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Viral Fate and Transport for COVID-19

National Virtual Biotechnology Laboratory

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Executive Summary

The NVBL Viral Fate and Transport Team includes researchers from eleven DOE national laboratories and is utilizing unique experimental facilities combined with physics-based and data-driven modeling and simulation to study the transmission, transport, and fate of SARS-CoV-2. The team was focused on understanding and ultimately predicting SARS-CoV-2 viability in varied environments with the goal of rapidly informing strategies that guide the nation's resumption of normal activities. The primary goals of this project include prioritizing administrative and engineering controls that reduce the risk of SARS-CoV-2 transmission within an enclosed environment; identifying the chemical and physical properties that influence binding of SARS-CoV-2 to common surfaces; and understanding the contribution of environmental reservoirs and conditions on transmission and resurgence of SARS-CoV-2.

- *Drivers of Airborne Transport and Fate Impacting SARS-CoV-2 Transmission in Enclose Environments:* The Viral Fate and Transport Team leveraged highly instrumented and configurable facilities and computational capabilities resident in the DOE national laboratories to provide robust and quantitative information about how behavioral, environmental, and operational conditions affect the risk of airborne transmission of COVID-19.
- *The Role of Surface Chemistry and Material Science for Viral Transmission and Spreading*: The Viral Fate and Transport team has designed new antiviral materials with a low potential toxicity to humans as well as those with high binding potential that could be used to trap virus particles. Direct imaging of virus-surface interactions was conducted using a range of imaging techniques available at DOE's scientific user facilities.
- *Transport and Emergence of SARS-CoV-2 from Environmental Reservoirs that Contributes to Human Transmission of COVID-19:* The Viral Fate and Transport Team analyzed existing data sets to produce validated models for the fate and transport of SARS-CoV-2 in wastewater and groundwater. Scenarios of particular interest are seepage of sewer water or septic tanks into groundwater and associated transport through the subsurface and potential exposure routes and risks to the population. Fate and infectivity of SARS-CoV-2 associated with genomic change was also analyzed by comparing sequences from wastewater and groundwater sites.

Introduction

The NVBL Viral Fate and Transport Team included researchers from eleven DOE national laboratories and utilized unique experimental facilities combined with physics-based and data-driven modeling and simulation to study the transmission, transport, and fate of SARS-CoV-2. The resulting information provided key insights required to understand factors involved in emergence, circulation and resurgence of pathogenic microbes and support the response to the COVID-19 pandemic. SARS-CoV-2 was originally thought to be passed principally between humans through inhalation of expelled droplets and aerosolized particles, although the potential for transmission through contact with contaminated surfaces, circulating air, and wastewater were poorly described. Data suggested aerosolized SARS-CoV-2 could persist in enclosed environments (especially in poorly ventilated environments) for several hours and that the virus could persist on some surfaces for days. A lack of understanding of the transport and fate of the virus and associated particles in the environment, including air, water, and surfaces, forced regulators to rely on data from different viral outbreaks and limited their ability to devise strategies to reduce the uptake of the virus and prevent infection considering unique properties of SARS-CoV-2. Controlling spread within our community and workplaces required an understanding of factors regulating COVID-19 viability, transmission, and transport as well as the prevalence of infectious virus in the environment. Research activities were designed to predict SARS-CoV-2 prevalence in varied environments and enable economic recovery through the generation of data-driven guidelines for optimized safe reopening of businesses, schools, restaurants and recreation.

The accomplishments are summarized in Task sections below, including manuscripts that have been published, currently in review, or in preparation for future submission.

Task 1: Improving Understanding of Drivers of Airborne Transport and Fate Impacting SARS-CoV-2 Transmission in the Built Environment

Task 2: Understanding the Role of Surface Chemistry and Material Science in Viral Transmission and Spreading

Task 3: Transport and Emergence of SARS-CoV-2 from Environmental Reservoirs that Contributes to Human Transmission of COVID-19

Task 1: Improving Understanding of Drivers of Airborne Transport and Fate Impacting SARS-CoV-2 Transmission in the Built Environment

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Task 1: Improving Understanding of Drivers of Airborne Transport and Fate Impacting SARS-CoV-2 Transmission in the Built Environment

INTRODUCTION

Pandemic management requires an understanding of how the virus responds to different environmental conditions, stressors and dynamics, and how that translates into risk to exposed populations and mitigation strategies. It is thought that the vast majority of SARS-CoV-2 transmission occurs within the built environment, where people commonly come into close contact, exchange air with each other, and touch the same surfaces. A range of environmental factors control the dispersion and transport of the aerosols that contain the virus particles. Wearing of face masks and physical distancing reduce virus transfer rates by interception of expelled respiratory fluid expulsion, reduction of exhalation momentum and deposition; but a substantial fraction of the aerosol expelled from coughing, talking and exhalation can travel tens of meters at common indoor air speeds and smaller aerosol droplets remain airborne for up to hours, until they are removed by ventilation or filtration. A study by four leading infectious disease laboratories found that SARS-CoV-2 retained infectiousness in simulated respiratory aerosols over 16 h for common indoor environmental conditions. Early in the pandemic, over 200 of the world's leading bioaerosol and indoor air quality scientists urged public health agencies to acknowledge this important transmission route and provide guidance on risk reduction, noting that "current measures do not adequately protect the population from the small virus-carrying particles exhaled by infected people, and inhaled by others who share the same not-well-ventilated environments."

Through this research, the National Lab consortium set out to fill critical gaps in our understanding of processes and systems within the built environment that impact the risk of airborne disease transmission, informing risk-based assessments of controls for classrooms, transit vehicles, and other shared, enclosed spaces of priority for a return to new normal operations. Investigation of environmental drivers that impact emissions, dispersion, transport, fate, and human exposure to virus-containing droplets and particles at varied scales in controlled environments and conditions extensible to atmospheric conditions, will inform prioritization of administrative and engineering controls (e.g., physical distancing, face masks, occupant density in buildings and transit compartments, ventilation, and filtration) for individual and group exposure reduction.

Reducing the risk of exposure based on solid scientific findings remains important as many areas of the U.S. and the world look to resume educational and commercial activities while protecting the most vulnerable members of society and reducing disease spread.

OBJECTIVES

This research consortium prioritized the study of environments with high-risk exposure populations, hard-to-reduce occupancy, and operations that enable resumption of high priority economic and educational activities. It leveraged national laboratory expertise in numerical physics-based modeling and unique experimental facilities, and it set out to develop a common framework for evaluating the transport and fate of airborne particles.

Near-field (Direct) viral transport within enclosed spaces

This research intended to provide information related to the effectiveness of measures to reduce direct transfer of virus between occupants in enclosed structures, including distancing, face coverings, barriers between individuals, and air distribution management. The proposed approach included physical experiments and physics-based modeling (e.g., computational fluid dynamics (CFD) and network-zonal models) to simulate droplet and aerosol emissions and airborne transport, to determine spatially and temporally resolved concentrations and fate of virus-containing droplets/aerosols within occupied enclosed spaces, including deposition to surfaces, removal by ventilation or filtration, and reductions achieved from interventions.

Transmission between occupants throughout a building and other structures

The research intended to establish quantitative estimates of relative benefits of measures that can be taken to reduce average concentration of virus-containing particles in individual rooms, enclosed transit spaces (e.g. buses) and connected spaces up to the building scale. Additionally, the study proposed to provide information on the most effective risk reduction measures, including the following: occupancy limits, outdoor air ventilation rates, airflow management between spaces, and filtration. This was to include simulation of aerosol transport within and between rooms and in HVAC, building ventilation systems, filtration, deposition and other loss rates, occupant density, potential number of infected persons, and emission characteristics (aerosol size distribution, droplet concentrations and distribution of virus by droplet size).

PROPOSED OUTCOMES

1. Physical experiments of dispersion and fate of expelled respiratory fluid during breathing, talking, coughing in the near-field and in buildings
2. Numerical experiments using computational fluid dynamics and whole-building models to describe aerosol dispersion and fate, and exposure assessment in a room or other shared environments
3. Effectiveness and relative risk reduction for physical barriers, including masks and partitions, and for interventions to building ventilation, filtration, and occupancy

RESULTS: Topic 1

Transmission within Classrooms and Meeting Rooms and throughout Buildings

- Large Eddy Simulation of Isothermal and Non-isothermal Turbulent Flows in Ventilated Classrooms (ANL1)
- Measured Influence of Overhead HVAC on Exposure to Airborne Contaminants from Simulated Speaking in a Meeting and a Classroom (LBL1)
- Investigation of Potential Aerosol Transmission and Infectivity of SARS-CoV-2 through Central Ventilation Systems (PNNL1)
- Experimental Evaluation of Respiratory Droplet Spread to Rooms Connected by a Central Ventilation System (PNNL2)
- Size Dependent Infectivity of SARS-CoV-2 via Respiratory Droplets Spread through Central Ventilation Systems (PNNL3)
- Characterization of the Indoor Near-Field and Far-Field Aerosol Transmission an a Model Commercial Office Building (ORNL1)

Large Eddy Simulation of Isothermal and Non-isothermal Turbulent Flows in Ventilated Classrooms

This research has been accepted for presentation at 13th International ERCOFTAC symposium on engineering, turbulence, modelling and measurements:

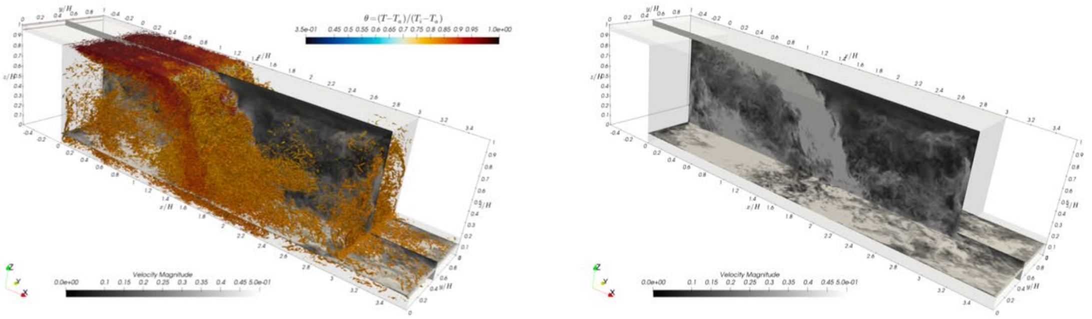
Citation: Balakrishnan, Ramesh; Kotamarthi, Rao; Fischer, Paul, Large Eddy Simulation of Isothermal and Non-isothermal Turbulent Flows in Ventilated Classrooms, ETMM13, September 15 – 17, 2021, Rhodes, Greece, Accepted for virtual presentation.

Practical Implications

- The ventilation pathways that are commonly seen in school classrooms, which are often of the kind where cool/hot air flows into the room from an inlet high up on a wall, creates a thermal stratification layer (in winter) that inhibits mixing of air.
- Thermal stratification exacerbates the formation of dead-zones where aerosols get trapped and cannot be expelled from the rooms merely by increasing the air changes per hour (ACH).
- It is shown that mixing of air can be improved, less expensively, by re-designing the ventilation pathway (as opposed to the expensive solution of increasing ACH by increasing the ventilation flow rate). The use of isolated fans in the dead-zone regions can improve mixing too.
- From a simulation standpoint, the study demonstrates that it is possible to use large-eddy simulation (LES) as an effective design tool to explore a wider parameter space, on CPU+GPU computing platforms, to improve classroom ventilation in existing buildings, and to design new classrooms.

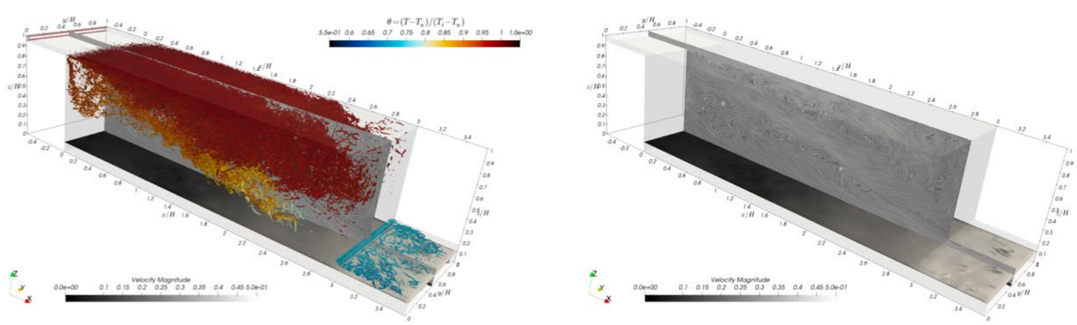
Summary

Over the last year, there has been renewed interest in simulating flows-particle interactions in enclosed spaces, in order to assess the length of time for which aerosol particles continue to remain in a ventilated room, and to estimate the deposition of aerosol particles in the neighborhood of people in a room. Due to the computational cost of doing resolved simulations of the flow-field, which is inherently unsteady by nature, the vast majority of these have been steady state simulations with Reynolds Averaged Navier-Stokes models, such as the $k - \varepsilon$ model (with known limitations for predicting separated and recirculating flows), and large eddy simulations on coarse meshes, and with very diffusive sub-grid scale models. The goal of this research at ANL, therefore, was twofold: (i) to advance our understanding of turbulent flows in enclosed rooms, via well-resolved large eddy simulations of the isothermal and non-isothermal flows at realistic ventilation rates, and (ii) to demonstrate the use of LES as a viable tool for designing indoor ventilation systems, on heterogeneous computing (i.e., CPU+GPU) platforms. We considered isothermal and non-isothermal flows in a classroom setting, with different placements of ventilation outlets and different layouts of student units within the classroom. The simulation results indicate that the locations and extents of dead-zones, or regions with very low velocity and turbulent kinetic energy can be altered, quite significantly, with changes in the ventilation pattern, as well with changes in the temperature of the ventilation jet, and which could, in turn, become highly infectious zones if aerosol particles with significant virion density tend to accumulate, preferentially, in these regions. These results are illustrated below.



(a) (b)

Figure Caption. Non-isothermal results with the inlet temperature 5 degrees Celsius cooler than ambient. (a) $\boldsymbol{\lambda}_2$ isosurface colored by the non-dimensional temperature (θ). (b) Instantaneous velocity indicates the extent of the dead-zones in the room.



(a) (b)

Figure Caption. Non-isothermal results with the inlet temperature 5 degrees Celsius warmer than ambient. (a) $\boldsymbol{\lambda}_2$ isosurface colored by the non-dimensional temperature (θ). (b) Instantaneous velocity indicates the extent of the dead-zones in the room.

Measured Influence of Overhead HVAC on Exposure to Airborne Contaminants from Simulated Speaking in a Meeting and a Classroom

This research has been peer-reviewed and accepted for publication:

Singer, BC; Zhao, H; Preble, CV; Delp, WW; Pantelic, J; Sohn, MD; Kirchstetter, TK (2021) Measured Influence of Overhead HVAC on Exposure to Airborne Contaminants from Simulated Speaking in a Meeting and a Classroom, *Indoor Air,* Accepted for publication.

Practical Implications

- Overhead HVAC systems, which are common in schools and office buildings, can create thermally stratified conditions during heating.
- Stratification interferes with dilution and reduces the effectiveness of ventilation to remove expelled respiratory aerosols that can carry infectious agents.
- Ceiling diffusers can achieve good mixing for effective dilution and ventilation of bioeffluents when supplying cooled or thermally neutral air.
- Fans, including portable air filters, can break up stratification and improve ventilation performance during the heating season.

Summary

Tracer gas experiments were conducted at Berkeley Lab's FLEXLAB facility in a 158 m^3 room with overhead supply diffusers to study dispersion of contaminants from simulated speaking in physically-distanced meeting and classroom configurations. The room was contained within a 237 m^3 cell with open plenum return to the HVAC system. Heated manikins at desks and a researcher operating the tracer release apparatus presented 8–9 thermal plumes. Experiments were conducted under conditions of no forced air and neutral, cooled, or heated air supplied at 980–1100 m^3h^{-1}, and with/out 20% outdoor air. CO_2 was released at the head of one manikin in each experiment to simulate small (<5 µm diameter) respiratory aerosols. The metric of Exposure Relative to perfectly-Mixed (ERM) is introduced to quantify impacts, based on measurements at manikin heads and at three heights in the center and corners of the room. Chilled or neutral supply air provided good mixing with ERMs close to one. Thermal stratification during heating produced higher ERMs at most manikins: 25% were ≥2.5 and the highest were >5× perfectly mixed conditions. Operation of two within-zone air cleaners together moving ≥400 m^3h^{-1} vertically in the room provided enough mixing to mitigate elevated exposure variations. These results are summarized in the figure below.

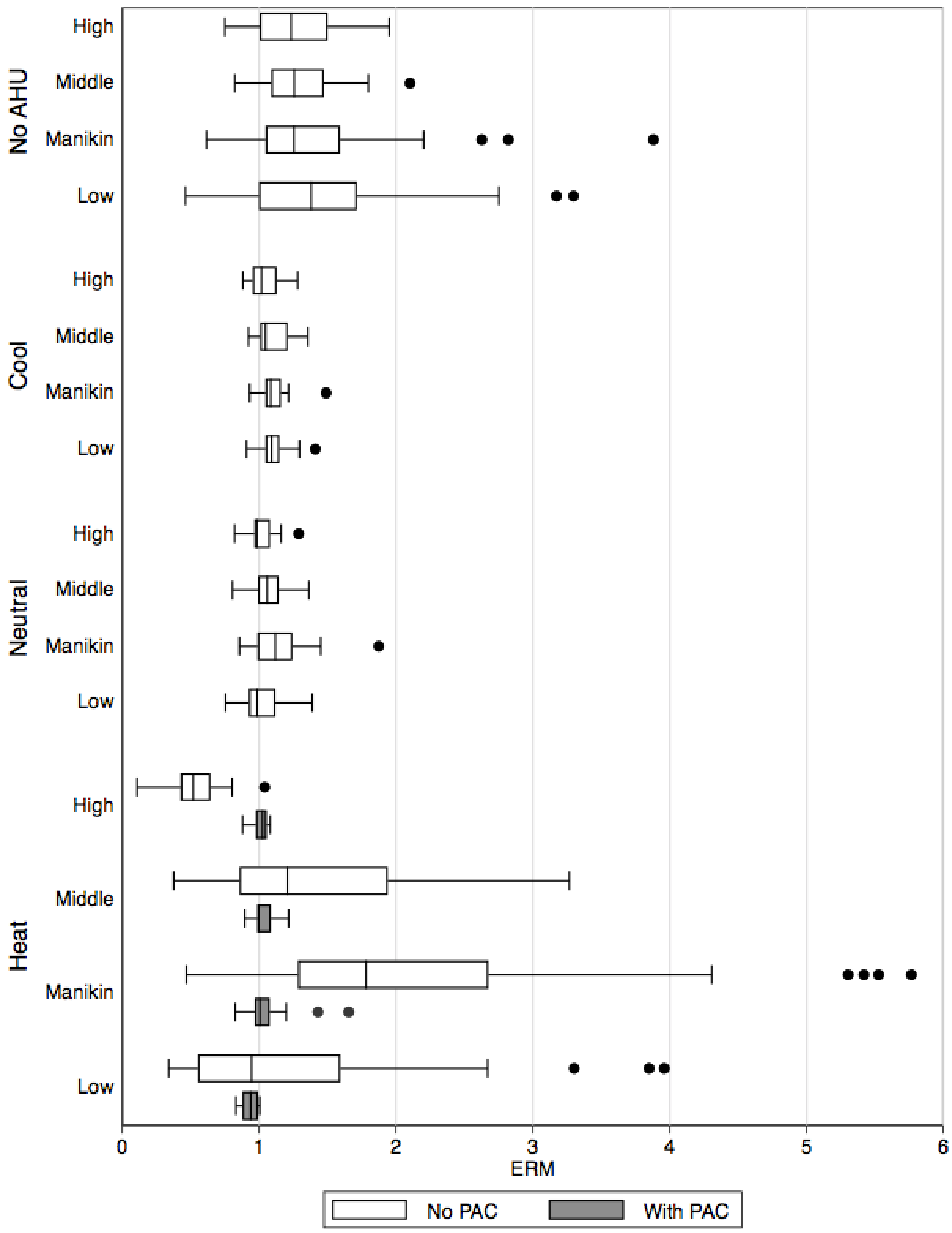


Figure Caption. Exposures Relative to perfectly Mixed (ERM) at each vertical level of the room under each HVAC condition in the meeting room experiments with no outdoor air. PAC refers to the operation of Portable Air Cleaners. Boxes show median and interquartile range (IQR) and whiskers extend to 1.5× IQR. Measurement heights: Low = 30 cm; manikins mostly seated at 105 cm, standing teacher at 121 cm; middle = 137 cm; High = 244 cm.

