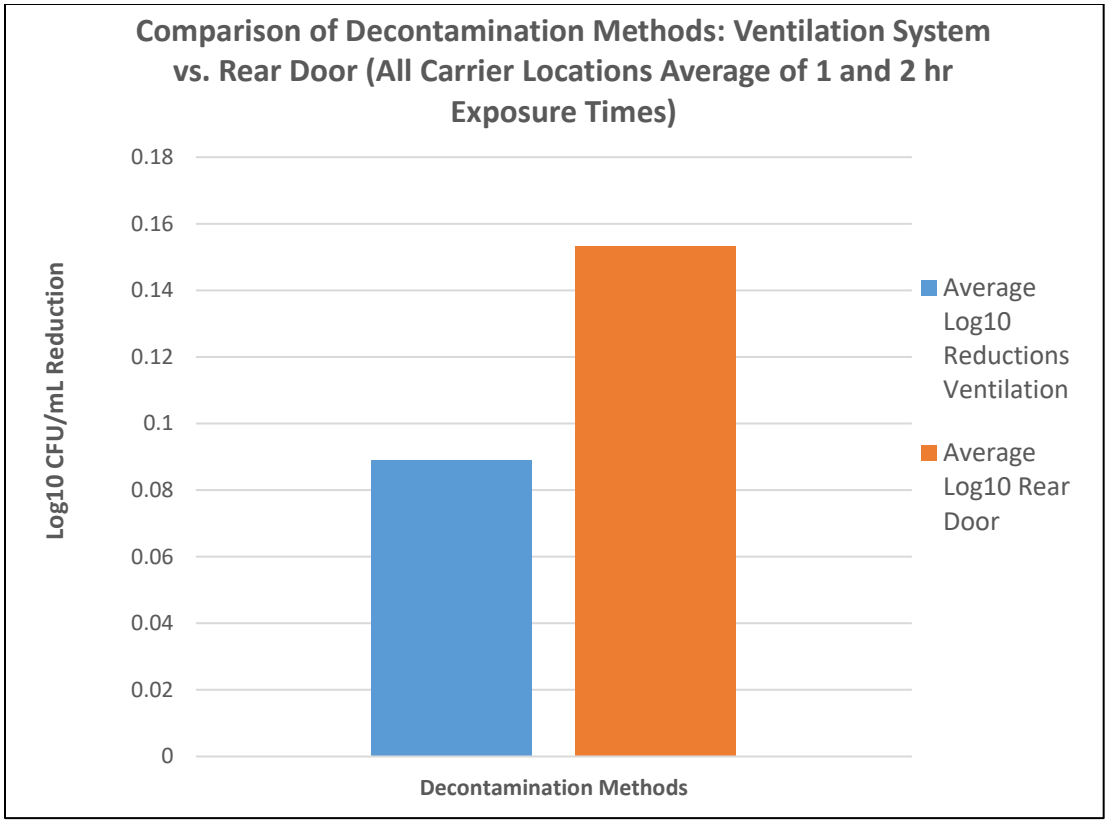

Figure 19. Log Reduction Variance between Two Delivery Systems

For the testing shown, the NRC indicated “The poor correlation between the antimicrobial effectiveness to ion concentration suggests that the use of ion concentration measurements alone is not sufficient to determine the disinfection rate of the test device inside the aircraft cabin. This is especially true when the air is not delivered in a predictable way or when the air velocities are likely low”. The susceptibility of microorganisms to air ionization differs based on phenotypic and genotypic characteristics.

Air Ionization Disinfection – New 787-10 Ground Testing

On a 787-10, from the low pressure ground connections to the cabin, the architecture involves air passing through multiple mufflers, a humidifier, the mixing manifold, and air distribution ducting for supply to the cabin and flight deck. It is suspected that the architecture and material that the ionized air passed through before entering the two test locations impacted the ion count. Moreover, turbulent flow can enable neutralization of ions by colliding into one another. New materials in the ECS system could have been off-gassing, prompting an expedited neutralization of ions as well.

Different configurations were run to see if it would help boost ion levels in the cabin. Ground cart flow was reduced to try and minimize turbulence in the ducting and mix manifold. The upper recirculation fans were shut off in an attempt to obtain a higher ion count (lower recirculation

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fans were already off). The lower ground cart flow ended up hurting ion count but the upper recirculation fans, when turned off, improved ion count slightly.

