Effective Air Purification for Aircraft Cabins

Anita T. Broach[1,2*], Ronald D. Blum[1], Mohamed Abuhegazy[3], Svetlana V. Poroseva[3], Stuart Sheldon[1], Kevin Karem[4**], Amara Rao Rama[5]

[1] *Air-Clenz Systems, Atlanta, GA, USA*
[2] *CSI: Create. Solve. Innovate. LLC Blacksburg, VA, USA*
[3] *Mechanical Engineering Department, University of New Mexico, Albuquerque, NM, USA*
[4] *Karem Consulting, LLC, Atlanta, GA, USA*
[5] *Department of Microbiology and Immunology, Emory School of Medicine, Emory University, Atlanta, GA, USA*

[*] *Corresponding email: anita@createsolveinnovate.com*
[**] *Director, FDA Southeast Food and Feed Laboratory, Atlanta, GA, USA*

SUMMARY
A new, patented technology - Air-Clenz™- quickly captures and cleans aircraft passengers' exhaled breath, cough, or sneeze, and returns it to the cabin in 10 seconds or less, thus effectively stopping and cleaning the flow of exhaled air before it spreads through the cabin. Most aircrafts use High Efficiency Particulate Air (HEPA) filters to clean cabin air. Airlines are quick to communicate that the cabin air within their aircraft is cleaned and/or changed every 2-3 minutes. Unfortunately, even the use of excellent HEPA filters and cabin air changes of every 2-3 minutes is not nearly enough to suppress the spread of highly infectious airborne diseases on board. As an example, one can contract certain variants of COVID within 10 seconds of an infectious breath, cough, or sneeze by a nearby individual. In addition, as this research shows, an infectious cough or sneeze by a seated passenger can infect another passenger within 20 seconds or less. The efficacy of this new technology in significantly reducing passenger cross-infection in a Boeing 737-800 cabin was proven by computational fluid dynamics (CFD) simulations. The CFD modeling utilized 368,000 particles in a 60-passenger coach class section of a Boeing 737-800. The 60 passengers included two contagious, infected passengers during flights of varying duration. Air-Clenz™ technology was placed in the back of all 60 seats; the existing cabin ventilation system operated as usual. Different versions of the Air-Clenz™ technology were compared to a base case of current Boeing 737-800 HEPA-enabled ventilation. The Air-Clenz™ technology proved to be especially beneficial and superior when face masks were not worn, and this beneficial effect was magnified during long flights.

KEYWORDS
Aircraft cabin, Boeing 737-800, exhaled air collection, exhaled air purification, aircraft cabin safety, airborne disease, airborne pathogen

1 INTRODUCTION
The transmission of airborne-transmitted diseases during flight has long been an issue, which was highlighted during the COVID-19 pandemic. Understanding the aerosol transmission of diseases in enclosed, multi-occupant spaces such as aircraft cabins and identifying effective and economically viable measures to limit infection transmission remains a pressing matter. To solve this issue, many published ventilation studies use computational fluid dynamics (CFD) to investigate and optimize ventilation systems on various aircraft, with the aim of improved air quality, and hence improved cabin safety, for passengers (Li et al. 2016; Talaat et al. 2021).

Our study is based on the recently published computational fluid-particle dynamic (CF-PD) simulation of a Boeing 737-800 coach section (Talaat et al. 2021). The Boeing 737-800 was selected for the study because it is one of the most popular aircraft across U.S. airline fleets. The cabin model accounts for 60 passengers (10 rows of six seats with a center aisle) at full capacity. Our study includes two of the 60 passengers already infected and contagious at the time of boarding. The infected passengers are positioned in a middle seat (seat 7B) and in a window seat (seat 5F). The ***Base Case*** scenario in our study does not alter the existing state-of-the-art ventilation and HEPA-assisted filtration system in the aircraft. Two additional scenarios in our study have the potential to improve cabin air quality and to reduce the airborne transmission of pathogens. In ***Scenario A,*** the novel Air-Clenz™ technology is integrated in the back of each seat in the cabin and quickly captures air exhaled by the passenger in the seat behind the seat, re-directs it down, and releases the exhaled air - and any additional captured cabin air - near the bottom of the seat and towards the cabin floor, where it is then removed from the cabin by aircraft air flow to existing air returns on the lower side wall of the cabin. The aircraft ventilation and HEPA filtration system remains intact. ***Scenario A with filter*** is the same as ***Scenario A*** plus the addition of a HEPA filter in the back of the seat, which filters the air captured and re-directed by the Air-Clenz™ unit before it is released towards the cabin floor. The aircraft ventilation and HEPA filtration system remains intact. ***Scenario B*** also utilizes the novel Air-Clenz™ technology integrated in the back of each seat to capture exhaled air. However, in ***Scenario B,*** 100% of cabin air exits the cabin through the technology within the seat back and then through conduits back to the existing HVAC return system. All four scenarios, ***Base Case***, ***Scenario A, Scenario A with filter***, and ***Scenario B***, use the same 60-seat coach class section of a Boeing 737-800, and have the two infected passengers in the same seats (5F, 7B). Each case assumes that no passenger wears a face mask and there is no passenger movement in the aircraft cabin. Thus, it is believed the results of this study should be considered as the best outcome for each case. It is also believed that the ***Base Case*** is the one most negatively affected by passenger movement within the cabin.