Investigation of Potential Aerosol Transmission and Infectivity of SARS-CoV-2 through Central Ventilation Systems

This research has been peer-reviewed and published:

Leonard F Pease, Na Wang, Timothy I Salsbury, Ronald M Underhill, Julia E Flaherty, Alex Vlachokostas, Gourihar Kulkarni, Daniel P James. Investigation of Potential Aerosol Transmission and Infectivity of SARS-CoV-2 Through Central Ventilation Systems, *Building and Environment* 197 (2021) 107633, DOI: 10.1016/j.buildenv.2021.107633.

Practical Implications

- Well-mixed multizone model evaluates COVID-19 infection probabilities under different system operating scenarios for internal and external exposure sources.
- This study shows for internal sources that: (i) More filtration lowers the probability of infection in connected spaces, (ii) Higher air change rates increase infection probabilities in connected rooms, and (iii) Increasing outdoor air decreases virus concentration.

Summary
The COVID-19 pandemic has raised concern of viral spread within buildings. Although the near-field transmission and the infectious spread within individual rooms are well studied, the impact of aerosolized spread of SARS-CoV-2 via air handling systems within buildings remains unexplored. This study at PNNL evaluates the concentrations and probabilities of infection for both building interior and exterior exposure sources using a well-mixed model of a multi-room building served by a central air handling system (without packaged terminal air conditioning). In particular, we compare the influence of filtration, air change rates, and the fraction of outdoor air. When the air supplied to the rooms comprises both outdoor air and recirculated air according to typical guidelines, we find filtration has the largest impact on lowering the concentration and probability of infection in both source and connected rooms. We find that increasing the air change rate removes virus from the source room faster but also increases the rate of exposure in connected rooms. Therefore, slower air change rates reduce infectivity in connected rooms at shorter durations. We further find that increasing the fraction of virus-free outdoor air is helpful unless outdoor air is infective, in which case pathogen exposure inside persists for hours after a short-term release. Increasing the outdoor air to 33% or the filter to MERV-13 decreases the infectivity in the connected rooms by 19% or 93% respectively, relative to a MERV-8 filter with 9% outdoor air based on 100 quanta/h of 5 µm droplets, a breathing rate of 0.48 m^3/h, and for the building dimensions and air handling system considered.

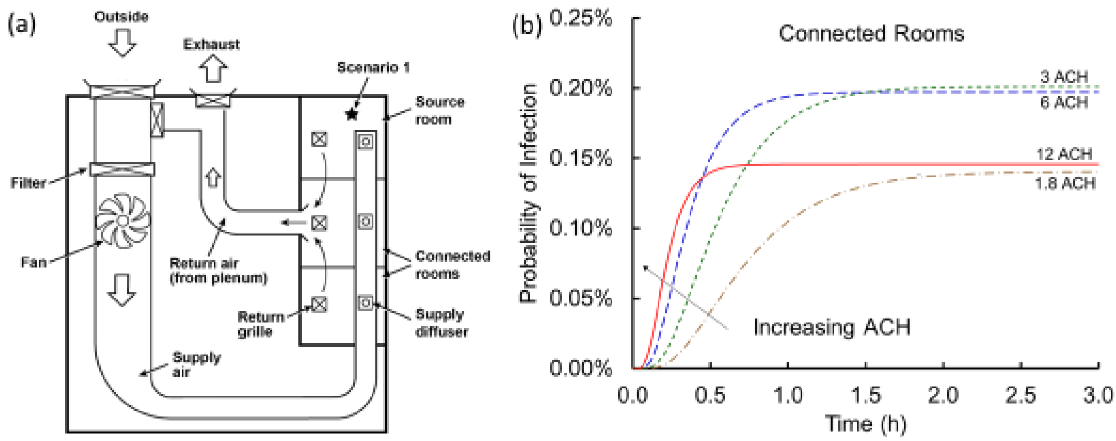


Figure Caption. (a) Essential elements of a central air handling system in a generic small building. The virus spreads to the connected rooms via a centrally connected plenum and air handling unit (AHU). (b) Cumulative probability of infection versus time for the connected rooms for air change rates of 1.8, 3, 6, and 12 air changes per hour (ACH).

Experimental Evaluation of Respiratory Droplet Spread to Rooms Connected by a Central Ventilation System

This work has been submitted for peer-review and publication:

Alex Vlachokostas, Carolyn A. Burns, Timothy I. Salsbury, Richard C. Daniel, Daniel P. James, Julia E. Flaherty, Na Wang, Ronald M. Underhill, Gourihar Kulkarni, Leonard F. Pease. Experimental Evaluation of Respiratory Droplet Spread to Rooms Connected by a Central Ventilation System. *Indoor Air* (2021) submitted.

Practical Implications

- This paper presents experimental results showing how transmissions of airborne viral particles that mimic SARS-CoV2 are affected by HVAC operations, including airflow rate, outdoor air fraction, and filtration.
- Experimental data has been used to validate the utility of simplified models such as those based on a well-mixed assumption
- Data from the physical experiments has provided evidence for researchers and practitioners to develop effective building operation strategies that not only assure a safer reopening after the COVID-19 pandemic but also protect building occupants from other airborne pathogens.

Summary

This study by PNNL presents results from an experimental study to ascertain the transmissibility of the SARS-CoV-2 virus between rooms in a building that are connected by a central ventilation system. Respiratory droplet surrogates made of mucus and virus mimics were released in one room in a test building and measurements of concentration levels were made in other rooms connected via the ventilation system. The paper presents experimental results for different ventilation system configurations, including ventilation rate, filtration level (up to MERV-13), and fractional outdoor air intake. The most important finding is that respiratory droplets can and do transit through central ventilation systems, suggesting a mechanism for viral transmission (and COVID-19 specifically) within the built environment in reasonable agreement with well-mixed models. We also find the deposition of these droplets on room walls to be negligibly small.

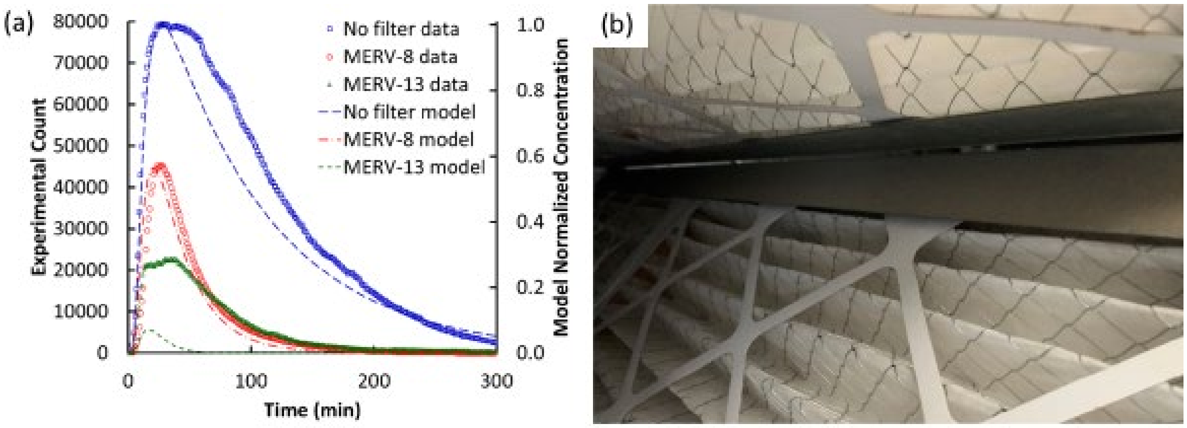


Figure Caption. (a) Optical particle counter differential particle counts averaged across two rooms connected to a source room via a central ventilation system versus time from respiratory droplet release for no filter, a MERV-8 filter, and a MERV-13 filter (see tests A, D, and E in Table 1) for size bins of 1-2 μm with corresponding model predictions. Secondary axis aligned to match the tallest peak magnitude. (b) Small gap (>1 mm) at the intersection of two filters arranged in a V configuration within a larger filter housing that permits respiratory droplets to bypass the filter.

Size Dependent Infectivity of SARS-CoV-2 via Respiratory Droplets Spread through Central Ventilation Systems

This research has been submitted for peer-review and publication:

Leonard F. Pease, Timothy I. Salsbury, Kevin Anderson, Ronald M. Underhill, Julia E. Flaherty, Alex Vlachokostas, Carolyn A. Burns, Na Wang, Gourihar Kulkarni, Daniel P. James. Size Dependent Infectivity of SARS-CoV-2 via Respiratory Droplets Spread through Central Ventilation Systems. *International Communications in Heat and Mass Transfer* (2021) submitted.

Practical Implications

- Bronchiole and larynx droplets readily transit central ventilation systems.
- Oral droplets rarely transit central ventilation systems.
- The probability of lower respiratory or deep lung infection will be higher than upper respiratory infections when viral particles are spread between rooms via a central air handling system.
- Raising humidity and temperature in air handlers reduces infectivity risk modestly.

Summary
PNNL evaluated the transport of respiratory droplets that carry SARS-CoV-2 through central air handling systems in multiroom buildings. Respiratory droplet size modes arise from the bronchioles representing the lungs and lower respiratory tract, the larynx representing the upper respiratory tract including vocal cords, or the oral cavity. The size distribution of each mode remains largely conserved, although the magnitude of each droplet mode changes as infected individuals breathe, speak, sing, laugh, cough, and sneeze. Here we evaluate how each type of respiratory droplet transits central ventilation systems and the implications thereof for infectivity of COVID-19. We find that while larger oral droplets can transmit through the air handling systems, their size and concentration are greatly reduced with but few oral droplets leaving the source room. In contrast, the smaller droplets that originate from the bronchioles and larynx are much more effective in transiting through the air handling system into connected rooms. This suggests that the ratio of lower respiratory or deep lung infections increases relative to upper respiratory infections in rooms connected by central air handling systems. Also, increasing the temperature and humidity in the range considered after the droplets have achieved an "equilibrium" size reduces the probability of infection.

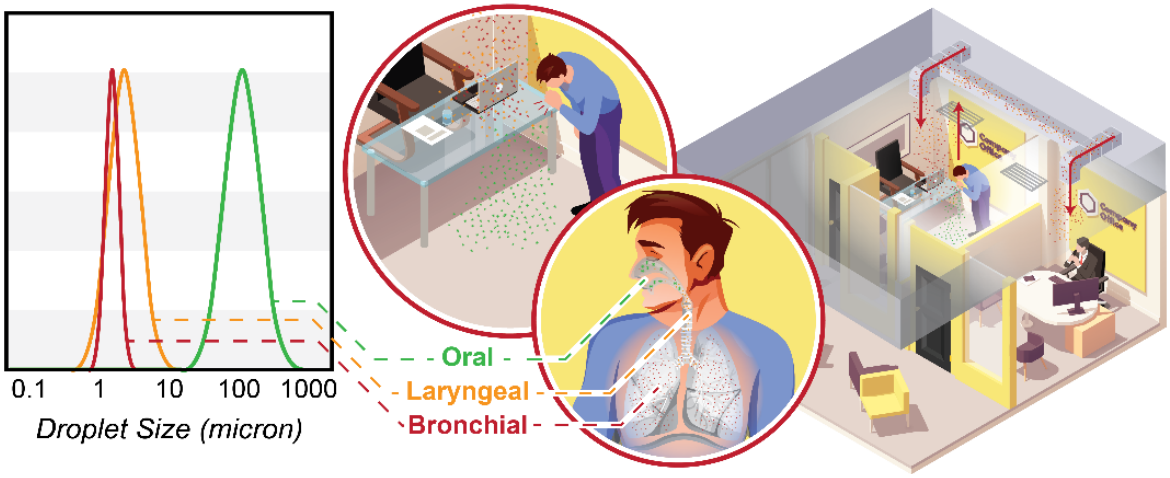


Figure Caption. The fate and transport of respiratory droplets through buildings with central ventilation systems depends on the droplet sizes. The larger droplets dominate the infectivity of the room in which they are released, but the small droplets transmit through the air handling systems to adjacent rooms.

Characterization of the Indoor Near-Field and Far-Field Aerosol Transmission an a Model Commercial Office Building

The work has been submitted for peer-review and publication:

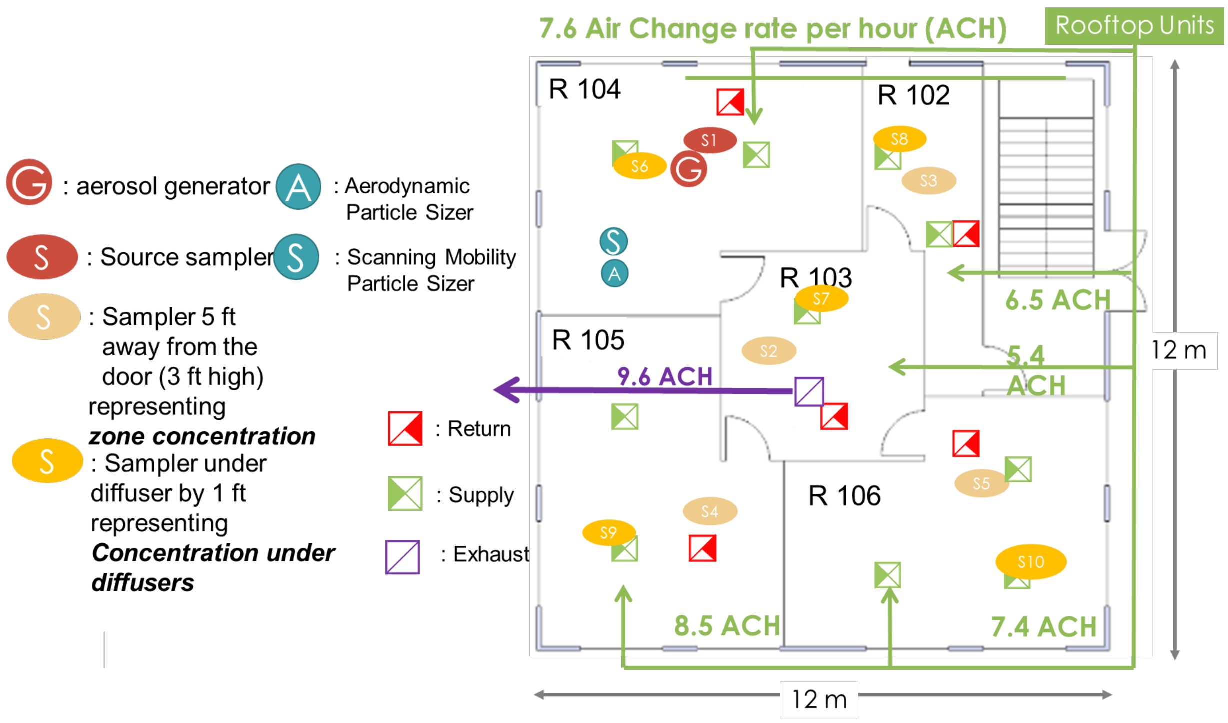
Chien, C.H.; Cheng, M.D.; Im, P; Nawaz, K; Fricke, B; Armstrong, A. Characterization of the indoor far-field aerosol transmission in a model commercial office building. *International Communications in Heat and Mass Transfer* (under review)

Practical Implications

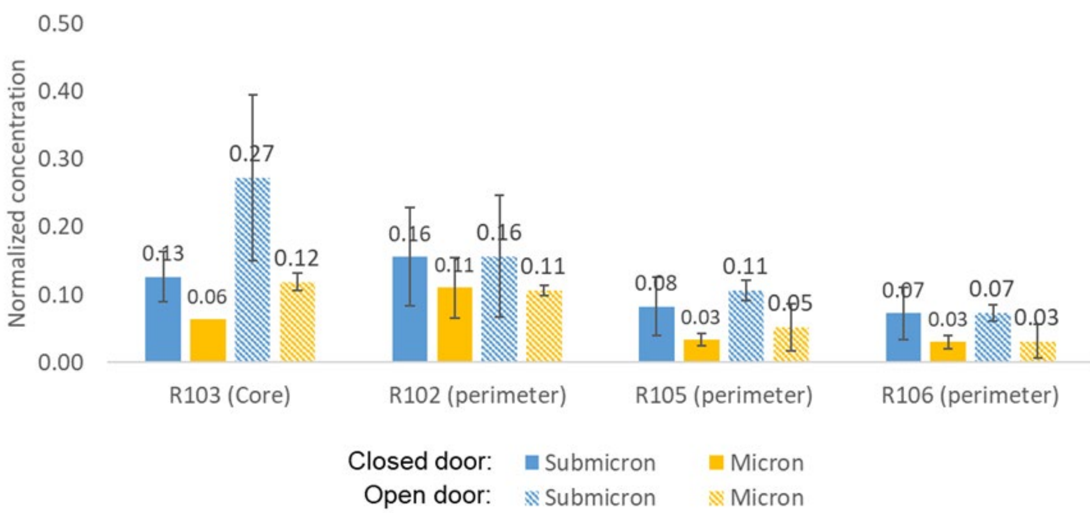
- In the near-field study, a well-mixed condition was established under the effect of heating, ventilation, and air conditioning (HVAC) in the test building with multiple zones at ORNL.
- Within the source zone in the test building, the analysis of aerosol concentrations shows the return air fraction dominates compared to other factors such as outside air ratio, filtration, transport loss in ventilation duct, and particle deposition.
- In the far-field study, the fraction of aerosol transmitted was < 16% and < 11% for submicron and micron aerosol, respectively, with doors closed.
- Opening the interior doors that connect different zones could significantly enhance the aerosol transmission for zones at the close proximity to the source but appeared to have less impact on those farther away.

Summary

Aerosol transmission under the effect of HVAC was studied in a multizone small office test building at the Oak Ridge National Laboratory. For the near-field campaigns, nine measurement points in a single zone using active aerosol impactors report that the coefficient of variation of the time-averaged concentration over one hour is < 10% in two campaigns and <15 % in one campaign indicating a nearly well-mixed condition. To understand the effect of the building HVAC system operation on the concentration of aerosols in office spaces, an aerosol transport model that includes factors such as outside air ratio, filtration, return air fraction, transport loss in duct, and particle deposition has been developed. The results of model fitting demonstrate excellent agreement with experimental data. Our investigation finds the return air fraction outweighs other mechanisms for the aerosol recirculation, and the air change rate (ACR) is more important than the small particle deposition for aerosol removal. Because ACR dominates the aerosol transport, the full model can be simplified to just one factor, the ACR, while maintaining acceptable representation of the experimental data. For the far-field study, data showed higher submicron-aerosol transmission than that for the larger ones. In campaigns with the doors closed, the submicron aerosol transmission was less than 16% and less than 11% for micron aerosol transmission. Opening the interior doors that connect different zones could significantly enhance the aerosol transmission for zones at the close proximity to the source but appeared to have less impact on those farther away. These results are summarized in the figure below.



(a)



(b)

Figure Caption. (a) Ventilation and sampler deployment in the far-field campaigns. (b) Comparison of cross-zone aerosol transmission: closed door vs. open door

RESULTS: Topic 2

Airborne Exposure Risk in Buses, Semi-Enclosed Dining Environments, and Outdoor Spaces

- Airborne Exposure Risk of Modelled Indoor and Outdoor Dining Environments Using a Rapid Response Model (LANL)
- Regional Relative Risk: a Physics-Based Metric for Characterizing Airborne Infectious Disease Transmission (LLNL2)
- Modeling and Mitigating Airborne Pathogen Risk Factors in School Buses (SNL1)
- High-Fidelity Large-Eddy Simulation Using a Directly Coupled Eulerian and Point-Lagrangian Tool: Coupling CFD with Dose-Response Modeling (SNL2)

Airborne Exposure Risk of Modelled Indoor and Outdoor Dining Environments Using a Rapid Response Model

Practical Implications

- Different outdoor dining configurations at restaurants can be assessed using the Quick Urban and Industrial Complex (QUIC) fast-running high-resolution 3-D wind and plume model to reduce the risk of airborne viral transmission.
- Airborne viral plume residence time within different courtyard areas depends on the area of the courtyard, the height of the surrounding walls, whether the walls are the same height or different heights, the wind speed and direction, and the location of the emitter within the courtyard.
- Partially enclosed dining areas should be designed to maximize air flow, taking into consideration different layouts, including wind breaks like interior dividers, shade canopies, and trees and bushes.
- For deeper outdoor courtyards, QUIC dispersal calculations suggest weaker ventilation, leading to airborne concentrations that are similar to those found in fast-food indoor restaurants.