The level of negative ions/cm^3 in the cabin from the air ionizations units were much lower than anticipated. Contributing factors may include hose and ECS materials, physical parameters (ionizer design, flow constrictions, turbulence, ECS ducting design, ECS mixing chamber, airplane configuration i.e. door position, fans, etc.), and physics (ion molecule distribution, ion molecule life/neutralization, and environmental factors i.e. sunlight, air flow, objects).

In addition, cabin ozone concentration exceeded regulatory standards for one of the technologies assessed, with peaks up to 380 ppb produced. Key variables to consider are safety (impact to occupants) and physical (impact to airplane and cabin materials). Because of this, ozone should be monitored during use.

Escherichia coli and *MS2 Bacteriophage* reductions in 30-60 minutes of treatment were much lower than the desired 3 $\log_{10}$ (99.9%) cabin disinfection, as seen in Tables 4 and 5. Key variables to consider are low negative ions/cm^3, ion concentration distribution, ion life/neutralization, physical constraints, and test microorganisms not representative of more easily inactivated enveloped viruses.

Table 4: Needlepoint Air Ionization Charleston Results

Unit	Location	Ion Introduction	Average Ion Level (ions/cc)	Ozone (ppb)	TVOC (ppb)	Exposure Time (minutes)	Sample Used	Efficacy ($\log_{10}$ Reduction)
NPBI	Row 43	4R door, air sock	63,000	16	281	60	*MS2*	<0.1
							E. coli	0.13
	Row 40	2 LPGC	525	35	82	90	*MS2*	0.16[a]
							E. coli	<0.1
						180	*MS2*	<0.1
							E. coli	<0.1
	Flight Deck	2 LPGC	900	41	133	90	*MS2*	<0.1
							E. coli	1.03[a]
						180	*MS2*	<0.1
							E. coli	<0.1

[a] *Reduction may be due to sample placement in direct sunlight or experimental error*

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Table 5: Corona Discharge Air Ionization Charleston Results

Unit	Location	Ion Introduction	Average Ion Level (ions/cc)	Ozone (ppb)	TVOC (ppb)	Exposure Time (minutes)	Sample Used	Efficacy (Log_{10} Reduction)
Corona Discharge	Row 43	4R door, air sock	11,400	97	253	60	MS2	0.18[c]
							E. coli	<0.1
	Row 40	2 LPGC	1,508	85	92	90	MS2	<0.1
							E. coli	0.90[b]
						180	MS2	<0.1
							E. coli	0.47[b]
	Flight Deck	2 LPGC	402	114	157	90	MS2	<0.1
							E. coli	<0.1
						180	MS2	<0.1
							E. coli	0.62[a]

[a] *Reduction of Escherichia coli in the Flight Deck may be due to a combination of exposure to sunlight and ozone levels of approximately 100 ppb*

[b] *Reduction of Escherichia coli at 90 min is likely at or below the reduction at 180 min and could reflect experimental error or delays in plating after sample exposure. The reduction of Escherichia coli at 180 minutes is likely due to exposure to ozone levels of approximately 100 ppb.*

[c] *Escherichia coli is more susceptible than MS2 and a combination of ionization and ozone provided no reduction; therefore, the reduction of MS2 is likely due to experimental error and/or delays in plating.*

Overall, higher levels of ion concentrations need to be achieved in order to fully assess the technology's impact on the airplane cabin environment and its effectiveness in combating pathogens on the airplane during standard use, whether on the ground or in flight.

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Conclusions and Recommendations

The use of air ionization in an airplane remains inconclusive as a methodology for deployment during the SARS-CoV-2 virus pandemic. Boeing's limited testing was unable to replicate supplier results in terms of antimicrobial effectiveness. The systems were unable to properly deliver and maintain the necessary ion levels in the airplane to achieve disinfection. Similarly, laboratory-based tests did not show proper rates of disinfection with higher ion concentrations. It is pertinent to be able to demonstrate effective performance in an airplane environment given aircraft installation constraints. This can include but not be limited to length and geometry of air distribution ducting, material compatibility, and dynamics of air velocities.