The goal of the study is to understand the ability of the novel technology to quickly capture and redirect the exhaled air before it spreads through the cabin, to reduce the risk of airborne infections during flights. The specific objectives of this study are to understand:

(a) What cross-infection of aircraft passengers by airborne viruses and bacteria could occur when aircraft passengers no longer wear face masks?
(b) The distribution of one-micrometer (1 μm) aerosols in a 60-seat coach section of a Boeing 737-800 at full capacity, using existing aircraft ventilation and HEPA-filtration system and cabin air changes of every 2-3 minutes (***Base Case***).
(c) 1 μm aerosol distribution for the same cabin as in the ***Base Case***, but with each seat back equipped with the Air-Clenz™ technology, which quickly captures the exhaled air from the passenger behind it and re-directs it towards the ground before releasing it back into the cabin. This occurs while the current 737-800 aircraft ventilation and HEPA filtration system remain unaltered (***Scenario A***).
(d) 1 μm aerosol distribution for the same cabin as in the ***Base Case***, but the captured and re-directed air by the Air-Clenz™ system, like in ***Scenario A***, passes through a HEPA filter before it is released back into the cabin (***Scenario A with filter***).
(e) 1 μm aerosol distribution for the cabin as in the ***Base Case***, but this time to consider the back of each seat being equipped with the new technology for capturing exhaled air but also to move 100% of the cabin air through the technology and into a conduit that moves the exhaled air and 100% of the cabin air out of the aircraft cabin (***Scenario B***).

(f) From the simulation results, calculate the following fractions: i) 1 μm sized aerosols that land on different surfaces in the cabin, ii) aerosols removed via outlets, and iii) aerosols being inhaled by the passengers. Utilizing the inhalation fraction values, calculate a possible number of newly infected passengers with airborne-transmitted infections, such as COVID-19, Influenza, common cold, pertussis, etc., in the same cabin section.

2 MATERIALS / METHODS

A three-dimensional model of a Boeing 737-800 cabin zone was previously developed by the University of New Mexico based on publicly available information from Boeing Commercial Airplanes. The UNM model represents the coach section of the aircraft containing 60 seats divided into ten rows, with a center aisle. Passengers were assumed to sit upright, face forward, and remain stationary. Accurate geometry was used for cabin walls and seats, but simplified human models were used to represent passengers (Talaat et al. 2021). Cabin ventilation in the model followed ASHRAE Standard 161-2018 for air quality in commercial aircraft; therefore, the model suppled 566 L/s of air to service the 60 passengers. ANSYS FLUENT 19.1 was used to estimate the velocity field of air and to simulate the particle dynamics following the methodology presented by Talaat et al. (2021). All passengers were assumed to inhale air at 9 L/min except for the two infected passengers (aerosol sources), who exhale at 9 L/min.