Summary

At LANL, the QUIC chemical, biological, and radiological (CBR) Plume Modeling System was used to simulate droplet emissions from a single infected diner sitting in an outdoor courtyard dining environment. A tracer gas, solid particles, and evaporating droplets of different sizes were used to assess the residence time and peak concentrations reached inside of different size courtyards with walls of different heights. Model results showed that small courtyards with tall walls of the same height generally resulted in the largest residence time of gas, particles, and evaporating droplets. With wall height and wind conditions fixed, contaminants were flushed out more rapidly in larger area courtyards. Walls of different height generally acted to produce more ventilation in the courtyard, leading to lower airborne concentrations. As shown below, the exposure levels in a tall square outdoor courtyard were somewhere between levels found in a typical fast-food restaurant and in a typical full-service indoor restaurant, while those with shorter walls were within a factor of two or three of the levels in a full-service indoor restaurant. These modeling results suggest that some outdoor dining spaces are not well ventilated and could result in heightened risk of infection if masks are not worn.

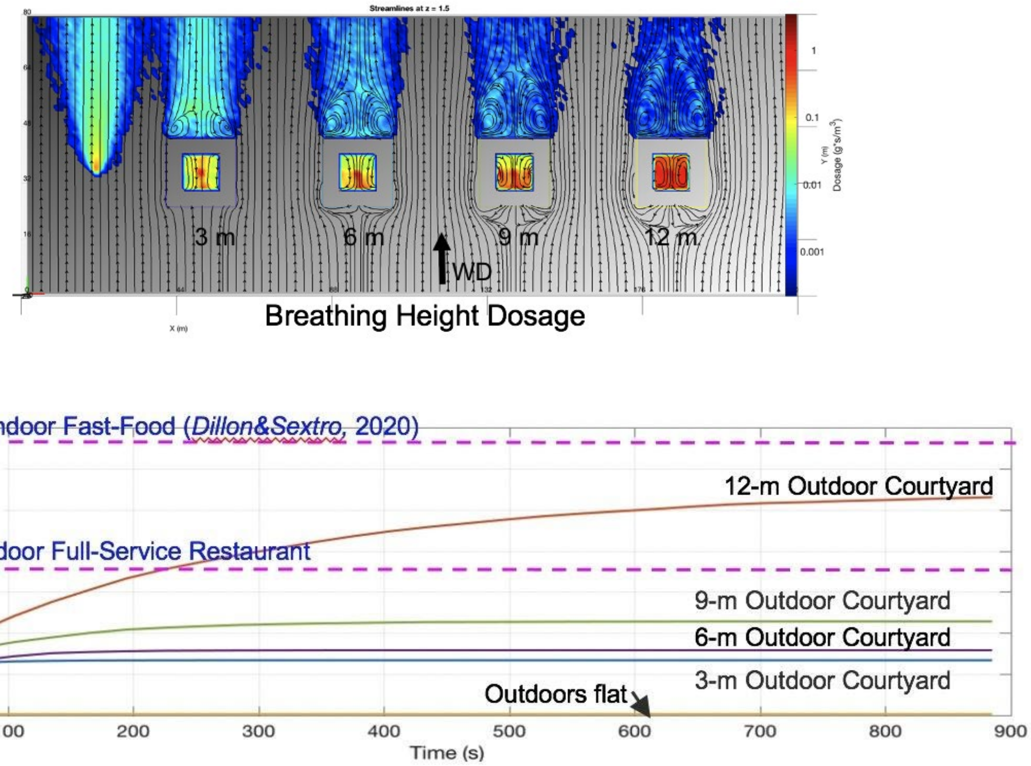


Figure Caption. (Top) Plan view of 3D courtyard plume simulation with an emitter at the center of the courtyard. The droplet emissions get transported and mixed out of the courtyard for shorter wall heights and trapped near the surface as the building height increases. Note that dosage (i.e., time-integrated concentration) levels are on a log scale. Streamlines show wind patterns and are denoted by black lines. (Bottom) For deeper courtyards, QUIC dispersal calculations suggest weaker ventilation, leading to time-integrated airborne concentrations that are similar to those found in fast-food indoor restaurants.

Regional Relative Risk: a Physics-Based Metric for Characterizing Airborne Infectious Disease Transmission

This research has been peer-reviewed and accepted for publication.

Charles F. Dillon and Michael B. Dillon, Regional Relative Risk, a Physics-Based Metric for Characterizing Airborne Infectious Disease Transmission, *Applied and Environmental Microbiology,* Accepted for publication

Practical Implications

- The Regional Relative Risk (RRR) is a new epidemiological metric that compares the risk between two geographic regions, which can range from individual rooms to large areas. Minimal information is required to use the RRR for distances ranging from 50 m to 20 km downwind.
- This work could enhance airborne disease outbreak assessment and management, as well as the control of chronically occurring airborne exposures.
- This work predicts a signature of single particle, airborne infection events.
- This work could inform future updates to remediation clearance and biosafety criteria, i.e., how clean is clean enough.
- This work demonstrates that even when infectivity is lost rapidly, 10 h^{-1}, infection probabilities are minimally impacted 100s of meters downwind.

Summary

Airborne infectious disease transmission events occur over a wide range of spatial scales and can be an important means of disease transmission. Physics- and biology- based models can assist in predicting airborne transmission events, overall disease incidence, and disease control strategy efficacy. LLNL developed a new theory that extends current approaches for the case in which an individual is infected by a single airborne particle, including the scenario in which numerous infectious particles are present in the air but only one causes infection, as shown below. A single infectious particle can contain more than one pathogenic microorganism and be physically larger than the pathogen itself. This approach allows robust relative risk estimates even when there is wide variation in (a) individual exposures and (b) the individual response to that exposure (the pathogen dose-response function can take any mathematical form and vary by individual). Based on this theory, we propose the Regional Relative Risk – a new metric, distinct from the traditional relative risk metric, that compares the risk between two regions (in theory, these regions can range from individual rooms to large geographic areas). In this paper, we apply the Regional Relative Risk metric to outdoor disease transmission events over spatial scales ranging from 50 m to 20 km demonstrating that in many common cases, minimal input information is required to use the metric. Also, we demonstrate that it is consistent with data from prior outbreaks. Future efforts could apply and validate this theory for other spatial scales, such as indoor environments. This work provides context for (a) the initial stages of an airborne disease outbreak and (b) larger scale disease spread, including unexpected low probability disease “sparks” that potentially affect remote populations, a key practical issue in controlling airborne disease outbreaks.

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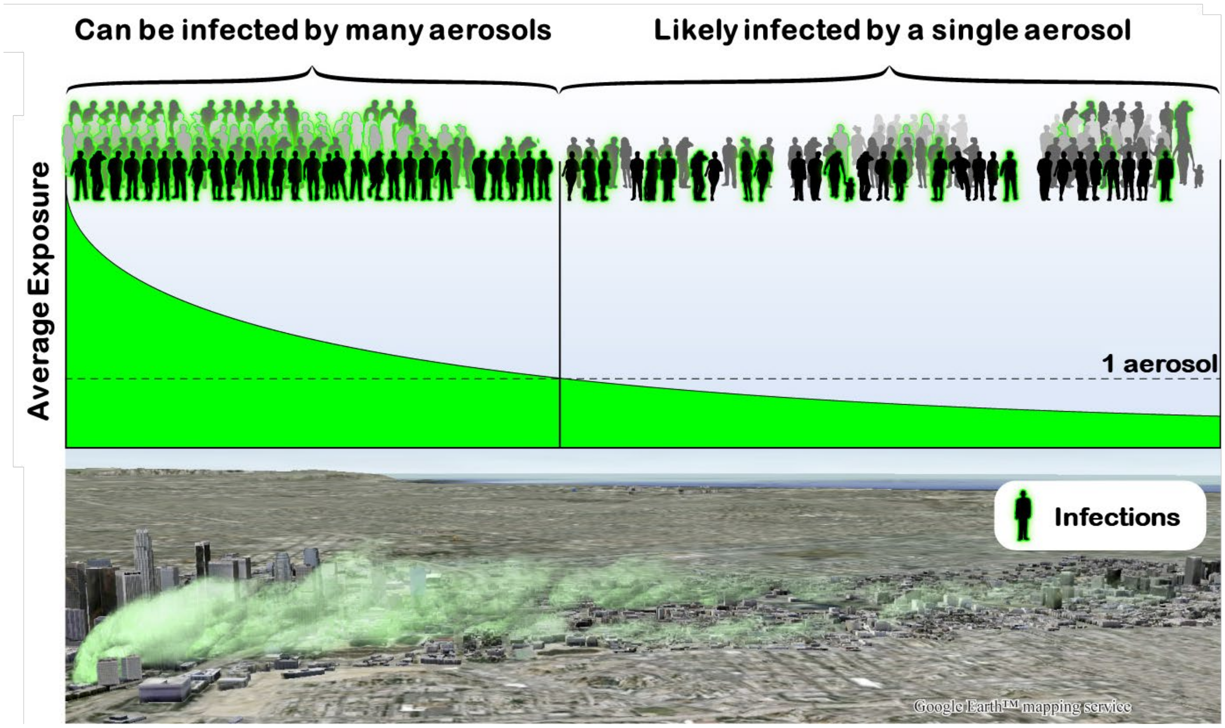

Figure Caption. Illustration of locations in which people can be infected by many (left) or a single (right) airborne particle. Single particle infections can occur far downwind. This illustration assumes that the inhalation of a single particle is sufficient to cause infection.

Modeling and Mitigating Airborne Pathogen Risk Factors in School Buses

This research has been submitted for peer-review and publication:

Ho, C.K. and R. Binns, 2021, Modeling and Mitigating Airborne Pathogen Risk Factors in School Buses, *Int. Comm. Heat Mass Transfer*, in review.

Practical Implications

- For stationary bus scenarios, including at least one set of openings when the heater is on is recommended to promote ventilation, dilution, and through-flow conditions.
- For moving bus scenarios, opening just the emergency hatch on top of the bus is not recommended. At least two sets of openings (e.g., hatch and back windows, front and back windows) are recommended to promote through-flow conditions, increase ventilation, and reduce exposure risks while maintaining thermal comfort. Opening every other window or all windows is recommended if environmental conditions allow it.
- In a moving bus with the front and back windows open, air tends to enter the bus toward the rear opening(s), move toward the front of the cabin, and leave the cabin through the front opening(s). Placing at-risk individuals near openings toward the rear of the vehicle may reduce the risks of exposure from "upstream" passengers.
- Recommendations from this study were implemented in new safety and operating procedures by the Albuquerque Public Schools Transportation Center.

Summary

SNL developed computational fluid dynamic models to simulate the impact of different ventilation scenarios on airborne exposure risks in a 72-passenger school bus resulting from an infected student exhaling aerosolized pathogens. Scenarios and factors that were investigated included a moving vs. stationary bus, impacts of a heating unit within the bus, and impacts of alternative ventilation scenarios with different combinations of openings (e.g., windows, door, emergency hatch). The models were compared against a limited set of tests that measured transient temperatures and air speeds when the heater was turned on to gain confidence in the methods and simulations. Results of the simulations showed that when the bus was stationary, use of the heater increased receptor pathogen concentrations unless there was another opening. When the bus was moving, simulations with at least two sets of openings separated from each other in the forward and aft directions produced a through-flow condition that reduced pathogen concentrations via dilution from outside air by a factor of ten or more. A single opening in a moving bus generally increased pathogen concentrations throughout the cabin due to increased mixing with minimal ventilation. The cumulative exposure risk (time-averaged concentrations) was found to be inversely correlated to the air exchange rate. Stationary and moving-bus scenarios that yielded above ~20 air changes per hour resulted in the lowest cumulative exposures (shown below). Recommendations from this study were implemented in new safety and operating procedures by the Albuquerque Public Schools Transportation Center, which consisted of opening the front windows, rear windows and hatches on buses while transporting students during the winter months. The heaters were on and the students wore extra layers to compensate for the additional cold air flow. During seasons with warmer temperatures, all windows were opened together with the roof hatch to create the necessary air flow and ventilation, and disinfection of the bus was maintained after each run.

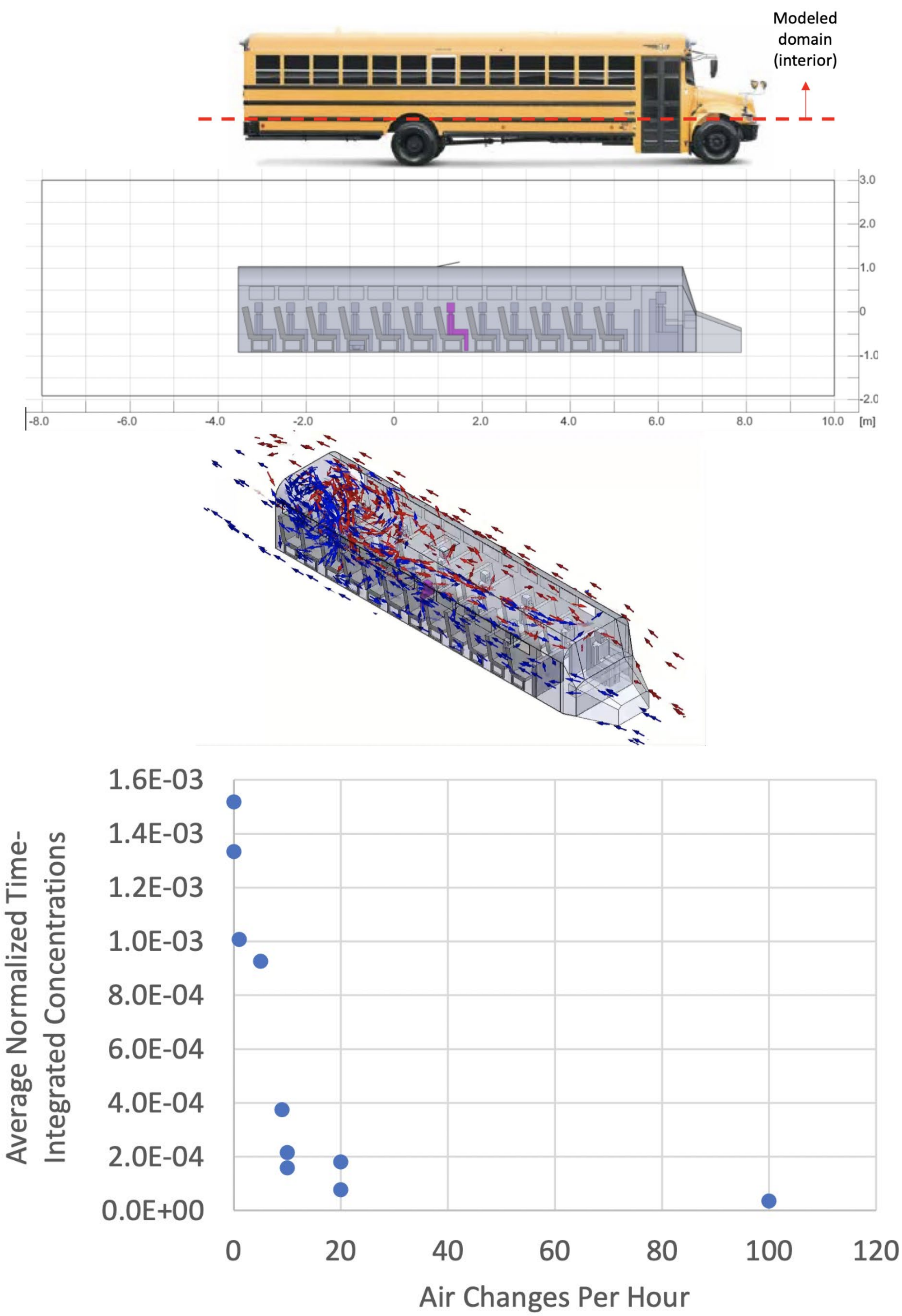

Figure Caption. (Top) CFD simulations of airflow and cumulative exposures in a school bus for different window openings and ventilation configurations. (Bottom) Plot of time-integrated concentrations after 30 min as a function of air changes per hour resulting from different ventilation scenarios within the school bus.

High-Fidelity Large-Eddy Simulation Using a Directly Coupled Eulerian and Point-Lagrangian Tool: Coupling CFD with Dose-Response Modeling

This work has been peer-reviewed and published:

Stefan P. Domino (2021) A Case Study on Pathogen Transport, Deposition, Evaporation and Transmission: Linking High-Fidelity Computational Fluid Dynamics Simulations to Probability of Infection, *International Journal of Computational Fluid Dynamics*,
DOI: [10.1080/10618562.2021.1905801](https://doi.org/10.1080/10618562.2021.1905801)

Practical Implications

- We deployed a high-fidelity, computational fluid dynamics approach that couples Eulerian/Lagrangian (fluids and particles) to simulate exposure risks in a common outdoor public configuration with and without environmental wind conditions.
- Close proximity to the coughing source, i.e. within 1 m, demonstrated the greatest risk for all configurations tested. Results indicate that with the added wind flow configurations, there exists a finite, non-zero risk even at distances in excess of 10 m from the cough source.
- Simulations for open-space social distance guidelines (10 foot diameter, 8 foot offsets) have been shown to be effective for reduction of primary droplet deposition, however, aerosols containing pathogens persists for long length- and time-scales in all configurations.

Summary

The SNL-developed high-fidelity, Sierra/Fuego low-Mach computational fluid dynamics simulation tool that includes evaporating droplets and variable-density turbulent flow coupling is well-suited to ascertain transmission probability and supports risk mitigation methods development for airborne infectious diseases such as COVID-19. A multi-physics large-eddy simulation-based paradigm is used to explore droplet and aerosol pathogen transport from a synthetic cough emanating from a kneeling humanoid. For an outdoor configuration that mimics the recent open-space social distance strategy of San Francisco, maximum primary droplet deposition distances are shown to approach 8.1 m in a moderate wind configuration with the aerosol plume transported in excess of 15 m. In quiescent conditions, the aerosol plume extends to approximately 4 m before the emanating pulsed jet becomes neutrally buoyant. A dose–response model, which is based on previous SARS coronavirus (SARS-CoV) data, is exercised on the high-fidelity aerosol transport database to establish relative risk at eighteen virtual receptor probe locations.

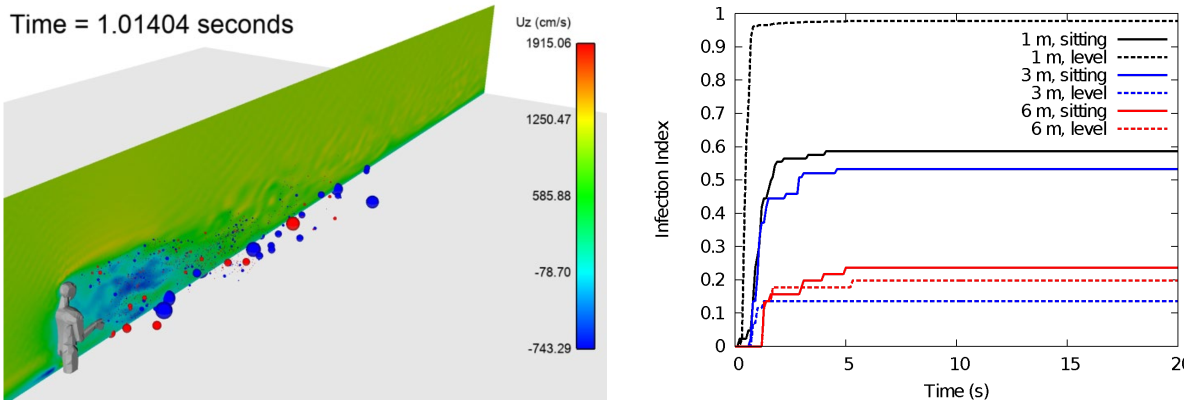

Figure Caption. (Left) Kneeling humanoid coughing simulation with a 10 m/s crossflow (from the back) illustrating the velocity shading recirculation zone (blue). Also included are the point-Lagrangian evaporating droplets that are found within the recirculation zone and deposited at long distances (roughly 8 meters) from the source. The droplet cloud consisting of roughly 5000 droplets evaporates to form a persisting aerosol that is transported out of the full domain (> 10 meters). Above, the red droplets represent those that include pathogen (roughly 30% of the droplets that emanate from the cough). (Right) Sample infection index for a set of virtual probes 1, 3, and 6 meters from the cough source; 10 m/s crosswind in the streamwise direction. The plot showcases that the highest risk is directly level with the emanating cough 1 meter from the cough source. The figure also captures the finding that sitting positions at large downwind locations have a higher infection index than at the level position - possibly due to crossflow and bluff body interactions effects along with boundary layer phenomena such as turbophoresis.