However, external research on air ionization indicated that the technology has the capability to achieve high levels of disinfection (99.9%, 3 $\log_{10}$ reduction). Due to a lack of both iterative and standardized protocols for testing the technology, there have been variances in test reports, from both Boeing and also external evaluations of similar nature. As such, Boeing's current position is that air ionization has not shown significant disinfection effectiveness for further inclusion in the Confident Travel Initiative Program.

In order for Boeing to support further development of this technology, academia and industry need to solve/substantiate the following problems/claims:

- Peer-reviewed documentation of the physical/chemical mechanisms resulting in virus inactivation as it relates to key characteristic environments and installation. The body of basic research on the interaction of ionized molecules and bio-particles needs to be strengthened.
- Industry standard test methodology and effectiveness evaluation needs to be developed in order to allow comparison to other proven methods of disinfection (e.g. chemical, thermal, U.V., etc.).
- Demonstrated effective performance in an aircraft environment given aircraft installation constraints (e.g. long, irregular duct runs, material compatibility, low cabin velocity, etc.).

In summary, Boeing recommends the continued study, development, and validation of antimicrobial effectiveness in airplane environment flow conditions. There remains significant interest in air ionization due to lack of byproduct production, minimal risk to human health, minimum risk to airplane materials and systems, and the potential for persistent disinfection of air and surfaces under specific flow conditions. Boeing will continue to review, provide recommendations and feedback for, and provide input to other industry-lead efforts to standardize, test, and evaluate air-ionization technology in aircraft disinfection applications.

Finally, Boeing would like to thank the airlines that had collaborative discussions regarding methods of evaluation for bipolar ionization. In particular, Boeing would like to thank Etihad Airways for utilization of their 787-10 airplane to perform bipolar ionization testing in Charleston, South Carolina.

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References

[1] Jayaweera M, Perera H, Gunawardana B, Manatunge J. *Transmission of COVID-19 virus by droplets and aerosols: A critical review on the unresolved dichotomy*. Environ Res 2020; DOI: 10.1016/j.envres.2020.109819.

[2] Junho Hyun, Sang-Gu Lee, et al. Application of corona discharge-generated air ions for filtration of aerosolized virus and inactivation of filtered virus Journal of Aerosol Science 107 (2017) 31–40 32 https://www.sciencedirect.com/science/article/pii/S0021850216302798?via%3Dihub

[3] Zeng Y, Stephens B, et al. *Evaluating a commercially available in-duct Bipolar ionization device for pollutant removal and potential byproduct formation* Building and Environment May 2021, Vol 195 107750 https://www.sciencedirect.com/science/article/pii/S036013232100158X

[4] Matys J, Dominiak M, and Grzech-Lesniak *Disinfectants and devices for surface and air disinfection in dental offices*, Journal of Stomatology, September 2020, https://www.researchgate.net/profile/JacekMatys/publication/344178288_Disinfectants_and_devices_for_surface_and_air_disinfection_in_dental_offices/links/5f59412e92851c0789585237/Disinfectants-and-devices-for-surface-and-air-disinfection-in-dental-offices.pdf DOI:10.5114/jos.2020.98267

[5] Waddell C, *How Needlepoint Bipolar ionization Reduces Particles, Odors, Pathogens & Energy,* Global Plasma Solutions https://globalplasmasolutions.com/uploads/customer-resources/Service-Logic/GPS-WhitePaper-NPBI-Explained.pdf

[6] How does bipolar ionization work?, 2020, https://www.iso-aire.com/blog/how-does-bipolar-ionization-work

[7] Safely Return to the Office with Bi-Polar Ionization, 2020, https://www.hi-reit.com/bi-polar-ionization/

[8] OSHA, *OSHA Occupational Chemical Database Standards and Exposure Limits*. OSHA. https://www.osha.gov/chemicaldata/

[9] Top Products Innovations, 2014, *https://www.slideserve.com/alban/top-products-innovations*

[10] Ozone – Friend or Foe, 2021, https://bioclimatic.de/en/2019/09/05/ozone-friend-or-foe/

[11] The Value of Auto-Cleaning for Needlepoint Bipolar Ionization Systems White Paper, 2019, https://globalplasmasolutions.com/uploads/customer-resources/Resource-Library/Research/White-Papers/White-Paper-Value-of-Auto-Cleaning-NPBI-October-2019.pdf

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