Aerosol particles were modeled as a discrete phase using the Lagrangian approach, which allows for direct incorporation of the effects of particle size on drag and gravitational forces on the particle. However, it requires the simulation of a large number of particles to obtain aerosol distributions sufficiently independent of the particle count. Present simulations used 184,000 particles exhaled from each of the two infected individuals for a total of 368,000 particles modeled for ***Base Case***, ***Scenario A, Scenario A with filter,*** and ***Scenario B***. As momentum diffusivity of air is the dominant mode of particle transport, the particles were approximated as spherical. One micrometer (1 μm) size aerosol particles were considered in the present study, since they were released during different exhaling events such as breathing, coughing, sneezing, and talking. The two infected passengers were the only sources of aerosol particles in the simulations. An impulse source in time was simulated to investigate the spatio-temporal dynamics of aerosol particles. The standard filtration efficiency of particulate filters used in the aerospace industry exceeds 99.99%. The same was assumed for the HEPA filter installed in the back of the cabin seats in ***Scenario A with filter***. Aerosols that exit through the outlet were assumed to be perfectly filtered and not recycled into the system. Susceptible passengers were assumed to inhale air at the rate of 9 L/min and could, therefore, inhale some of the aerosol particles present in the air. The inhalable aerosol fraction and the fraction of aerosol deposited on various surfaces (including passengers) were quantified for relative risk assessment, useful for relative comparison of the intervention measures and do not represent absolute values for inhalation dosimetry.

The number of passengers infected during the flight by the two original infected passengers was calculated for each of the simulated scenarios by considering the simulated inhalable fractions and the minimum infective doses for nine airborne-transmitted viral and bacterial infections. The nine airborne transmitted pathogens considered in this study, along with their minimum infective doses, are in Table 1 (Basu 2021; Chen et al. 2021; Karimzadeh et al. 2021; Yezli and Otter. 2011).

Table 1. Minimum infective doses for several viral and bacterial airborne-transmitted pathogens

Pathogen	Minimum infective dose

	(number of pathogens)
SARS-Cov-2	100-1000 (300 in this study)
Influenza H1N1	600
Rhinovirus RV15	100
Norovirus	10-100 (10 in this study)
Adenovirus type 4	10-500 (10 in this study
M. tuberculosis	1-200 (1 in this study)
Bordetella pertussis	1-150 (1 in this study)
Bacillus anthracis	1-100 (1 in this study)
Mycoplasma pneumoniae	1000

The average shedding rate of 30 of pathogen-containing particles per minute from the two infected passengers was assumed. Each of the considered pathogens, *viz.* SARS-Cov-2, *Influenza, Norovirus, M. tuberculosis* and others, transmits via airborne aerosols and droplets, except for the *Rhinovirus* which main transmission route is via droplets. For pathogens larger than 1 μm, it was assumed that the aerosols and droplets containing such pathogens (few microns in size) flow in the cabin in a similar way as the simulated 1 μm particles. Furthermore, during each hour spent in the aircraft cabin, the infected individuals were assumed to breathe normally for 50 minutes and to talk for 10 minutes. Two coughs per hour were assumed for each of infected individual. It is known that different exhaling events, such as breathing, talking, coughing sneezing and so on, produce different quantities of droplets and aerosols with different particle size distributions (Basu 2021; Chen et al. 2021). Therefore, accounting for the number of particles generated during the breathing, talking and coughing by the two infected passengers and the average probability that the exhaled particles contain pathogens, the number of pathogen-containing particles are given in Table 2. It was also assumed that no movement by passengers, flight attendants, or crew occurs in the 60-seat section.

Table 2. Number of potential pathogen-containing particles released during different expiratory events

Expiratory event	Pathogen-containing particles	Total pathogen-containing particles exhaled from 2 infected individuals (per hr)
Breathing	30 (per minute)	3000 (aerosols only)
Talking	300 (per minute)	6000 (aerosols / droplets 40/60)
Coughing	250 (per cough)	1000 (aerosols / droplets 40/60)

3 RESULTS AND DISCUSSION

As expected, simulation results show that air flow in the cabin is mainly influenced by the aircraft ventilation system and the geometry of objects and walls in the cabin. The simulated 1 μm size aerosol particles are also mainly influenced by cabin air flow, primarily due to relatively low gravity for the simulated 1 μm particles compared to the effect of cabin air flow. The three-dimensional distribution of 1 μm aerosol particles at different points in time after exhalation by the two infected passengers is shown in Figure 1. Within 10 s of release, susceptible passengers even several rows from the two infected passengers begin to inhale infectious particles. At the same time, particles also rise to the ceiling level, i.e., in the breathing zone for the affected passengers, shown as red particles in Figure 1. This is especially noticeable with ***Base Case, Scenario A***, and ***Scenario A with filter***, although particle spread is more localized and the breathable portion of the particles is less for ***Scenario A*** and ***Scenario A with filter*** compared to the ***Base Case***. The particle cloud in ***Scenario A with filter*** is the same as in ***Scenario A***. The only real difference between the two is that air returned to the cabin is completely free from aerosol particles, as they have been captured by the HEPA filter in the back of the seat in