RESULTS: Topic 3

Numerical Simulation of Expiratory Event and Impact of Aerosol Physics and Environmental Conditions on Dispersion and Infectivity

- Quantifying the Effect of Size, Release Location and Evaporation on HVAC-Induced Respiratory Aerosol Dispersion using High-Resolution Large Eddy Simulations (ANL2)
- Direct Numerical Simulation of the Turbulent Flow Generated During a Violent Expiratory Event (ANL3)
- Direct Numerical Simulation of Turbulent Dispersion of Evaporative Aerosol Clouds Produced by an Intense Expiratory Event (ANL4)
- Simulating Near-field Enhancement in Transmission of Airborne Viruses with a Quadrature-Based Model (BNL1)
- The Missing Layer in COVID-19 Studies: Transmission of Enveloped Viruses in Mucus-Rich Droplets (PNNL2)
- Sensitivity of Airborne Transmission of Enveloped Viruses to Seasonal Variation in Indoor Relative Humidity (BNL2)

Quantifying the Effect of Size, Release Location and Evaporation on HVAC-Induced Respiratory Aerosol Dispersion using High-Resolution Large Eddy Simulations

This research is in preparation for peer-review and publication:

Dutta, S., Obabko, A., Balakrishnan, R., Feng, Y., & Kotamarthi, R. (2021). Quantifying the effect of size and release location on HVAC induced respiratory aerosol dispersion in using high-resolution large eddy simulations. In preparation for submission to *Physics of Fluids*.

Dutta, S., Obabko, A., Balakrishnan, R., Feng, Y., & Kotamarthi, R. (2021). Quantifying the effect of evaporation on HVAC induced respiratory aerosol dispersion. In preparation for submission to *Physical Review Fluids*.

Practical Implications

- This research provides accurate quantification of the turbulence in a mid-sized room, providing benchmark data to validate and test Reynolds Averaged Navier-Stokes model simulations.
- The sweeping out time of aerosols is not directly correlated with distance from outlet, with aerosols released farthest from the outlet not taking the most time to leave the room.

Summary
Using high-resolution large eddy simulations (LES), ANL investigated the respiratory aerosol transport induced by heating, ventilation, and air conditioning (HVAC, at 6 air changes per hour) in a 2.3 m x 4.3 m x 3.6 m empty room. This is one of the first simulations at this scale that has strived to resolve all the important scales of turbulence accurately, including the turbulence property of the flow entering the room. The simulations have been conducted using Nek5000, a computational fluid dynamics code that simulates fluid flow with thermal and passive scalar transport, with aerosols being modeled using the Lagrangian particle tracking approach. Aerosols of the sizes 0.5-32 microns were released at four different locations in the room, helping us quantify the effect of aerosols size and position on their dispersion, as illustrated below. The simulations provide unprecedented information about deposition patterns and dispersal mechanisms of aerosols of different sizes. The study also quantified the effect of evaporation on the aerosols deposition and dispersion patterns.

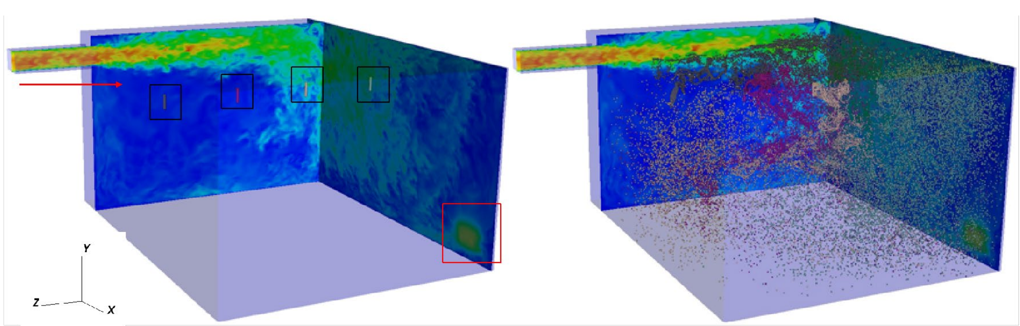

Figure Caption. Difference in particle dispersion based on initial release location in a simulated empty room.

Direct Numerical Simulation of the Turbulent Flow Generated During a Violent Expiratory Event

This research has been peer-reviewed and published:

Fabregat, A., Gisbert, F., Vernet, A., Dutta, S., Mittal, K., & Pallarès, J. (2021). Direct numerical simulation of the turbulent flow generated during a violent expiratory event. *Physics of Fluids*, 33(3), 035122.

Practical Implications

- This research produced one of the first fully resolved turbulent simulations of an idealized cough.
- Differences between the actual buoyant turbulent puff dispersion process and the theoretical model of a cough are illustrated.
- The fully resolved hydrodynamics can be used to inform new analytical models, leading to improved prediction of cough-induced pathogen-laden aerosol dispersion.

Summary

ANL investigated the hydrodynamics produced by a violent expiratory event resembling a mild cough. Coughs can be split into an initial jet stage during which air is expelled through the mouth and a dissipative phase over which turbulence intensity decays as the puff penetrates the environment. Time-varying exhaled velocity and buoyancy due to temperature differences between the cough and the ambient air affect the overall flow dynamics. The direct numerical simulation (DNS) of an idealized isolated cough is used to characterize the jet/puff dynamics using the trajectory of the leading turbulent vortex ring and extract its topology by fitting an ellipsoid to the exhaled fluid contour. The three-dimensional structure of the simulated cough shows that the assumption of a spheroidal puff front fails to capture the observed ellipsoidal shape. Numerical results suggest that, although analytical models provide reasonable estimates of the distance traveled by the puff, trajectory predictions exhibit larger deviations from the DNS. The fully resolved hydrodynamics presented here can be used to inform new analytical models, leading to improved prediction of cough-induced pathogen-laden aerosol dispersion.

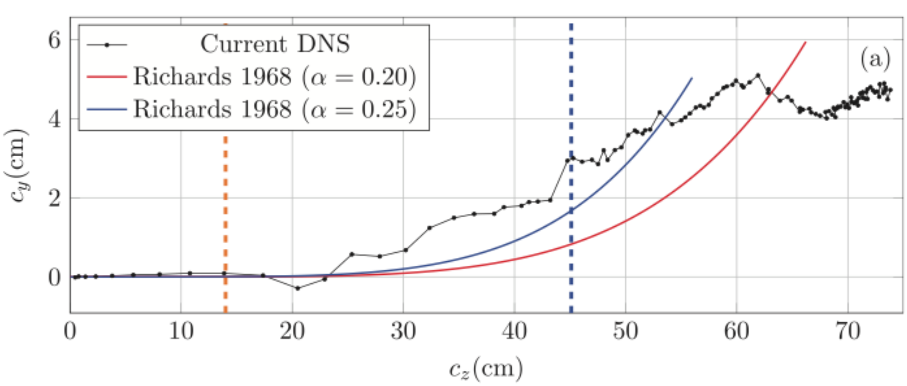

Figure Caption. Comparison of the puff front trajectory centroid from the DNS (thin dotted black) against the theoretical model for different values of the entrainment coefficients 0.20 (red) and 0.25 (blue). This shows that the theoretical model does not capture the evolution of the cough.

Direct Numerical Simulation of Turbulent Dispersion of Evaporative Aerosol Clouds Produced by an Intense Expiratory Event

This research has been peer-reviewed and published:

Fabregat, A., Gisbert, F., Vernet, A., Ferré, J. A., Mittal, K., Dutta, S., & Pallarès, J. (2021). Direct numerical simulation of turbulent dispersion of evaporative aerosol clouds produced by an intense expiratory event. *Physics of Fluids*, 33(3), 033329.

Practical Implications

- One of the first fully resolved turbulent simulations of an expiratory event with evaporative respiratory aerosols.
- Modeling the transport of different size aerosols (4-256 microns), illustrating the effect of evaporation and turbulence on transport of respiratory aerosols. The study clearly shows that aerosols of sizes 4-32 micron show maximum effect due to evaporation. (fig. 1)
- The probability density function generated from the simulation shows that largest aerosols/droplet sizes (> 128 micron) are the ones transported the furthest longitudinally.
- Longitudinal and vertical spread of different sized droplets/aerosols clearly show 3 different regimes based on aerosol/droplet size, first is less than equal to 16 microns, second regime is 32-128 microns, and third is larger than 128 microns. (fig. 2)

Summary

ANL investigated the aerosol/droplet transport during a violent expiratory event resembling a mild cough. While the dynamics of the largest droplets are dominated by gravitational effects, the smaller aerosol particles, mostly transported by means of hydrodynamic drag, form clouds that can remain afloat for long times. In subsaturated air environments, the dependence of pathogen-laden particle dispersion on their size is complicated due to evaporation of the aqueous fraction. Particle dynamics can significantly change when ambient conditions favor rapid evaporation rates that result in a transition from buoyancy- to drag-dominated dispersion regimes. To investigate the effect of particle size and evaporation on pathogen-laden cloud evolution, a direct numerical simulation of a mild cough was coupled with an evaporative Lagrangian particle advection model. As illustrated below, the results suggest that while the dispersion of cough particles in the tails of the size distribution are unlikely to be disrupted by evaporative effects, preferential aerosol diameters (30–40 microns) may exhibit significant increases in the residence time and horizontal range under typical ambient conditions. Using estimations of the viral concentration in the spewed fluid and the number of ejected particles in a typical respiratory event, we obtained a map of viral load per volume of air at the end of the cough and the number of virus copies per inhalation in the emitter vicinity.

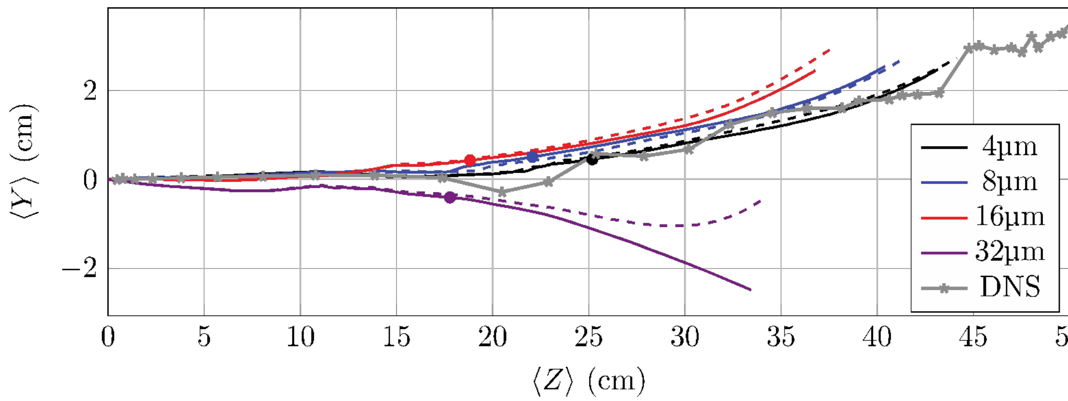

Figure Caption. Trajectory of particle cloud centroid for evaporative (dashed) and non-evaporative (solid) aerosols for 4 different aerosols sizes (4-32 microns), compared against the centroid of the buoyant air puff (DNS).

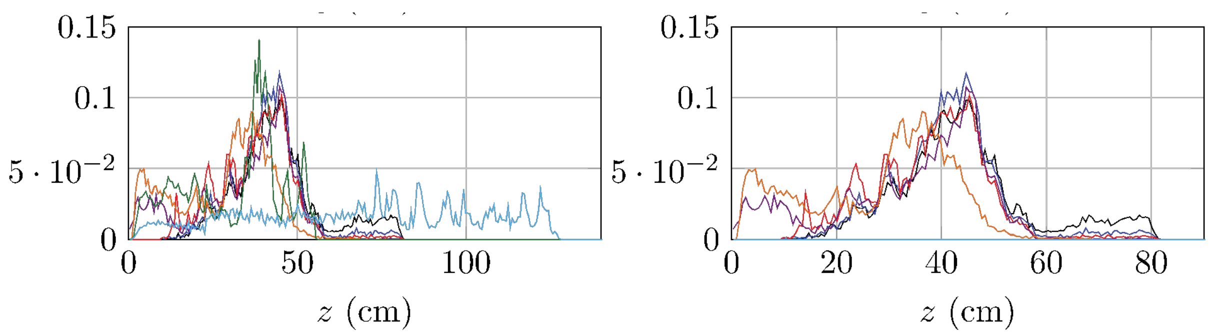

Figure Caption. Probability density distribution (PDF) of the terminal spatial location in each coordinate for evaporative particles. (Left): all sizes, (Right): 4–64 microns.

Simulating Near-field Enhancement in Transmission of Airborne Viruses with a Quadrature-Based Model

This work has been peer-reviewed and published:

L. Fierce, A. J. Robey, and C. Hamilton, Simulating near-field enhancement in transmission of airborne viruses with a quadrature-based model. *Indoor Air*, 1-17 (2021) DOI: 10.1111/ina.12900.

Practical Implications

- The risk of airborne transmission is orders of magnitude greater in the expiratory jet of an infectious person than in a well-mixed room.
- The horizontal extent of near-field airborne transmission extends beyond the travel distance of large droplets.
- Variability in the horizontal extent of near-field effects is driven primarily by variability in the expiration velocity.

Summary

The particles that carry airborne viruses are created in the respiratory system through expiratory activities such as sneezing, coughing, talking, or breathing. A particle's size at the time it is expelled dictates the distance it travels before settling to the ground. If a particle is transported to another individual and inhaled, its size influences if and where in the respiratory system it is most likely to deposit. For this reason, the QuaRAD model is designed to accurately and efficiently represent the size distribution of expelled particles and their evolution through evaporation, transport, and removal. Transmission of airborne viruses depends on factors that are inherently variable and, in many cases, poorly constrained. Quantifying this uncertainty requires large ensembles of model simulations that span the variability in input parameters. However, models that are well-suited to simulate the near-field evolution of respiratory particles are also computationally expensive, which limits the exploration of parametric uncertainty. In order to perform many simulations that span the wide variability in factors governing airborne transmission, we developed the Quadrature-based model of Respiratory Aerosols and Droplets (QuaRAD). Quadrature methods have a long and productive history of development at BNL for the representation of aerosol and cloud droplets in atmospheric models. Their application here introduces a highly efficient framework for simulating the airborne fate and transport of virus-laden particles, from their expiration from an infectious person to their deposition in the nasal cavity of a susceptible person, and the subsequent risk of initial infection. Using this model, we simulated 10,000 scenarios to quantify the risk of initial infection through airborne transition of the particular virus SARS-CoV-2.

Data Availability Statement: The QuaRAD source code, input files, and processing script are available for download at: https://github.com/lfierce2/QuaRAD/. Simulation ensembles were created using latin hypercube sampling with pyDOE: https://pythonhosted.org/pyDOE/. The sensitivity analysis was performed using the Sensitivity Analysis Library in Python, which is available at: https://salib.readthedocs.io/en/latest/.

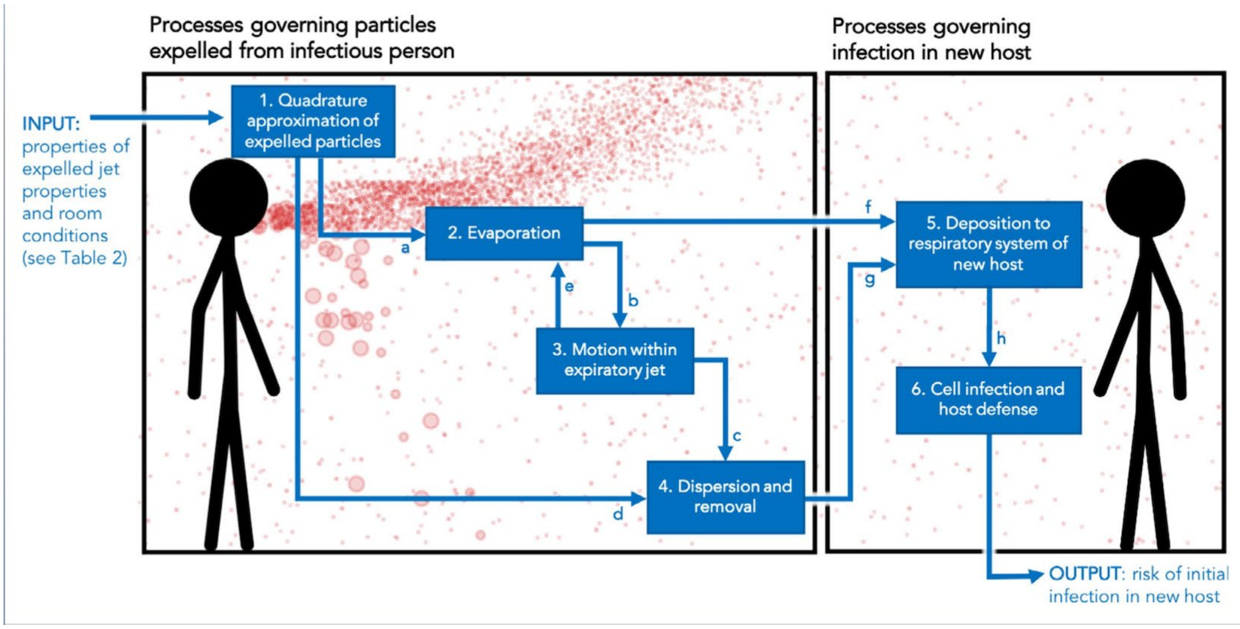

Figure Caption. A schematic depiction of processes represented in the Quadrature-based model of Respiratory Aerosols and Droplets (QuaRAD). These include the key processes governing the evolution of expelled particles (left) and processes governing infection in a new host (right) for statistical ensembles of exposure conditions. Model inputs are provided in Table 1 and model components (1–6) and the connections between them (a–h) are described in the text of Section 2 of the cited paper.

The Missing Layer in COVID-19 Studies: Transmission of Enveloped Viruses in Mucus-Rich Droplets

This work has been submitted for peer-review and publication:

Leonard F. Pease, Na Wang, Gourihar R. Kulkarni, Julia E. Flaherty, Carolyn A. Burns. The Missing Layer in COVID-19 Studies: Transmission of Enveloped Viruses in Mucus-rich Droplets. *International Communications in Heat and Mass Transfer* (2021) submitted.

Practical Implications

- Analysis shows that mucus shells increase the drying time by orders of magnitude so that enveloped virions may remain well hydrated and, thus, fully infective at substantial distances.
- Aerosolized particles that remain infectious can potentially transmit through ventilation systems in buildings.
- Analysis will help guide public health policies such as social distancing.

Summary
PNNL evaluated the influence of mucus layers on the evaporation time and transport of enveloped viruses, including SARS-CoV-2. Enveloped viruses must remain moist to be fully infective. Yet, the simple but enduring Wells model based on water droplets divides respiratory droplets into either quickly evaporated aerosolized particles termed droplet nuclei (<10 s) or liquid droplets that fall to the nearest surface, leaving no physical mechanism for airborne transmission of fully infective enveloped viruses over large distances (greater than a few meters). Yet, the role of mucus layers on evaporation times has not been considered even though the formation of mucus shells around liquid cores of respiratory droplets has been shown experimentally. Here we show that mucus shells increase the drying time by orders of magnitude so that enveloped virions may remain well hydrated and, thus, fully infective at substantial distances. This provides a mechanism by which infective enveloped virus particles can transmit as aerosols within buildings and between buildings over extended distances. This analysis is important because public health agencies typically follow the Wells model to establish health policies including social/physical distancing guidelines.