Scenario A with filter. The particle distribution in ***Scenario B*** is even more localized over smaller number of affected passengers compared to the other three scenarios, while the breathable portion of the particles for this scenario is significantly lower - almost zero. After the initial 10 s, particles start to deposit on different surfaces in the cabin or be inhaled by susceptible passengers, as can been seen from the particle distributions with time in Figure 1.

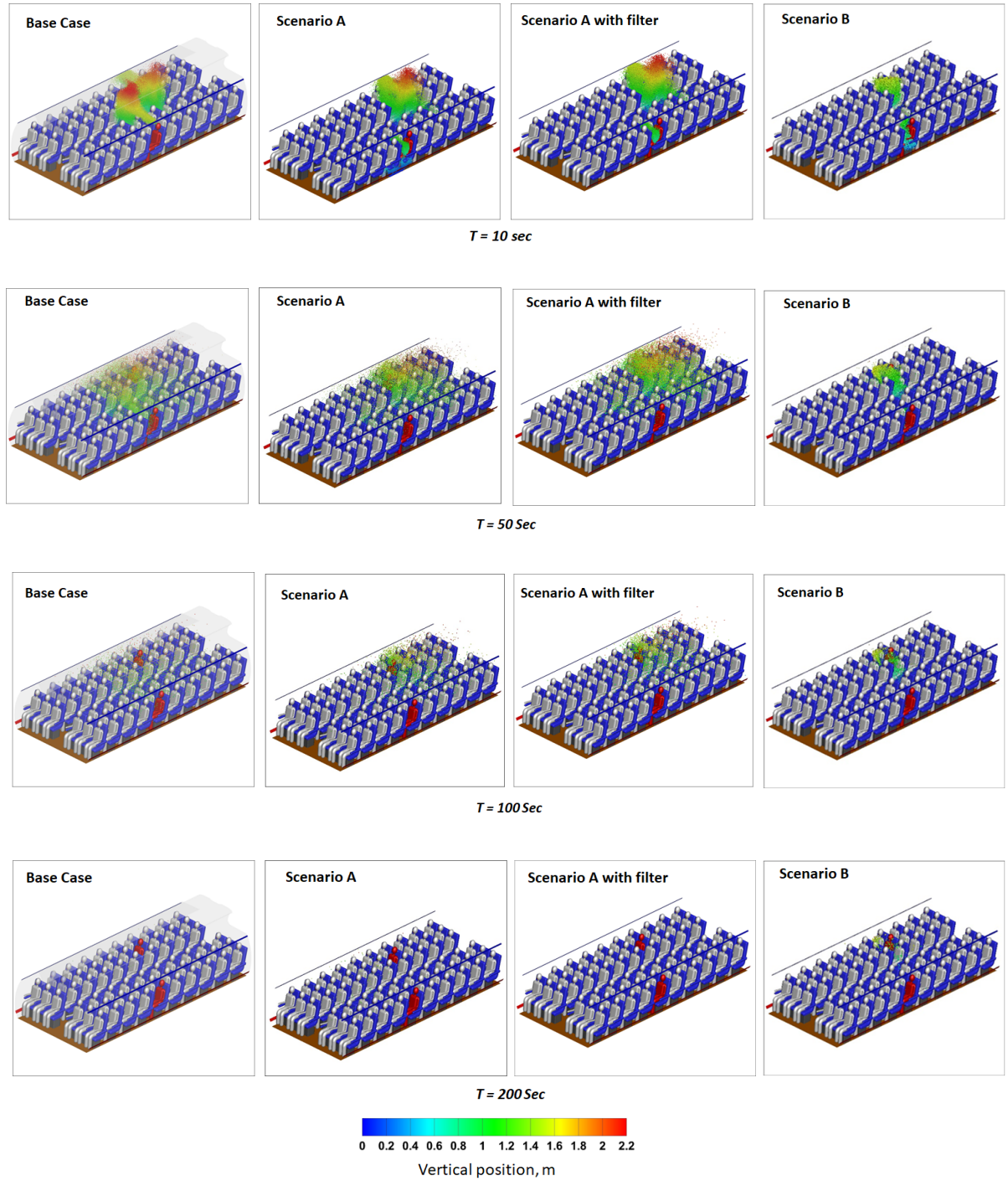

Figure 1. Distribution of 1 μm particles with time after being exhaled from the two infected passengers in the coach section of Boeing 737-800 operating at full capacity.

Since complete cabin air change occurs every 2-3 minutes, most of the particles are either already deposited or inhaled by that point in time, and, surprisingly, only about 15 % of the

particles exited the cabin. The most important observation from Figure 1 is that particles do not disperse through the entire cabin at any point in time. Particles remain within a few rows of the two infected passengers. This suggests that infected passengers do not contaminate the entire cabin but do affect multiple passengers near them. Also, more passengers are affected by the middle seat infected passenger (seat 7C) compared to the infected passenger in a window seat (seat 5F). Analysis of the inhalable fraction of the simulated aerosol particles for all simulated scenarios shows that the highest inhalable fraction (0.26 %) was identified for the ***Base Case***. The inhalable fractions for ***Scenario A, Scenario A with filter*** and ***Scenario B*** were 0.09%, 0.07% and 0.01%, respectively, all significantly lower than the 0.26% of ***Base Case***. In ***Scenario A*** and ***Scenario A with filter***, where exhaled air was re-directed towards the cabin floor, i.e., below passengers' knees, the inhalable fraction was reduced by 65% and 73% respectively compared to the ***Base Case***. In ***Scenario B***, where captured air is ducted completely out of the cabin after capture by Air-Clenz™, the inhalable fraction is reduced by 96%.

Integration of the Air-Clenz™ technology, capturing exhaled air before it spreads through the cabin, is indeed an efficient method of reducing the risks of airborne-transmitted infections. Depending on the contagiousness of the specific airborne infection and the duration of the flight, even relatively low values for the inhalable fractions have been found to be infective for the passengers who inhale them. It is worth mentioning here that these inhalable fraction quantities are useful for relative comparison of the four scenarios and not for inhalation dosimetry. The distribution of the inhalable particles over the susceptible passengers in the coach zone for all four simulated scenarios is given in Figure 2.

Fellow passengers inhaling the aerosol particles exhaled by the two infected passengers (red-colored persons in Figure 2) are marked with red numbers; these numbers indicate the particular inhaled fractions by those passengers. A total of up to nine newly infected passengers in the ***Base Case*** inhale fractions of the aerosols released by the previously infected passengers. The novel Air-Clenz™ technology reduces this number to at most only five newly infected passengers in ***Scenario A*** and maximum of three newly infected passengers in ***Scenario A with filter*** due to the efficient filtration of 99.99% of the particles of the air fraction that passes through the back of the seat. In ***Scenario B***, where the cabin seats are equipped with the technology in the back of the seats that captures the exhaled air from each passenger while also removing 100% of the cabin air through the seats into conduits and out of the cabin, the maximum number of passengers who would inhale infectious particles exhaled from the two infected individuals is just one single person total. In addition to the pronounced effect of the minimum infective dose for each infection, flight duration also impacted the final number of newly infected passengers: the longer the flight, the more new infections occur. The results for the total number of infected passengers, in addition to the two initially infected passengers, are given in Tables 3, 4, and 5 for 1-hr, 2-hr and 6-hr-long flights, respectively.