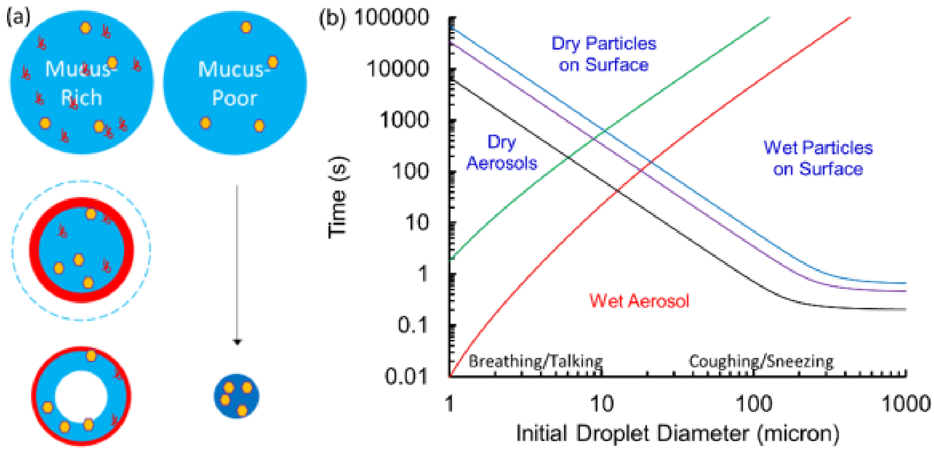

Figure Caption. (a) Comparison of mucus-rich droplets that form mucus shells around liquid cores and mucus-poor droplets that do not. Mucus-poor droplets dry disrupting the enveloped coating of enveloped viruses. (b) Time to complete drying of a core-shell mucus particle with a wet shell as a function of initial droplet diameter for gelation to initial concentration ratios of 5 (green) and 50 (red) along with fall times corresponding to fall distances of 2 m (blue), 1 m (purple), and 0.2 m (black) at 25ºC at standard temperature and pressure under quiescent conditions. Relative humidity values (20-80% RH) collapse on the same curves.

Sensitivity of Airborne Transmission of Enveloped Viruses to Seasonal Variation in Indoor Relative Humidity

This work has been submitted for peer-review and publication:

A. J. Robey, and L. Fierce (2021) Sensitivity of airborne transmission of enveloped viruses to seasonal variation in indoor relative humidity, Submitted for publication in *International Journal of Heat and Mass Transfer*.

Practical Implications

- Dry indoor conditions typical of the winter season lead to slower virion inactivation rates as compared to the more humid summer season. This effect increases the concentration of active virions when the susceptible person is farther than 2 m downwind of the infectious person.
- Our process analysis revealed that the greater virion exposure at RH = 40% than at RH = 65% was caused by differences in virion inactivation rate and not by RH-induced changes in particle removal rates through gravitational settling and deposition.

Summary
While outdoor temperatures and humidity levels vary dramatically throughout the year, humans spend around 90% of their time indoors where temperatures remain stable but relative humidity (RH) displays consistent summer highs and winter lows. Several mechanisms pertinent to the airborne transmission of viruses are sensitive to this variability in RH, such as faster inactivation of enveloped virions at extreme RH levels and shorter travel distance of mid-sized particles at high RH levels due to changes in growth rate and equilibrium particle size. However, it is unclear which mechanism, RH-mediated differences in droplet removal, or RH-mediated virion inactivation, drives the seasonality of enveloped viruses.

BNL used the Quadrature-based model of Respiratory Aerosol and Droplets (QuaRAD) to explore whether the seasonal variation in enveloped viruses, specifically SARS-CoV-2, is driven by differences in particle removal rates or in the rate at which virions are inactivated. Through a large ensemble of simulations, we found that the dry indoor conditions typical of the winter season led to slower inactivation relative to the more humid summer season; in poorly ventilated spaces, this reduction in inactivation rates increases the concentration of active virions when the susceptible person is farther than 2 m downwind of the infectious person. On the other hand, changes in particle settling velocity with relative humidity did not significantly affect the removal or travel distance of virus-laden particles.

Data Availability Statement: The QuaRAD source code, input files, and processing script are available for download at: https://github.com/lfierce2/QuaRAD/. Simulation ensembles were created using latin hypercube sampling with pyDOE: https://pythonhosted.org/pyDOE/.

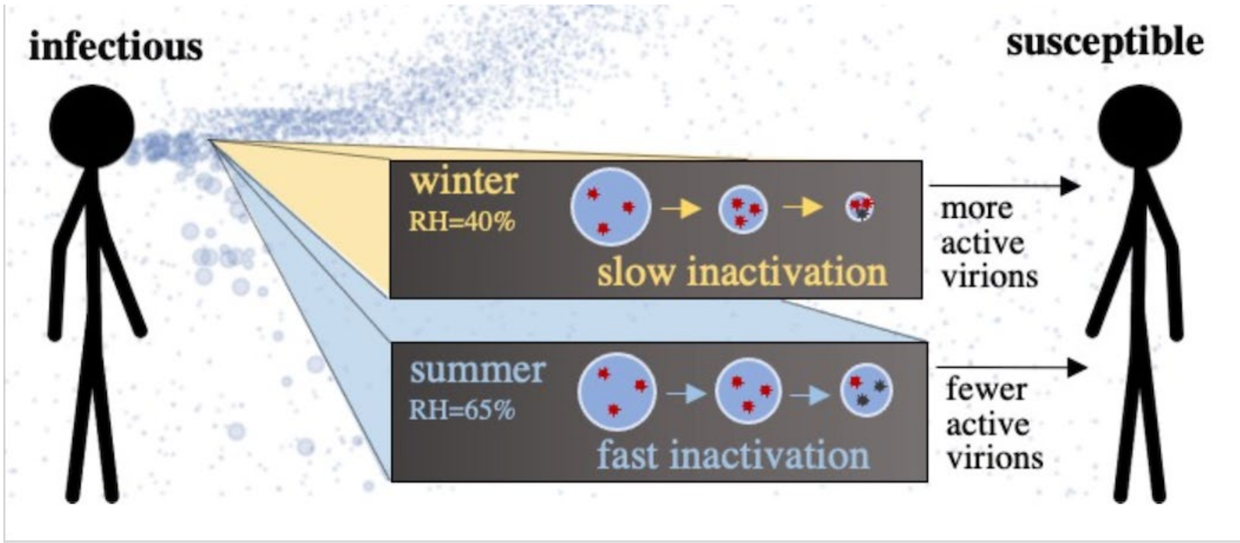

Figure Caption. In this research, we show that a lower relative humidity (RH), typical of the winter season, increases airborne virion exposure by slowing the virion inactivation rate, not by increasing the travel distance or residence times of respiratory particles due to changes in particle settling velocity.

RESULTS: Topic 4

Efficacy of Controls for Reducing Exposure to Airborne Pathogens

- High Efficacy of Layered Controls for Reducing Exposure to Airborne Pathogens (BNL2)
- Control of Airborne Infectious Disease in Buildings: Evidence and Research Priorities (LBL2)
- Protecting Building Occupants Against the Inhalation of Outdoor-Origin Aerosols (LLNL-LBNL)
- Simplified Screening Method to Measure Indoor Airborne Particle Removal Rates (LLNL3)
- Multi-Scale Airborne Infectious Disease Transmission (LLNL1)

High Efficacy of Layered Controls for Reducing Exposure to Airborne Pathogens

This work has been submitted for peer-review and publication:

L. Fierce, A. J. Robey, and C. Hamilton (2021) High efficacy of layered controls for reducing exposure to airborne pathogens. Submitted for publication to *Indoor Air*.

Practical Implications

- Focusing on SARS-CoV-2, we simulated thousands of scenarios with QuaRAD to quantify the efficacy of individual and combined controls on airborne transmission.
- For each scenario, we compared the risk of initial infection in the susceptible person for cases without controls (low ventilation, no masks) and for cases with different combinations of controls.
- In this study, we showed that layered controls are highly effective in reducing transmission of airborne pathogens like SARS-CoV-2. The combination of social distancing, masking, and increasing ventilation led to a reduction in the median risk of infection by more than 99%.

Summary
Controls on airborne transmission may reduce the number of virus-laden particles inhaled by a susceptible person and depositing to the infection site, but the efficacy of any given control depends on factors that are inherently variable and, often, poorly constrained. For example, while the size-resolved collection efficiencies of different types of face masks have been measured, the reduction in the risk of infection also depends on factors such as rates of viral shedding, characteristics of expiratory jets, room conditions, and immune responses, all of which are highly variable. This uncertainty can be represented in models by simulating ensembles of scenarios, but models well-suited for simulating the evolution of respiratory particles in indoor spaces are often computationally expensive, limiting their ability to represent uncertainty. To optimize strategies for curbing the transmission of airborne pathogens, the efficacy of three key controls - face masks, ventilation, and physical distancing - must be well understood. In this study at BNL, we used the Quadrature-based model of Respiratory Aerosol and Droplets (QuaRAD) to quantify the efficacy of controls across thousands of scenarios that represent the tremendous variability in factors governing airborne transmission. While the efficacy of any individual control was highly variable among scenarios, combining universal mask-wearing with distancing of 1 m or more reduced the median exposure by more than 99% relative to a close, unmasked conversation, with further reductions if ventilation is also enhanced. These findings suggest that layering controls is highly effective for reducing transmission of airborne pathogens and will be critical for curbing outbreaks of novel viruses in the future.

Data Availability Statement: The QuaRAD source code, input files, and processing script are available for download at: https://github.com/lfierce2/QuaRAD/. Simulation ensembles were created using latin hypercube sampling with pyDOE: https://pythonhosted.org/pyDOE/. The sensitivity analysis was performed using the Sensitivity Analysis Library in Python, which is available at: https://salib.readthedocs.io/en/latest/.

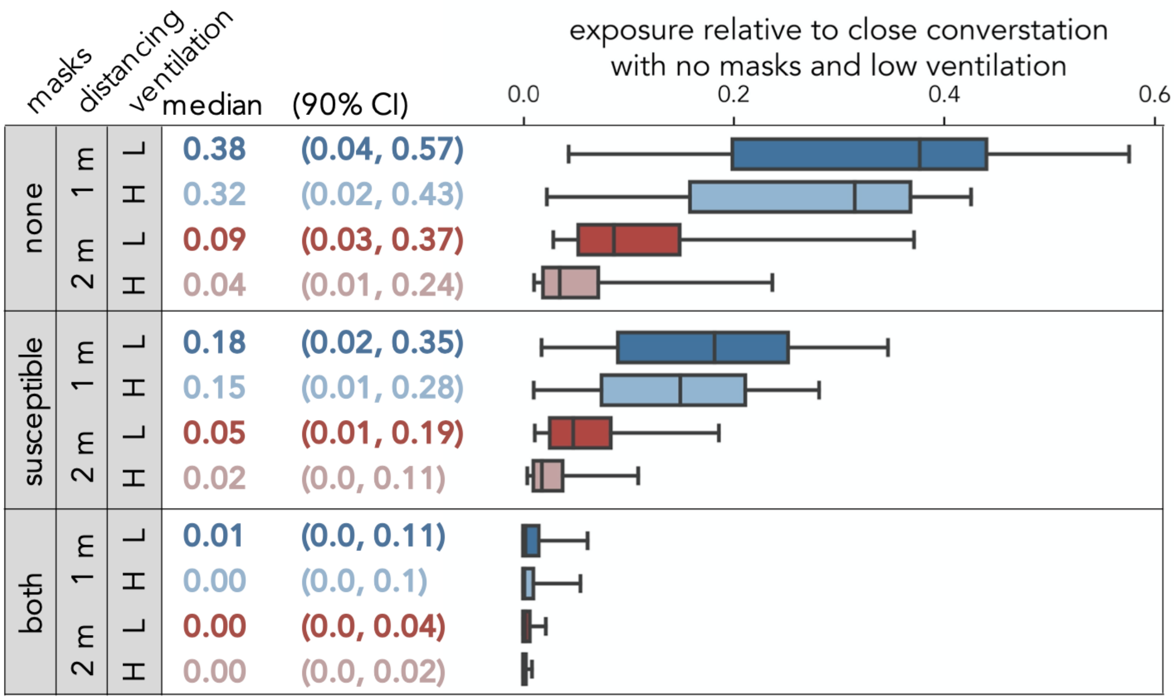

Figure Caption. Efficacy of layered controls. Median (solid line), quartiles (boxes), and 90% confidence interval (whiskers) of the fraction of airborne pathogens reaching the infection site when different combinations of controls are employed in comparison with a close (0.5 m) conversation at the baseline (low) ventilation rates. The median and 90% confidence intervals of the relative exposure are also shown.

Control of Airborne Infectious Disease in Buildings: Evidence and Research Priorities

This work has been submitted for peer-review and publication:

Bueno de Mesquita, PJ; Delp, WW; Chan, WR; Bahnfleth, WP; Singer, BC. (2021) Control of airborne infectious disease in buildings: evidence and research priorities. Under review at *Indoor Air*.

Practical Implications

- Emerging variants of SARS-CoV-2 have led to increased infectivity by the aerosol inhalation mode and increasing infection incidence.
- Even in the absence of symptoms, people infected with respiratory viruses can exhale infectious aerosols that can be inhaled, deposit in the respiratory tract, and initiate infection.
- Indoor environments are the predominant settings for respiratory infection transmission because people spend most of their time indoors, and because concentrations of infectious aerosols can accumulate, resulting in hazardous inhalation exposure at close-interactive, room (even at distances much greater than two meters), and building scales.
- We illustrate the relative respiratory aerosol transfer and exposure at these scales, provide an overview of the scientific basis of engineering controls that can be deployed in buildings to reduce transfer between people, and outline priority research directions to guide widespread implementation of controls in buildings.

Summary

The evolution of SARS-CoV-2 virus has resulted in variants more readily transmitted through respiratory aerosols, underscoring the increased potential for indoor environmental controls to mitigate risk. Use of tight-fitting face masks to trap infectious aerosol in exhaled breath and reduce inhalation exposure to contaminated air is of critical importance for disease control. Administrative controls including the regulation of occupancy and interpersonal spacing are also important, while presenting social and economic challenges. Indoor engineering controls including ventilation, exhaust, air flow control, filtration, and disinfection by germicidal ultraviolet irradiation can reduce reliance on stringent occupancy restrictions. However, the effects of controls—individually and in combination—on reducing infectious aerosol transfer indoors remain to be clearly characterized to the extent needed to support widespread implementation by building operators. In this study, LBNL reviews aerobiologic and epidemiologic evidence of indoor environmental controls against transmission and presents a quantitative aerosol transfer scenario illustrating relative differences in exposure at close-interactive, room, and building scales. We identify an overarching need for investment to implement building controls and evaluate their effectiveness on infection in well-characterized and real-world settings, supported by specific, methodological advances. Improved understanding of engineering control effectiveness guides implementation at scale while considering occupant comfort, operational challenges, and energy costs.

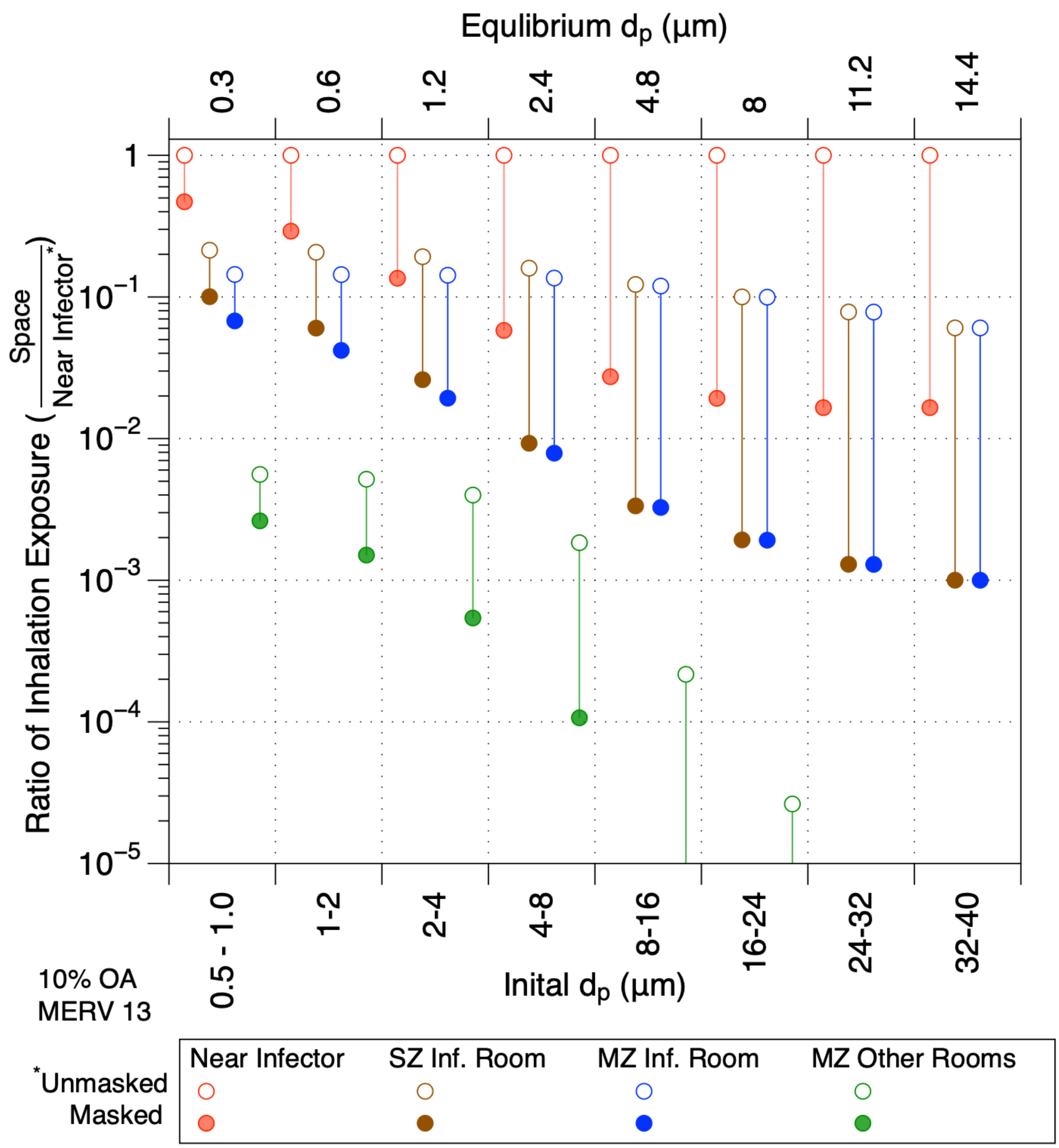

Figure Caption. Relative inhalation exposure attributed to aerosols at different exposure scales compared with close-interactive exposure in the SZ Inf. Room. SZ Inf. Room = Single-zone HVAC system serving 93 m^2 with an infector in the room; MZ = mixed-zone HVAC system serving a total 929 m^2 with infector in the room; d_p = aerosol diameter; OA = outdoor air.

Protecting Building Occupants Against the Inhalation of Outdoor-Origin Aerosols

This research has been submitted for peer-review and publication:

Michael B. Dillon, Richard G. Sextro, and W Woody Delp, Protecting Building Occupants Against the Inhalation of Outdoor-Origin Aerosols, *Atmospheric Environment,* Under Review.

Practical Implications

- We estimate the protection that the existing US building stock provides their occupants from outdoor-origin airborne particulate hazards, such as infectious aerosols and wildfire smoke.
- We compile published deposition, penetration, filtration, and building operation data. This data is used in subsequent research (not presented in this paper) that assesses the US building, indoor-origin aerosol exposure risk and mitigation measure efficacy.
- Building protection varies widely by occupancy type, particle-size, and airborne loss rate. Furthermore, variability within a given building type – due to variability in weather, building construction, and operating conditions – is similar to variability between different building types.

Summary
During normal operations, buildings can protect their occupants from outdoor airborne particle hazards of all types, including airborne pollutants. A long-term international research effort has advanced our knowledge of building protection physics. Recently we have developed an operationally efficient, regional-scale methodology - Regional Shelter Analysis - to account for both building protection effects and the typical distribution of people in and among buildings. To provide input to this capability, LLNL and LBNL partnered to estimate the degree of protection afforded by the currently existing US building stock. We first assemble and summarize the published literature relevant to indoor particle losses including (a) deposition to indoor surfaces, (b) losses that occur when particles penetrate through the building envelope, and (c) heating, ventilation and air conditioning (HVAC) system filtration efficiencies as well as general building operating conditions. Building protection against inhaling particulate hazards varies strongly, by orders of magnitude, according to building use (occupancy), particle-size, and airborne particle loss rate. Protection increases modestly as particle size increases from 0.1 to 1 µm and significantly as particle size increases from 1 to 10 µm, as illustrated in the figure below. Model results are placed in context with previously reported measurements. Suggestions for future work, including enhanced validation datasets are provided.

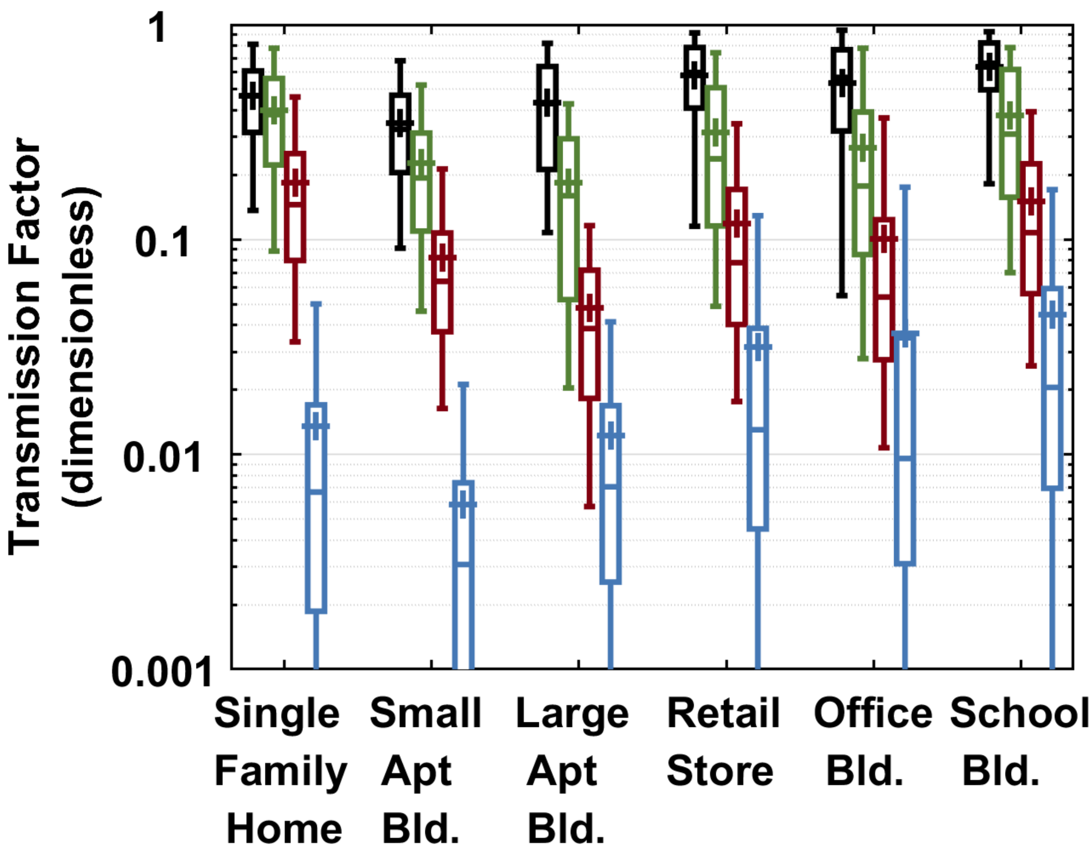

Figure Caption. Distribution of transmission factor (ratio of indoor to outdoor exposure) for select building types by particle size for the no airborne loss case. Box and whisker plot shows the median (line), interquartile (box), 5 and 95 percentiles (whiskers), and mean (+ symbol). Particle diameter varies from left to right for each building type: black, 0.1 µm; green, 1 µm; red, 3 µm; and blue, 10 µm.

Simplified Screening Method to Measure Indoor Airborne Particle Removal Rates

This work has been submitted for peer-review and publication:

Michael B. Dillon, Matthais Frank, and Elizabeth K. Wheeler, Simplified screening method to measure indoor airborne particle removal rates, *Journal of Occupational and Environmental Hygiene,* Under review.

Practical Implications

- This paper demonstrates an approach that rapidly assesses the overall airborne particle removal rates.
- This method can be used to quickly screen if indoor environments pose a notable exposure risk and evaluate mitigation measure efficacy.
- This method can be used in occupied spaces.

Summary

There is increasing evidence that COVID-19 can be spread at distances ≥2 m indoors through the inhalation of airborne, infectious particles. To reduce disease spread, US governmental and industrial standard setting groups have emphasized increasing outdoor air ventilation and the use of various air cleaning technologies, including filtration. While a method exists to assess overall aerosol removal rates (including ventilation and filtration), its use can be time-consuming and/or costly. This paper demonstrates the use of an alternative, faster approach often used in research. Particulate matter was injected into room air, raising airborne particle concentrations well above ambient levels, and the aerosol removal rate is directly estimated from the resulting decay in aerosol concentration with time. This method, either by itself or in conjunction with established ventilation assessment methods, provides an opportunity to quickly screen indoor environments to rapidly identify those that may pose a notable exposure risk, e.g., poorly ventilated or filtered rooms, with respect to particle emissions within the same room. It can also be employed to evaluate mitigation efficacy. This approach could be used in occupied buildings, as was done with this demonstration.

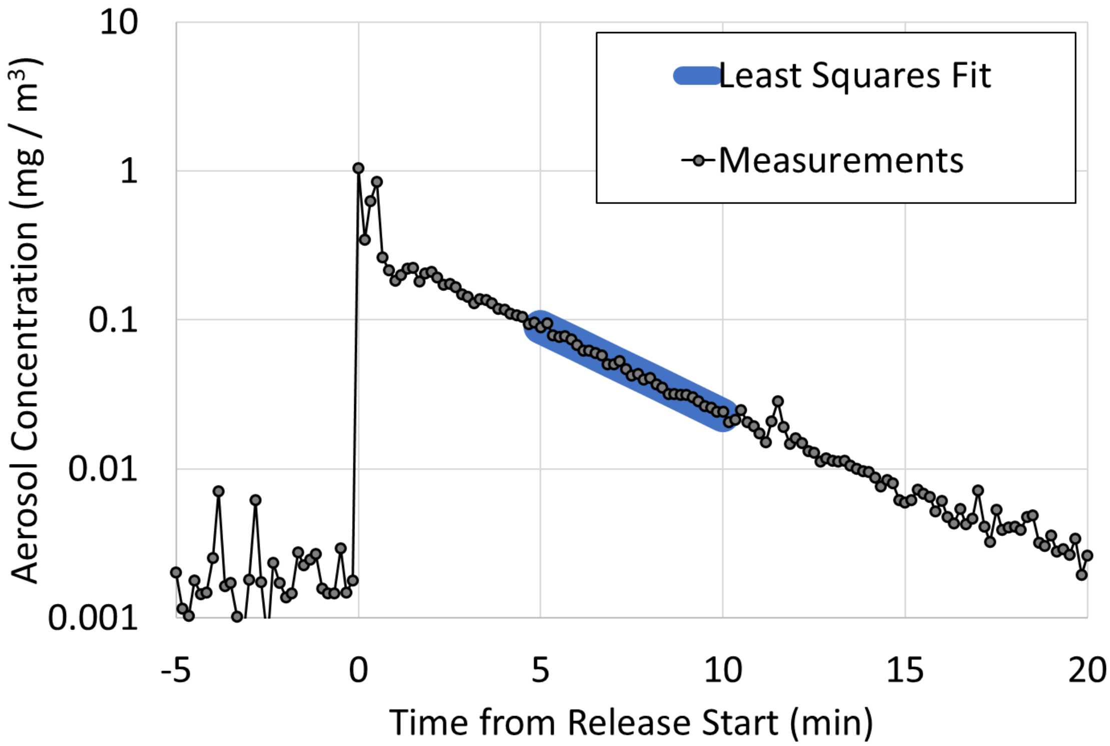

Figure Caption. Timeseries of measured (symbol) airborne particle concentrations with corresponding least squares fit (line). The slope corresponds to the overall aerosol removal rate.

Multi-Scale Airborne Infectious Disease Transmission

This work has been peer-reviewed and published:

Charles F. Dillon and Michael B. Dillon, Multiscale Airborne Infectious Disease Transmission, *Applied and Environmental Microbiology* 87.4 (2020): e02314-20.

Practical Implications

- The overall importance of airborne disease transmission is underappreciated in the scientific literature, although the cumulative body of knowledge across the scientific disciplines is large. As a consequence, airborne precautions may not be taken when airborne transmission is important, but unrecognized.
- This literature review demonstrates, through well-established examples, that airborne viruses, bacteria, and fungal pathogens can cause disease in plants, animals, and humans over distance scales ranging from a few meters to continental.
- The overall airborne disease burden may be underreported, particularly for opportunistic pathogens that can spread through multiple pathways.

Summary

Airborne disease transmission is central to many scientific disciplines including agriculture, veterinary biosafety, medicine, and public health. Legal and regulatory standards are in place to prevent agricultural, nosocomial, and community airborne disease transmission. However, the overall importance of the airborne pathway is underappreciated, e.g., US National Library of Medicine's Medical Subjects Headings (MESH) thesaurus lacks an airborne disease transmission indexing term. This has practical consequences as airborne precautions to control epidemic disease spread may not be taken when airborne transmission is important, but unrecognized. Publishing clearer practical methodological guidelines for surveillance studies and disease outbreak evaluations could help address this situation.

To inform future work, this study by LLNL highlights selected, well-established airborne transmission events - largely cases replicated in multiple, independently conducted scientific studies. Methodologies include field experiments, modeling, epidemiology studies, disease outbreak investigations and mitigation studies. Collectively, this literature demonstrates that airborne viruses, bacteria, and fungal pathogens have the capability to cause disease in plants, animals, and humans over multiple distances – from near range (< 5 m) to continental (> 500 km) in scale. The plausibility and implications of undetected airborne disease transmission are discussed, including the notable underreporting of disease burden for several airborne transmitted diseases.

Task 2: Understanding the Role of Surface Chemistry and Material Science for Viral Transmission and Spreading

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Task 2: Understanding the Role of Surface Chemistry and Material Science for Viral Transmission and Spreading

INTRODUCTION

The current COVID-19 pandemic has been caused by a SARS-type enveloped coronavirus that is wrapped in a lipid bilayer membrane, bearing glycoproteins directed outward. These spike proteins enable the virus to attach itself to surfaces of abiotic objects; attachment that allows the viral particles on such surfaces to serve as reservoirs for further viral transmission. Like other coronaviruses, SARS-CoV-2 can spread human-to-human mainly via respiratory droplets although other mechanisms remain possible. Early in the pandemic, the stability of the virus under various conditions, transmission routes and many other properties related to virus-material interaction were unknown. Despite previous research on SARS and other related pathogens, the mechanism of their attachment to abiotic surfaces and the factors that drive their adherence to different types of materials are not known. Unknown remains also the role of virus-surface interactions in the viral transport within enclosed spaces and how such interactions may impact key exposure pathways and scenarios. Therefore, there is a need to understand the ability of various materials to bind SARS-CoV-2 to provide information on how the virus might be transferred and/or reside on common surfaces. Additionally, identification of materials with selective adsorption of viruses have important potential uses in technological applications such as in novel personal protective equipment (PPE) or diagnostics.

OBJECTIVES

Critical, multidisciplinary approaches are needed to generate datasets that address the persistence of enveloped coronaviruses on non-biological surfaces. Supporting this research, direct imaging of virus-surface interactions has been conducted using a range of imaging technologies available at DOE's scientific user facilities. Ultimate goals of Task 2 include 1) understanding various - materials interactions that may define fate and transmission of coronaviruses in the built environment, and 2) the ability of surface-bound viruses to serve as a reservoir for air-born transmission, which is complimentary to Task 1 of this project.

Generation and screening of materials commonly found in the built environment

A library of materials, including metals/alloys, oxides and polymers with different surface chemistries and degrees of roughness, will be assembled to assess the impact of surface chemistry and morphology on retention, transmission, and stability of coronaviruses. Diverse imaging approaches, such as Cryo-EM (SLAC), SEM/STEM (Ames, PNNL, ORNL), atomic force microscopy (AFM) (PNNL), as well as direct visualization in near-native environment using correlative fluorescence microscopy and electron microscopy in liquid phase (Ames) will be employed to explore materials features and their interactions with spike proteins of coronaviruses. A limited number of materials will be tested at BSL-3 with SARS-CoV-2 (SNL) as needed. The research intended to determine a range of materials' properties responsible for repelling or trapping SARS-CoV-2 and enable development of mitigation approaches preventing transmission and spreading of virus in the built environment.

PROPOSED OUTCOMES

1. Selection of surrogate viral test system, initial set of materials for testing, and most appropriate material characterization techniques for materials chosen – 1 month
2. Assessment of the virucidal behavior of selected man-made and natural materials, including metals (stainless steel, copper, brass) and oxide (iron oxides, clay-like and complex oxides) as well as polymeric materials
3. Determine material composition/surface morphologies with enhanced or reduced affinity to viral proteins and contribute to the ability of surface-bound pathogens to serve as reservoirs for viral transmission

RESULTS: Topic 1

Generation and screening of materials commonly found in the built environment

- S/TEM imaging of materials' interactions with virus-like nanoparticles and inactivated SARS CoV-2 virus nanoparticles – Ames Laboratory
- Evaluation of COVID-19 spike protein adhesion to common surfaces with atomic force microscopy and infrared nanospectroscopy – Pacific Northwest National Laboratory
- Profiling material-virus interactions for selective adsorption of SARS-CoV-2 using Vesicular stomatitis virus (VSV) based pseudoviruses – Sandia National Laboratory & Ames Laboratory
- Imaging SARS CoV-2 on substrates with FIB/HRSEM – SLAC National Accelerator Laboratory
- Towards correlative spatio-chemical imaging of SARS-CoV-2 Virus Like Particles (VLPs) bound to common surfaces – Oak Ridge National Laboratory

Manuscripts:

- O'Callahan, Brian; Qafoku, Odeta; Balema, Viktor; Negrete, Oscar A.; Passian, Ali; Engelhard, Mark; Waters, Katrina. "Atomic force microscopy and infrared nanospectroscopy of COVID-19 spike protein for quantification of adhesion to common surfaces" *Langmuir*, in press.
- Oscar Negrete, Anupama Singh, Ihor Z. Hlova, and Viktor Balema "Profiling materials for selective adsorption to SARS-CoV-2 using Vesicular stomatitis virus (VSV) based pseudoviruses." Manuscript in preparation. Anticipated submission to *ChemComm*: Oct 2021.
- Elizabeth A. Dobisz, William Thompson, K. Phadkeb, B. Bellaire, and Anne Sakdinawat. "Dual Beam Focused Ion Beam - Scanning Electron Microscope Imaging and Cross-Sectioning on SARS-CoV2", *Nature Nanotechnology*, to be submitted.
- A. Passian et al., "Viral stability on surfaces: a brief review of surface characterization," In preparation, to be submitted to ACS Nano (2021).

S/TEM imaging of materials' interactions with virus-like nanoparticles and inactivated SARS CoV-2 virus nanoparticles – Ames Laboratory

Goals:

- Developed and optimized scanning transmission electron microscopy imaging of material interactions with virus-like nanoparticles and inactivated SARS CoV-2 virus nanoparticles. The developed procedure of imaging of biological specimens with inherently poor contrast incubated with the high-contrast inorganic particles is expected to be broadly applicable to imaging and characterization of materials-virus interactions for a wide variety of inorganic materials.
- Aqueous suspension of ball-milled ceria particles and alumina nanospheres were incubated with virus-like nanoparticles, inactivated SARS CoV-2 virus nanoparticles, and imaged using BF-TEM and HAADF- STEM imaging modes, utilizing staining.

Summary:

An aqueous suspension containing ceria nanoparticles was incubated with spike protein trimer solution for 30 min at room temperature before proceeding with S/TEM imaging.
The sample was drop-casted on a grid: following the 30-min incubation with ceria suspension, a microvolume of sample incubated inactivated virus nanoparticles solution was deposited on a hydrophylized ultrathin carbon support grid. The samples were allowed to stay on a grid for 3 min, after which time they was washed with copious amounts of water and stained with UraniLess for 20 sec. Results are shown in Figure below.

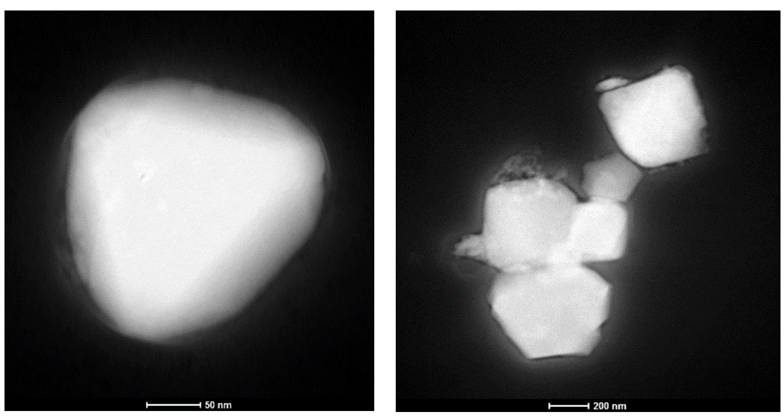

Figure Caption: HAADF-S/TEM images of ceria particles incubated with inactivated SARS CoV-2 virus nanoparticles. Left: heat-inactivated virus. Right: glutaraldehyde-inactivated virus.

Evaluation of COVID-19 spike protein adhesion to common surfaces with atomic force microscopy and infrared nanospectroscopy – Pacific Northwest National Laboratory

Goals:

- To aid the understanding of the spread and persistence of SARS CoV-2 on commonplace surfaces and help mitigate future outbreaks of coronaviruses and other pathogens, we proposed to study the binding and interaction of viral proteins with non-biological surfaces. To achieve this objective, we employed a combination of IR scattering-type scanning near-field optical microscopy (*s*-SNOM) and atomic force microscopy (AFM) based approach.
- The overarching objective of our study is to gain insight into attachment and binding of SARS CoV-2 spike glycoproteins on common selected inorganic materials. such as aluminum-, copper-, iron-, silica-, and ceria-oxides as well as metallic gold.

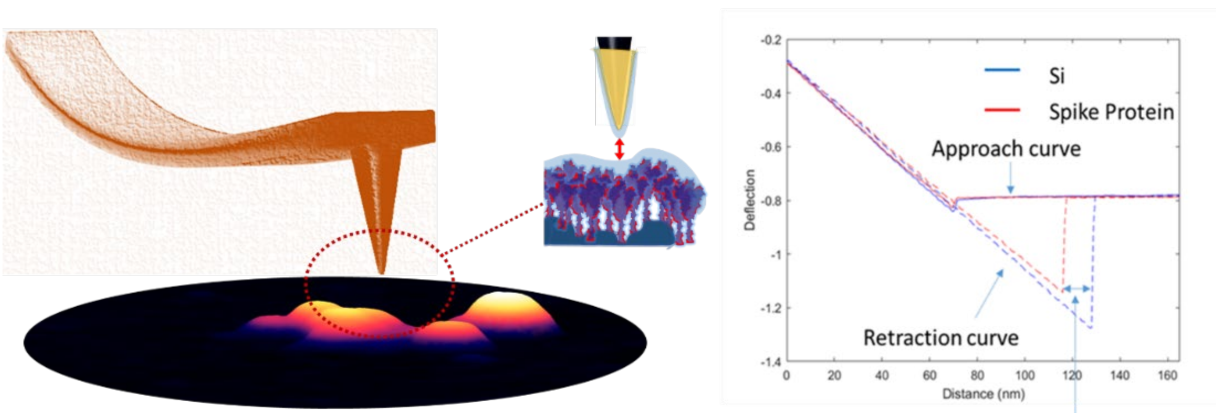

Figure Caption: Schematic of a gold coated AFM cantilever probe tip interacting with spike proteins deposited on an Si substrate. Forces of interaction are shown on the insert on the right. Force-curve measurements are analyzed to extract the adhesion force between the spike protein and the tip material.

Summary:

We show the topography of spike proteins acquired by AFM and phase image acquired by s-SNOM at 1650 cm^{-1}, and we show a plot that summarizes adhesion forces measured by AFM based on the interaction of the spike protein with metal or metal oxide coated tips (Figure below). The measured forces between spike proteins and metal or metal oxides coated AFM tips varied over an order of magnitude from the lowest 1-2 nN for CeO_2 and iron oxide, to the highest ~20-25 nN for Au. We have plotted the normalized forces by radius per each coated tip, for spike proteins as well as for ferritin coated surface and for SiO_2 surface using the same AFM tips. The results indicate that except for Cu oxide, the adhesion forces between spike protein and metal or metal oxides are similar to that of ferritin. The Cu oxide adhesion measurements showed a factor of three times weaker adhesion of spike protein compared to ferritin or Si-substrate. Most significantly, for both ferritin and spike glycoproteins the data indicates much stronger adhesion forces on Au. We note that, the orientations of the spike proteins in our study are not controlled and are expected to be random. The conformational state of the proteins can be 'open' or 'closed', which plays a key role in the infectivity properties of the virus. We expect the conformational state of the protein to be a mixture of both the 'open' and 'closed' states or partially denatured protein. Nevertheless, these measurements aim to emulate real-world adhesion of the SARS CoV-2 virus in workplace and household environments which may be determined by non-site-specific interactions.