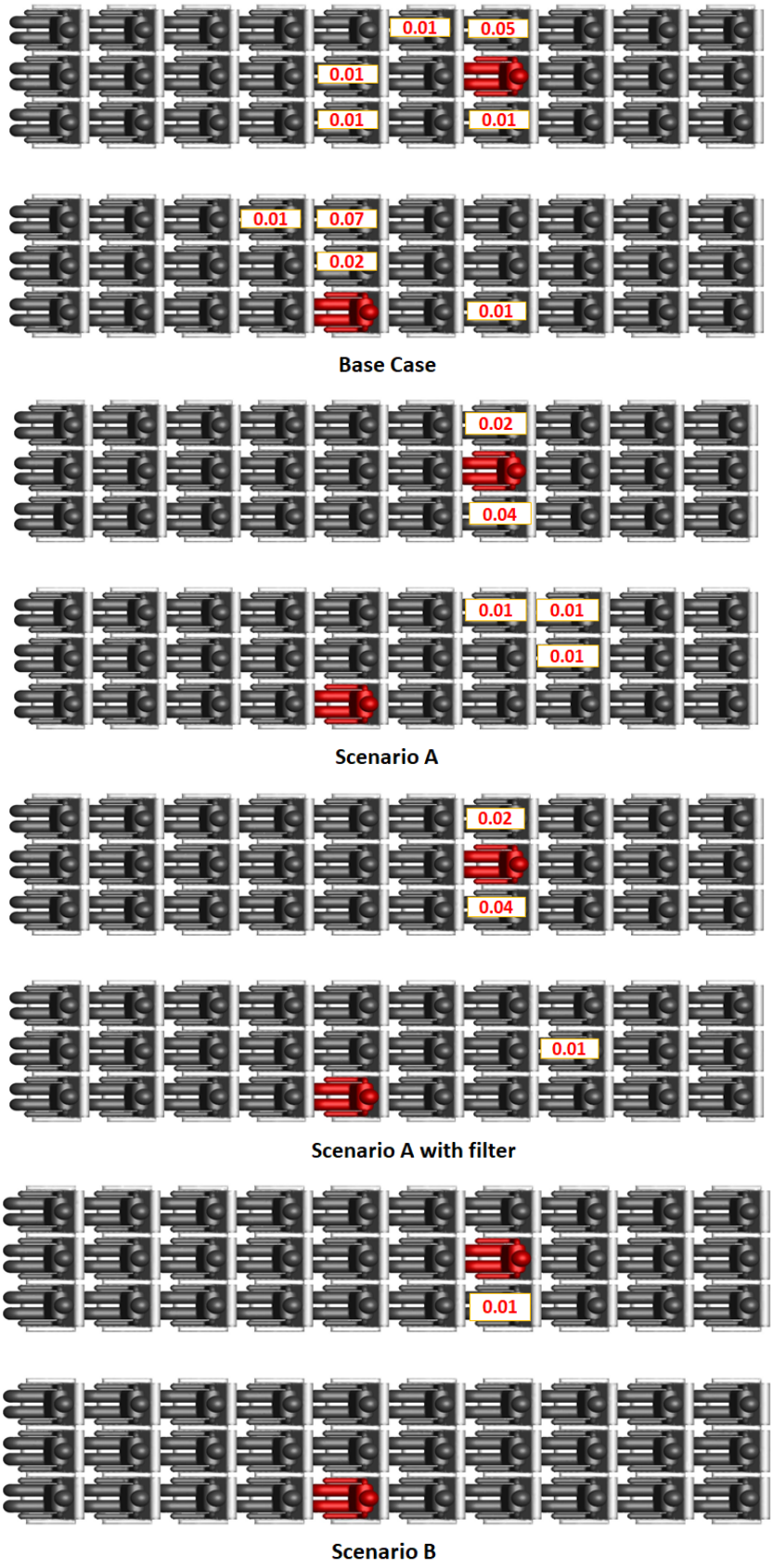

Figure 2. Distribution of potential passengers who are inhaling the aerosol particles released from the infected, red-colored passengers. Red numbers represent the inhaled fractions of the aerosols by susceptible fellow passengers.

Table 3. Numbers of newly infected passengers based on the simulation results assuming the average shedding rate from the two infected passengers in the coach section of a Boeing 737-800 during a **1-hr flight**.

Infection caused by:	Base Case	Scenario A	Scenario A with filter	Scenario B
SARS-Cov-2	2	1	1	0
I*nfluenza* H1N1	1	0	0	0
Rhinovirus RV15	2	1	1	0
Norovirus	9	5	3	1
Adenovirus type 4	9	5	3	1
M. tuberculosis	9	5	3	1
Bordetella pertussis	9	5	3	1
Bacillus anthracis	9	5	3	1
M. pneumoniae	0	0	0	0

Table 4. Numbers of newly infected passengers with airborne infections based on the simulation results assuming the average shedding rate from the two infected passengers in the coach section of a Boeing 737-800 during a **2-hr flight**.