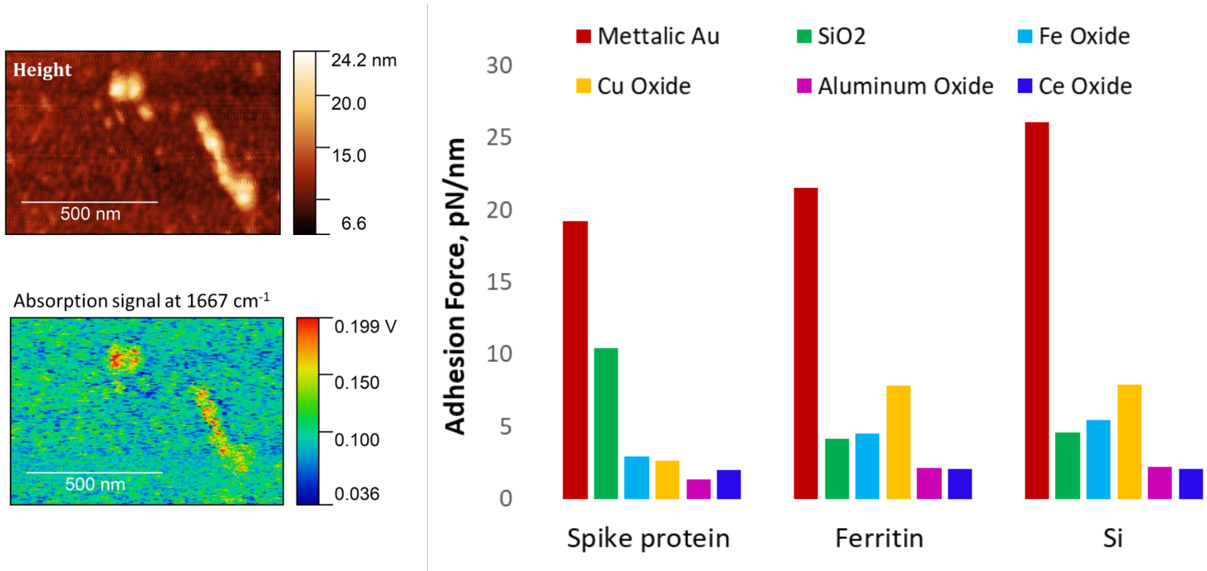

Figure Caption: AFM topography of SARS CoV-2 spike protein on a gold substrate and (Left, bottom) corresponding s-SNOM phase image acquired at 1650 cm-1. (Right) Relative adhesion forces between AFM tips coated with different metals and spike protein (blue) and ferritin (red).

Profiling material-virus interactions for selective adsorption of SARS-CoV-2 using Vesicular stomatitis virus (VSV) based pseudoviruses – Sandia National Laboratory & Ames Laboratory

Goals:

- To understand the ability of various materials to bind SARS-CoV-2 to provide information on how the virus might be transferred and/or reside on common surfaces.
- Identification of materials with selective adsorption of viruses have important potential uses in technological applications such as in novel personal protective equipment or diagnostics.

Summary:

To profile materials for their ability to bind and/or inactivate SARS-CoV-2 pseudoviruses, we coupled a rapid adsorption method to an infection assay as illustrated in the Figure below. A set concentration of purified vesicular stomatitis virus (VSV)-SARS particles was incubated with various materials sent from the Ames laboratory, rotated for 1hr and then centrifuged to pellet the material. As these low centrifugation rates were not capable of pelleting virus alone, materials that bound virus allowed for analysis of viral titers from pellet and non-pelleted mix. Comparison of the fold titer changes between the mixed sample (virus-material slurry) to the pelleted samples allowed for a rapid understanding if the virus remained active after material interactions and additionally, the relative binding strength of the materials. As a control, VSV was also used to understand the selective material adsorption properties. Upon profiling various metal oxides, cellulose and others, we found that cerium oxide (CeO_2) was highly active in adsorption of both VSV and VSV-SARS2 pseudoviruses using this rapid screening assay (Figure below, B).

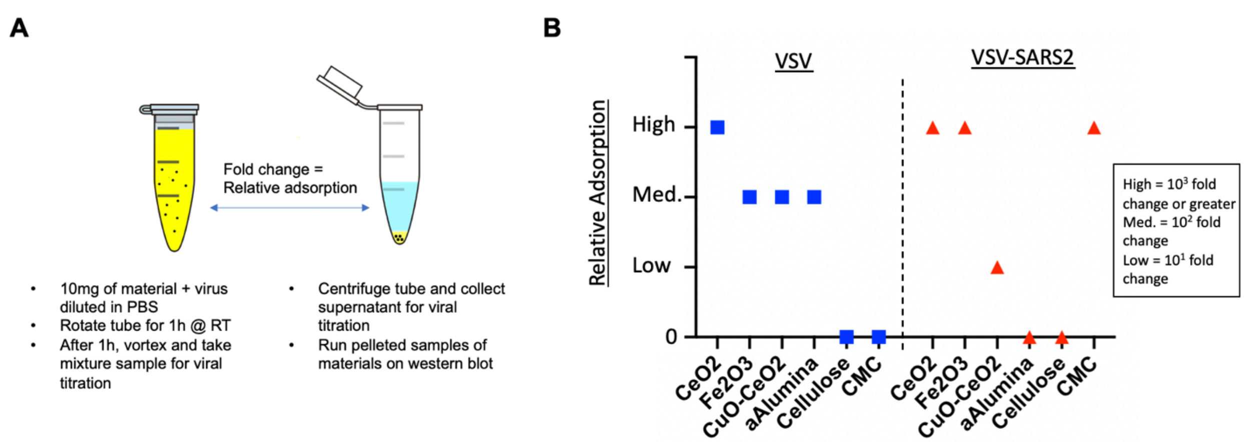

Figure Caption: A pseudovirus-based infection assay to profile material-virus interactions

To verify the strong binding properties of cerium oxide (CeO2) to both VSV and VSV-SARS2, we performed western blot analysis on the pellet samples from the profiling assay described the Figure below. The samples were blotted using either antibodies against VSV-G or spike protein of SARS-CoV-2 (SARS2-S) (Fig. 2). The results confirmed the strong binding properties of cerium oxide to the surface glycoproteins of these viruses and the lack of their binding to cellulose. However, for the other samples, the results from the screening assay compared the western blot differed for reasons that were not fully characterized. As cerium oxide bound these pseudoviruses with high affinity without inactivation, we set out to characterize time and concentration dependent adsorption to SARS-CoV-2 pseudoviruses.

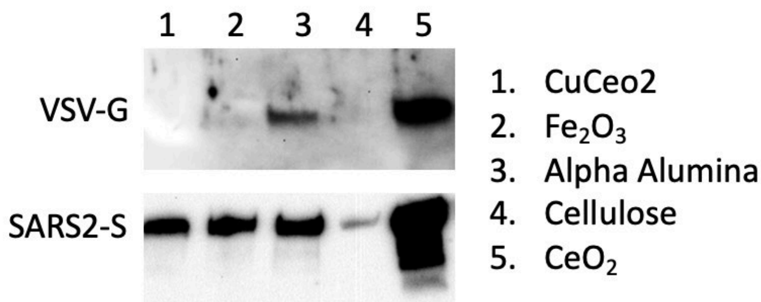

Figure Caption: Western blot analysis of material-virus interactions

We then determined that there was a concentration dependent adsorption of VSV-SARS2 to cerium oxide with 10mg serving as the highest-level binding per 10^7 pfu of virus (Figure below). Also, adsorption occurred quickly as it was measurable within 10mins of incubation with cerium oxide.Cerium oxide is a non-toxic and biocompatible material suitable for applications in virology. Although the full potential of CeO2 in technological applications remain to be understood, we have identified a novel material-virus interaction that can be further pursued in the future. Confirmation with live SARS-CoV-2 under BSL-3 containment will follow.

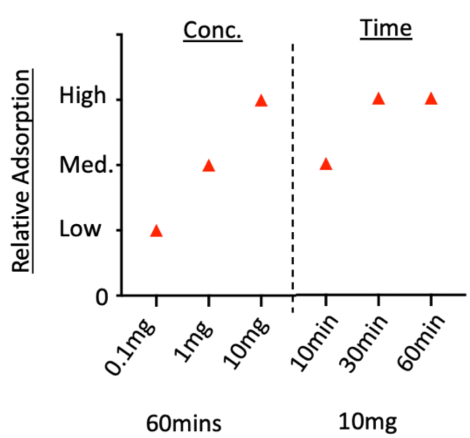

Figure Caption: Time and concentration depending binding properties for cerium oxide against VSV-SARS2

Imaging SARS CoV-2 on substrates with FIB/HRSEM – SLAC National Accelerator Laboratory

Goals:

- To identify procedures and guidelines for imaging small virions on surfaces by Scanning Electron Microscopy (SEM).
- Demonstrate the ability to image SARS-CoV-2 at room temperature with SEM.
- Demonstrate methods to cross section the virus and the viral surface interface with substrate materials.

Summary:

Because the size of SARS-CoV-2 virions are of the order of ~ 100 nm or less, imaging requires very high resolution only obtainable by electron microscopy, primarily by Transmission Electron Microscopy (TEM). TEM imaging of viral and cellular materials is limited to thin slices that are transparent to electrons. Little or no work has been done on imaging of virus on surfaces outside of an organism. Due to the dry nature of the viral interaction with dry substrates and the limited water content within the virus, rapid freeze and cryogenics may not be necessary. Room temperature SEM imaging has many advantages in ease of preparation and handling over cryo-EM. SEM observation of biological materials is attractive in ease of sample preparation, larger available area of view, and 3-dimensionality of view, as compared to TEM. When combined with a focused ion beam (FIB) in a dual beam system, one can cross-section very localized selected regions of material. By combined FIB slicing and SEM imaging, one can image 3-dimensional viral interactions with the substrate and adjacent virions in a cluster. Only recently has high resolution low voltage SEM become an available tool been applied to biological samples. SARS and many other viruses are typically much smaller (1-2 orders of magnitude) than biological cells and tissue and require much higher resolution. In this project, we examine SARS-CoV-2 on a variety of surfaces to develop procedures for understanding the virus outside of organisms and aid in the selection of surfaces to limit virus spread.

Shown in the figure below are micrographs of SARS-CoV-2 on different substrates. The substrate (a) and (b) was carbon membrane (C), (c) and (d) was copper (Cu) grid, (e) and (f) was aluminum (Al) stub, and (g) was gold (Au) grid. Comparing (a) and (b), we see more indications of merging of clusters of viral clusters in planar clusters on the C than a vertical cluster (b). The base of the virions on the Cu grid appeared to be spreading at the substrate and difficult to image. Fine particles of size 20 nm and below are seen over the substrate surface. The small particles on the substrate were particular to the Cu substrate. In the Figure below, the size of isolated virions on C and Al are ~ 60 nm, while the isolated virions on Cu and Au are > 100 nm.

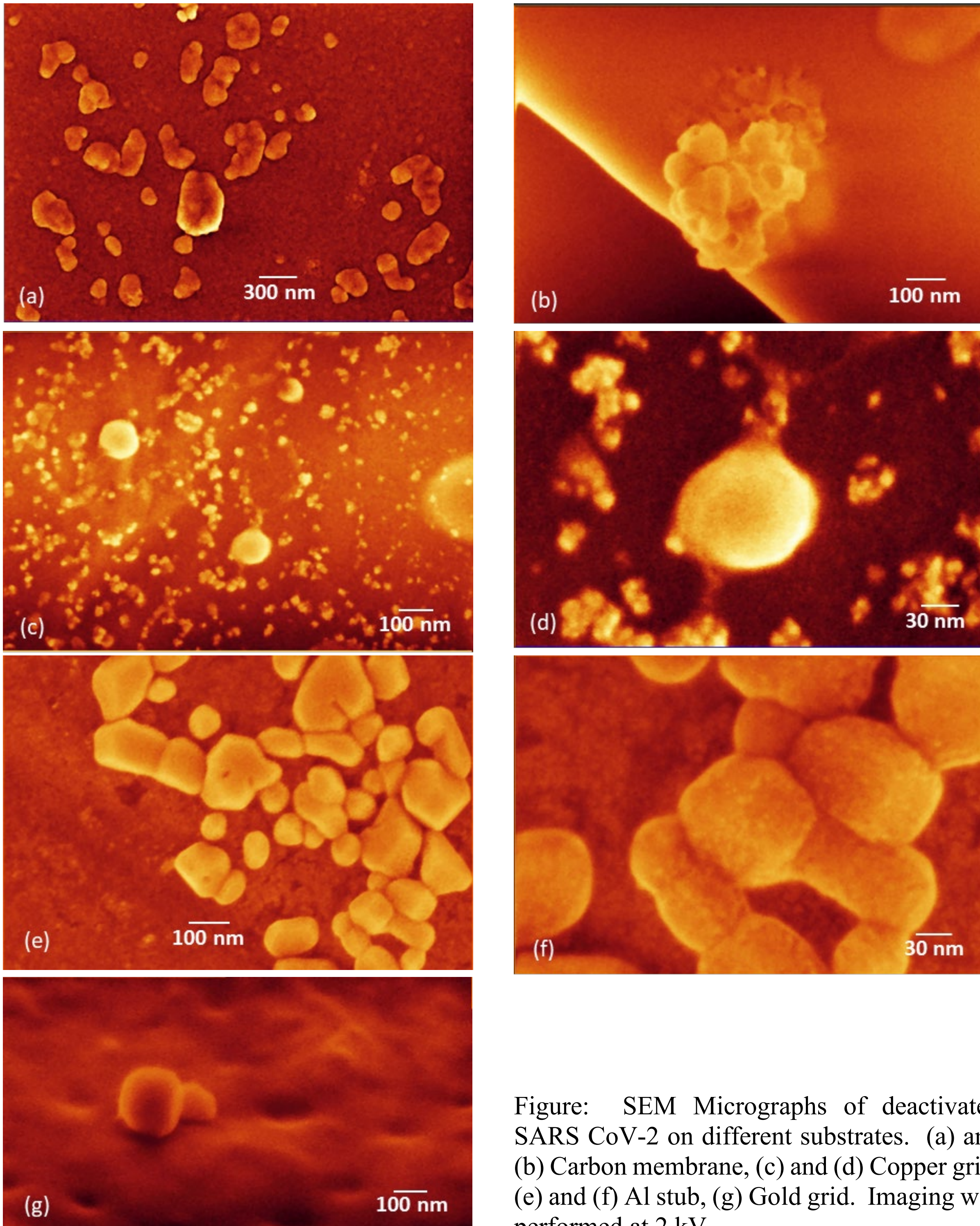

Figure: SEM Micrographs of deactivated SARS CoV-2 on different substrates. (a) and (b) Carbon membrane, (c) and (d) Copper grid, (e) and (f) Al stub, (g) Gold grid. Imaging was performed at 2 kV.

To investigation the internal structure of the virus, virus to virus interaction, and viral substrate interaction methods for cross sectioning the virus were developed. FIB cross-sectional methods are shown here. Samples were sputter coated with ~ 2 - 4 nm of platinum (Pt) in a sputter coater tool for conductivity and protection of the virus during FIB etching. It would have been desirable to deposit a thicker layer of Pt for protection but location of the virus became more difficult with increasing metal thickness. The figure below shows a cross section of a viral cluster coated with 2 nm of Pt and dropped on a silicone (Si) surface. One can see entire cluster of virions beneath a small bump on the surface. Virion sizes ranged from 100 nm to 500 nm, indicating virion merging at some points in viral storage or the sample processing. The p-RNA complexes became more apparent with e-beam scanning of the cross section, indicating some viral interaction with the e-beam. In the micrograph, none of the virions were observed to be in contact with the Si wafer surface. Dried carrier fluid occupied the 100 nm space directly in contact with the Si surface.

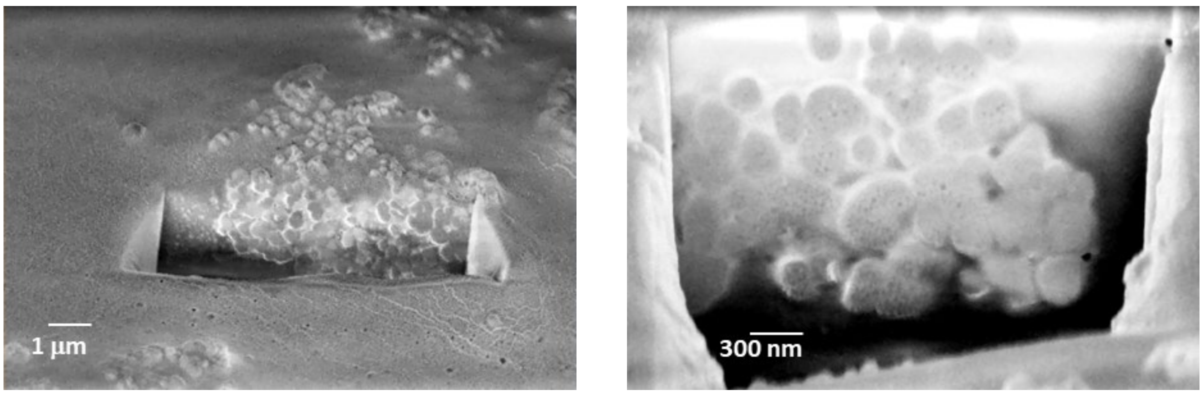

Figure Caption: FIB cross sections of SARS in solution dropped onto a Si wafer.

Towards correlative spatio-chemical imaging of SARS-CoV-2 Virus Like Particles (VLPs) bound to common surfaces – Oak Ridge National Laboratory

Goals:

- Investigate the morphological and chemical effects expressed by SARS CoV-2 when adsorbed onto common surfaces.
- Identify and characterize acceptable surrogates.
- Investigate interaction of surrogates with infrared radiation to understand limitation of spectroscopic characterization and their deactivation and thermo-optic effects on viruses.
- Contribute toward addressing the following question: can determination of the nanoscale physical and chemical properties of deposited virus-laden particles provide a viable methodology for understanding how COVID-19 spreads through contact transmission?

Summary:

When a virus approaches a surface, multiphysics interactions occur as the distance is reduced. Therefore, spectroscopic, and microscopic characterization of surfaces are required independently of the virus but under ambient conditions. Upon surrogate adsorption to a given material surface, the virus-surface properties may vary sufficiently to characterize attachment, detachment, and deactivation physics and chemistry for different materials. To establish a framework for optimizing surrogate preparation, chemical identification, and morpho-chemical analysis of viruses at high spatial and spectral resolutions using scanning probe microscopy and infrared spectroscopy, it is necessary to obtain baseline measurements. Therefore, we began by addressing the following details:

– Focused on three surrogate systems: Bacteriophage MS2, Escherichia coli C3000, and Bacillus thuringiensis subsp. israelensis (BGSCID 4Q7) spores
– Measured infrared micro-spectra of surrogates to guide nanoscale resolution chemical mapping
– Test measurements via AFM of e-coli, and spike proteins on Au substrates, XPS of test substrates
– Developed computational model to predict photothermal response of surface adsorbed VLPs

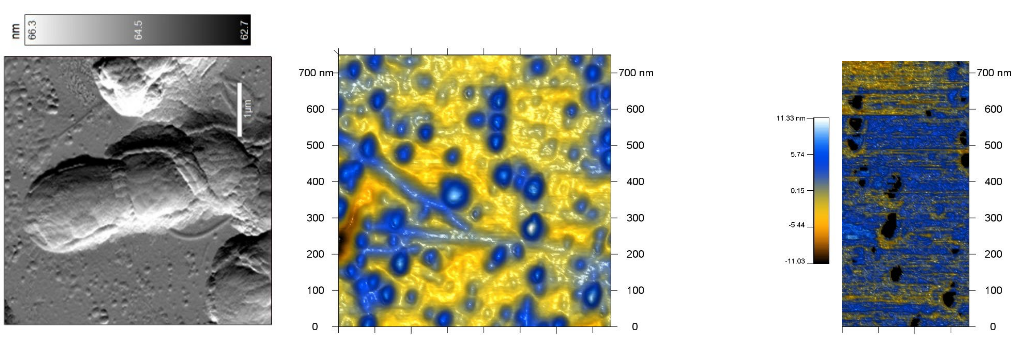

Figure Caption. Preliminary AFM of e-coli (left) and MS2 (middle and right) paving the way to improve sample preparation to isolate surrogates.