Infection caused by:	Base Case	Scenario A	Scenario A with filter	Scenario B
SARS-Cov-2	3	2	2	0
I*nfluenza* H1N1	2	1	1	0
Rhinovirus RV15	3	2	2	0
Norovirus	9	5	3	1
Adenovirus type 4	9	5	3	1
M. tuberculosis	9	5	3	1
Bordetella pertussis	9	5	3	1
Bacillus anthracis	9	5	3	1
M. pneumoniae	2	1	1	0

Table 5. Numbers of newly infected passengers with airborne infections based on the simulation results assuming the average shedding rate from the two infected passengers in the coach section of a Boeing 737-800 during a **6-hr flight**.

Infection caused by:	Base Case	Scenario A	Scenario A with filter	Scenario B
SARS-Cov-2	9	5	3	1
I*nfluenza* H1N1	9	5	3	1
Rhinovirus RV15	9	5	3	1
Norovirus	9	5	3	1
Adenovirus type 4	9	5	3	1
M. tuberculosis	9	5	3	1
Bordetella pertussis	9	5	3	1
Bacillus anthracis	9	5	3	1
M. pneumoniae	3	2	1	0

From Tables 3-5, it is clear that the Air-Clenz™ technology incorporated in the back of the cabin seats in ***Scenario A***, where it collects the exhaled air from each passenger, re-directs it towards the ground, and then air leaves the cabin though existing return vents on the lower cabin walls, helps to reduce the number of newly infected passengers by 33% -100% depending on: 1) flight duration and 2) infectiousness of the disease compared to the number of newly infected

passengers in the ***Base Case***. ***Scenario A with filter*** further reduces the number of newly infected passengers by 50% - 100%, again depending on: 1) flight duration and 2) infectiousness of the disease compared to the ***Base Case*** due to the efficient filtration of all particles that are passing through the back of the seat. Installing Air-Clenz™ technology in ***Scenario B***, where 100% of both cabin air and exhaled air from each passenger is collected in the back of the seat in front of the passenger and then removed from the cabin via conduits to cabin HVAC outlets, results in an even more significant reduction in the number of newly infected passengers (down 89 % or more) compared to those infected in the ***Base Case***. Regardless of the contagiousness of the infection and the flight duration, the number of newly infected passengers in ***Scenario B*** is 0 or 1. Thus ***Scenario B*** should be considered a solution that yields none or one passenger infected with a airborne transmitted disease in-flight. Although technically possible, ***Scenario B*** is the most difficult scenario to install in existing aircrafts. Therefore, ***Scenario A with filter*** is the easiest scenario in existing aircrafts, always yielding newly infected passengers rates at least 50% lower than ***Base Case***.

4 CONCLUSIONS

The present work shows promising ways to reduce airborne disease transmission in an aircraft cabin. A 60-passenger coach section of a Boeing 737-800 operating at full capacity with no mask wearing by the passengers (among which two already infected passengers boarded and were seated), was simulated and presented here as the ***Base Case***. The ***Base Case*** utilized the current state of the art 737-800 aircraft ventilation and HEPA filtering system. Three additional scenarios, ***Scenario A, Scenario A with filter,*** and ***Scenario B*** were simulated for the same coach section, air systems, lack of mask wearing, and locations of the two infected passengers. The only variable was the novel Air-Clenz™ technology. All scenarios: ***Scenario A, Scenario A with filter*** and ***Scenario B*** effectively reduced the number of newly infected passengers compared to the ***Base Case***. Specifically, ***Scenario A*** reduced the number of newly infected passengers by 33% -50%, while ***Scenario A with filter*** reduced the number 50%-100%. ***Scenario B*** reduced this number by more than 89 % for a maximum of one newly infected passenger for the highly infectious diseases during longer flights. While ***Scenario B*** gives yields the lowest number of newly infected passengers, it seems that this scenario is the hardest one to be implemented in a n existing aircraft. Therefore, ***Scenario A with filter*** is an ideal balance of easy installation and best protection provided against cross-infections. The novel, patent-protected Air-Clenz™ technology discussed in this paper significantly reduced the in-flight spread of infectious airborne diseases such as COVID-19, influenza, the common cold, etc. The results of this comprehensive study strongly indicate that the novel Air-Clenz™ technology could be a viable solution for the pressing challenge of significantly reducing in-flight airborne transmitted infections that occur for many non- mask wearing air travelers, flight attendants, and crew.

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