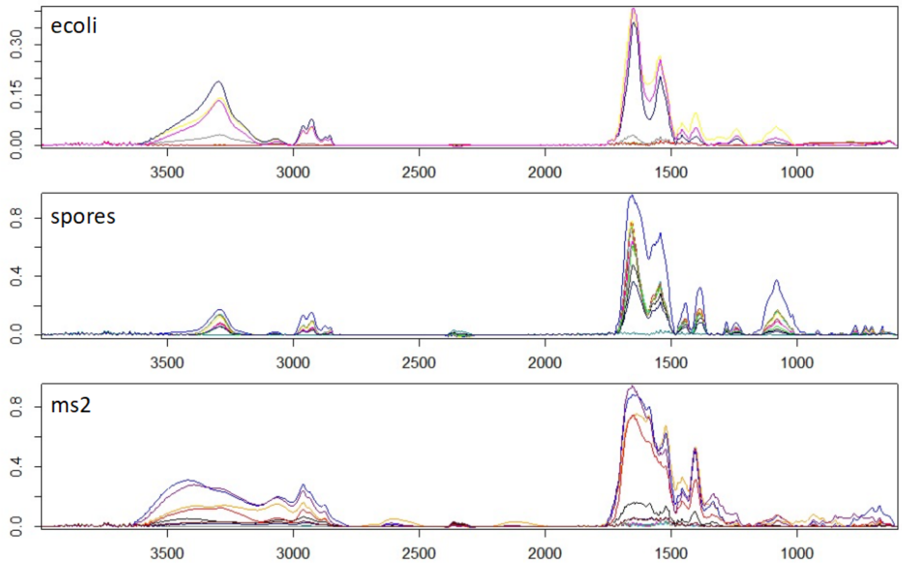

Figure Caption: Infrared spectra of surrogates to guide AFM-based nanospetcroscopy. Common spectral features likely receive contributions from the buffer.

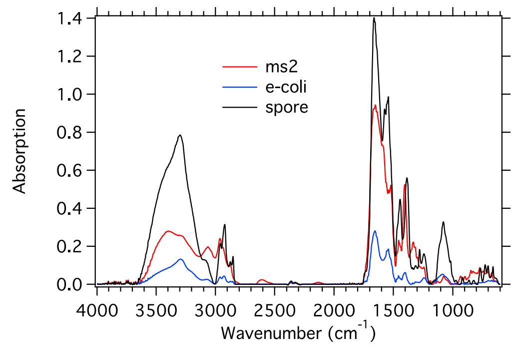

Figure Caption: Spectral comparison of the considered surrogates.

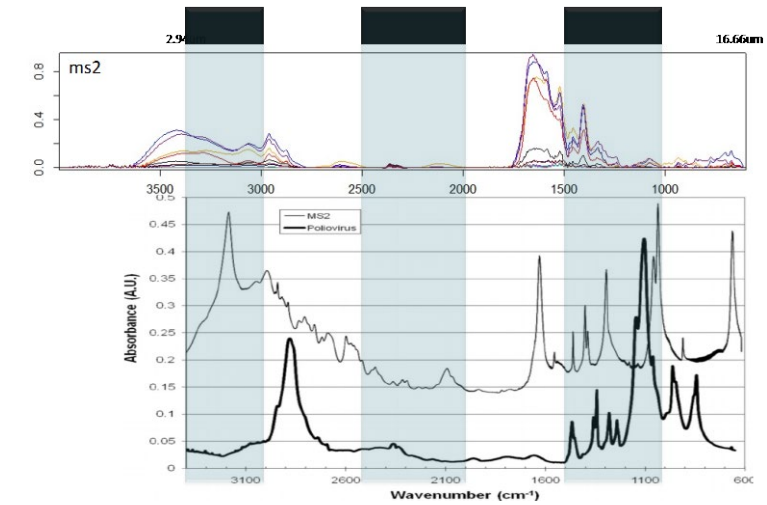

Figure Caption. Our measured spectral features in part agree with Vargas, et al. [Applied and Environmental Microbiology, 2009. 75(20)] though further work is needed to isolate the MS2 features from the buffer.

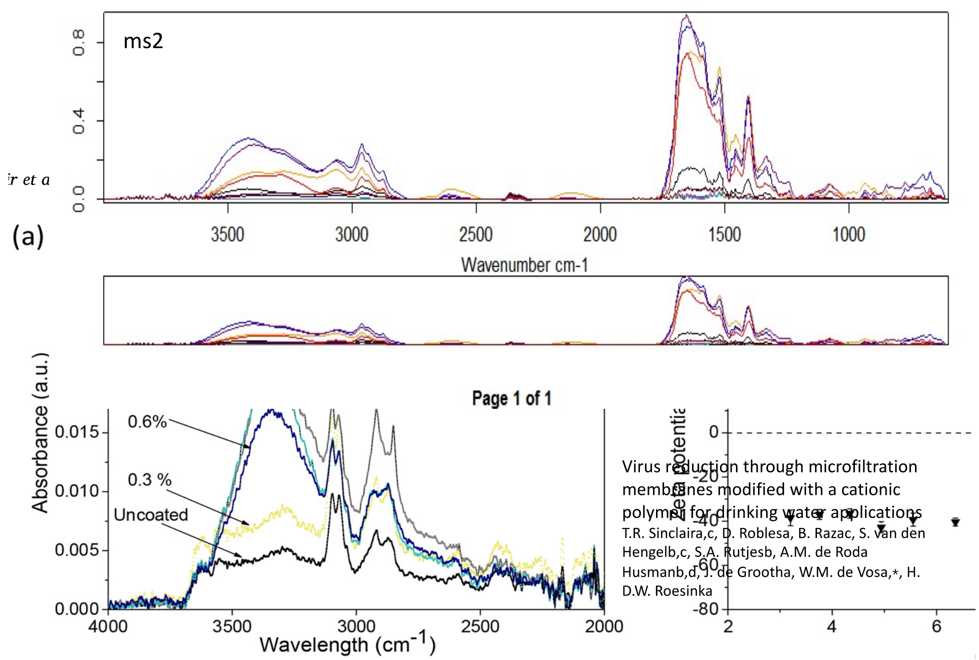

Figure Caption. Our measured NIR spectra (top) agree with spectrum reported by Sinclaira et al. (bottom).

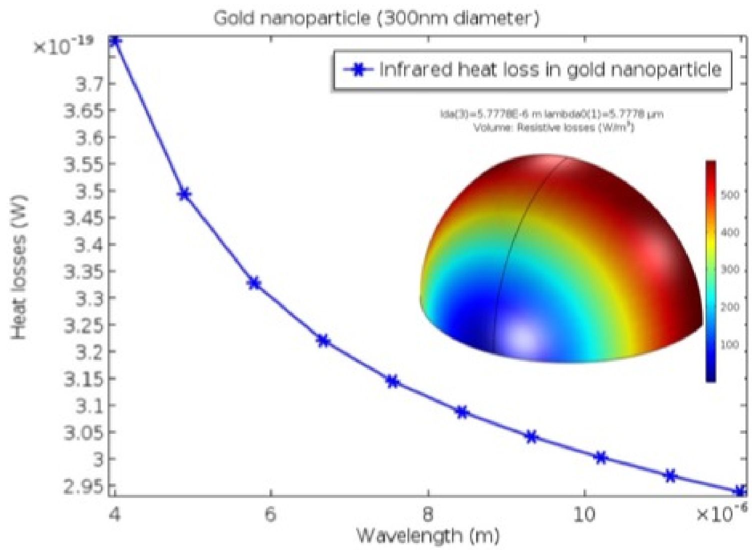

Figure Caption: Preliminary computational model developed to investigate virus photothermal effects due to infrared radiation of particle (shown) and planar substrates.

Task 3: Transport and Emergence of SARS-CoV-2 from Environmental Reservoirs that Contributes to Human Transmission of COVID-19

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Task 3: Transport and Emergence of SARS-CoV-2 from Environmental Reservoirs that Contributes to Human Transmission of COVID-19

INTRODUCTION

Viral agents are known to survive in water for varying periods of time. In standing pools, natural water with organic material, sewage, or wastewater with biosolids the viral species may persist. SARS-CoV-2 has been isolated from human feces, so fecal transmission may represent a significant form of environmental contamination, through aerosolized dispersions from wastewater treatment plants, septic system failure resulting in groundwater contamination, and sewer overflow triggered by extreme weather events. Characterization and quantification of SARS-CoV-2 present in wastewater may define or be an indicator for potential routes of transmission, may reveal previously unknown hot spots of transmission, and possibly new genotypes. Several reports of SARS-CoV-2 identification in wastewater streams have raised questions about the potential for enteric transmission of COVID-19, similar to what was observed during the 2003 outbreak of SARS, as reported by the World Health Organization. SARS-CoV-2 can enter groundwater through leaching of virus contaminated surface water or leaking of septic systems. Once in the groundwater, potential exists for contamination of wells and oral ingestion by humans or animals. Transport in groundwater will be contingent on virus-specific adsorption and inactivation rate, water chemistry, flow rate, and soil properties, including content and temperature, meaning that the potential for virus transport may change due to climatic shifts in future years. While SARS-CoV-2 has not yet been identified in groundwater, microbial contamination of water sources from wastewater have been documented, coronaviruses have been shown to survive several days in water sources, and wells in certain types of aquifers are more susceptible to enhanced virus transport.

OBJECTIVES

This research will establish the modeling framework to understand how results from monitoring of SARS-CoV-2 in US wastewater and surface waters conducted by others can help understand the spatial and temporal features of SARS-CoV2 community spread, and its use as a source tracking methodology regionally and nationwide. This task has the potential for cost-effective source tracking of community spread, including from asymptomatic and asymptomatic carriers, as hypothesized by others. This effort is distinct from the EPA wastewater virus monitoring and detection effort in that our study will perform no measurements for identification, infectivity, persistence or treatment efficacy; we only utilized data from their studies where available to parameterize the models.

Virus fate and transport monitoring and modeling in water and wastewater systems

This task develops a system for evaluating of SARS-CoV-2 presence in sewerage, wastewater and surface waters sources that will vary as a function of population infection loading and environmental factors. To establish fundamental proof of concept understanding of viral fate and transport in wastewater systems, we leverage current ongoing SARS-CoV-2 studies and associated data from CDC/EPA and other sources related to wastewater fate and transport measurements. We leverage the raw data available and our understanding of wastewater processing and chemistry, including real time virus data, to create unique theoretical models targeted to quantitatively determine SARS-CoV-2 load, its detection, transport behavior, and correlation to predicted clinical outcomes on the populace. We will be analyzing data from multiple data sets for generating models from several regional areas in the US. We will develop a hydraulic model of the sewer and wastewater system and use literature (initial) and historic data (chem/phys water analysis, flow rates, weather and water consumption data), to understand virus transport behavior, quantitative viral presence and resilience. The developed data-based modelling method will improve regional assessment of virus signal quantification, potential locations of virus transport, degrees of infection prevalence, and virus emergence and could be used for identifying potential spread scenarios and routes. The modeling tool developed in this deliverable will help understand virus transport in wastewater system, improve predictions, and identify potential spread scenarios and routes.

SARS-CoV-2 viability in groundwater and implications for the current outbreak and potential resurgence

The development of a refined groundwater and sub-surface transport model which can predict the movement of SARS-CoV-2 and the potential for spread of the viable virus is a key tool in understanding whether this vector of spread requires further examination both for the current pandemic and potential future pandemics. This task combines existing groundwater and sub-surface transport modeling to create a modeling framework to assess the potential for contamination of groundwater by SARS-CoV-2 as well as the potential for future resurgence of the virus. This research intends to identify existing relationships and data as well as the results of recent and upcoming studies regarding the factors contributing to the viability of SARS-CoV-2 to assess whether viable virus can exist and be sustained in groundwater. We utilized the existing subsurface transport model and refine it by incorporating new transport parameters from recent literatures to develop a subsurface virus transport model to simulate the virus transport behavior including virus loading, adsorption, inactivation rate, and travel time under various scenarios.

PROPOSED OUTCOMES

1. Understand the relationship among infection rates, environmental factors, water chemistry, wastewater plan processing, and genetic signal using artificial intelligence tool. Assess virus transport behavior in wastewater and sewage system using hydraulic modeling; improve infection prevalence quantification, hot spot identification, and early detection of reemergence using modeling tool coupled with bioinformatics.
2. Identify potential exposure scenarios and routes from wastewater and sewage as well as contributing factors for virus reduction using modeling tool and developed relationships contributing to virus transport.
3. Understand controlling factors for the viability of SARS-CoV-2 in groundwater; Relationships between the SARS-CoV-2 and environmental factors including sub-surface temperature, moisture and organic contents, water chemistry, and soil properties were developed to refine and improve the modeling framework. This work focused on those relationships that will affect virus loading, adsorption, and inactivation rate, which control the viability of SARC-CoV-2 while it migrates through groundwater system.
4. Using the refined model, analyses assessed the potential for sub-surface transport of SARS-CoV-2 in groundwater. We also assessed how predicted changes to the climate may impact future viral transport vectors. Specific scenarios identified were simulated to provide specific real-world examples of quantitative viability measures of virus in groundwater for urban and rural regions.

RESULTS: Topic 1

Virus fate and transport monitoring and modeling in water and wastewater systems

- The Small World Network Model for SARS-CoV-2 Wastewater Sewershed Fate and Transport
- The Extended Susceptible-Exposed-Infectious-Removed (SEIR) Small World Sewershed Model
- Genomic Sequencing of SARS-CoV-2 in Wastewater

Submitted and planned publications:

- Brigmon, R. L., Hamm, L. and Dichosa, A. “SARS-CoV-2 Wastewater Fate and Transport: A Model to Estimate Outbreaks and Infected Sewersheds.” Journal TBD
- Dichosa, A., Hamm, L. and Brigmon, R. L. “Methods for sampling-to-qPCR-to-sequencing and establishing a "genomic stamp" for multiple WWTP sites.” Journal TBD

The Small World Network Model for SARS-CoV-2 Wastewater Sewershed Fate and Transport

Goals:

- Attain data from several communities in the southeast (i.e., SC, GA, and VA). This data will provide specific information associated with viral history at their WWTFs along with other critical data (e.g., population demographics, potential super spreader events, etc.)
- Development Phase - Creation of a FORTRAN-based algorithm (i.e., a forward running working model). This model will stochastically predict disease spread coupled to a sewershed model to ultimately predict the viral content entering a WWTF.
- Benchmarking Phase – To assist in parameter calibration of this working model, a few (based on a down-selection process) of the WWTF specific databases will be employed in a benchmarking activity. Given the scarcity of data associated with certain key COVID-19 viral aspects, open literature information will supplement these databases.

Summary:

Based on the most recent successes within the open literature associated with disease spreading dynamics of SARS-CoV2 within communities, a "Small World" approximation method has been chosen to address the viral source term entering into a specific sewershed system's wastewater treatment facility (WWTF). This Small World approximation employs a regular undirected weighted nodal network to represent individuals within its domain where the more traditional stochastic epidemic algorithms are utilized. This approach is ideal for addressing a viral source term that is supplying fecal material to a local specific WWTF of a small community.

Our small world network approximation conforms to the basic graph theory geometric restrictions. Both the fate and transport model and the stochastic network epidemic source term model have been introduced. Both models rely on a geometric nodal network scheme. In this section the two models are coupled on a common nodal network layout. Generally, the term "a small world network" implies a closed system which in our case represents a fixed population size. An overview of the two models being overlaid onto one nodal network diagram is shown in the figure below.

For the viral source term perspective, at each of the vertices a single individual person resides (typically at their residence or at a hospital). Transmission events are the key processes that are assumed to occur by a Markovian process where:

- **Short range** – household members that interact on a high frequency. The number of household members is an inputted number that is fixed during a given set of runs.
- **Long range** – daily acquaintances that occur on a lower frequency (e.g., workplace or shopping). The average number of daily acquaintances is an inputted number that can be fixed during a given set of runs or varied.

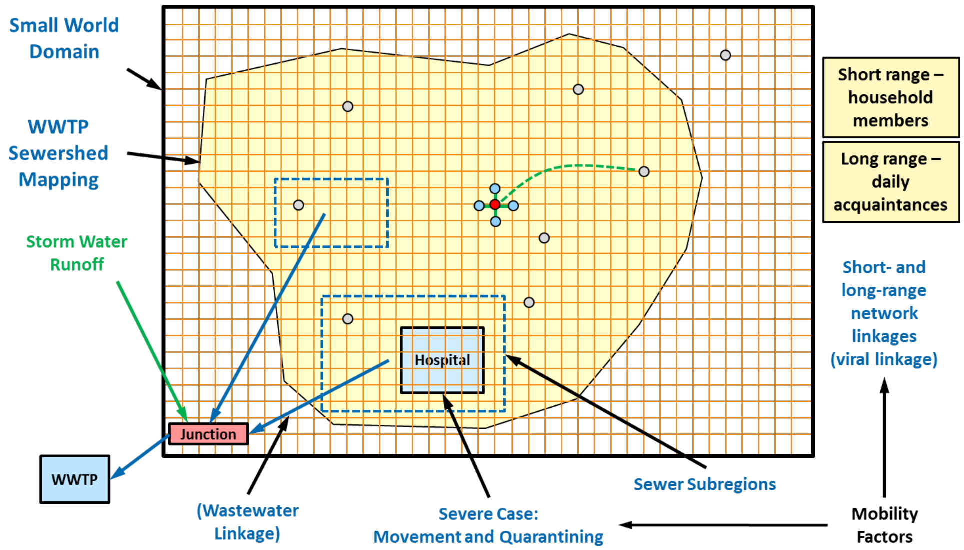

Figure Caption: “Small World” network grid overlaid onto a sewer system.

Individuals who reside within this small world domain can in principle come into contact with any other individual with this domain. These potential contacts occur based on the long-range daily acquaintance’s linkages. However, fecal material associated with any given individual is limited to occur only at that person’s household location. The transport timing associated with each node location is related to its physical distance from the entrance point for its WWTF and its average tortuosity factor. Travel times are generally only approximation where the highly time dependent volumetric flow rates are time-averaged and transport velocities are assumed based on systems design guidelines (e.g., 1-3 ft/hr phasic water velocities in open channel flow conditions). For the two-sewer example the following travel time variations are shown in the figure below. Based on an average water consumption of ~100 gal of water daily (US-EPA estimate) 10,000 people within a single sewer system would be sending ~1 MGD to a WWTF. Thus, travel times are related to population density and sewershed footprint size.

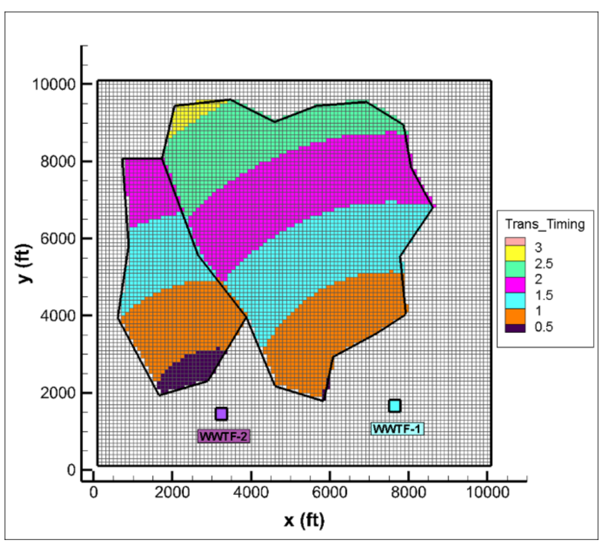

Figure Caption: An example of a Small World nodal network illustrating travel time variations associated with 2 sewersheds.

The Extended Susceptible-Exposed-Infectious-Removed (SEIR) Small World Sewershed Model

Goals:

- Integration of Susceptible-Exposed-Infectious-Removed (SEIR) epidemic model overlay with Small World sewershed fate and transport model
- To model outbreak dynamics from a sewershed exposure event and estimate the numbers of infected individuals based on wastewater RNA concentrations.

Summary:

To accomplish the goals provided above, a “Small World” approximation approach was selected where the viral source term is based on a stochastic based (i.e. Markovian processes) extended SEIR model. This viral source term model is applied on a nodal network that defines the Small World and is coupled to a simplified viral transport equation that also in overlaid upon the same nodal network. During each realization a Markovian process is model where randomly chosen seeds locations start the process and the subsequent randomly selected SEIR parameter settings progress over time. Multiple realizations are then run in a Monte Carlo fashion until convergence of key measures of merit are achieved. For the conditions specified, the following series of plots illustrate the source term model’s behavior for a single realization (i.e., the first one). Each rectangle shown represents a specific individual and has been colored coded as shown in the legends (i.e., class/status of individuals being either [S], [E], [I], or [R]). The specific extended SEIR model employed is where no distinction is made between symptomatic and asymptomatic individuals.

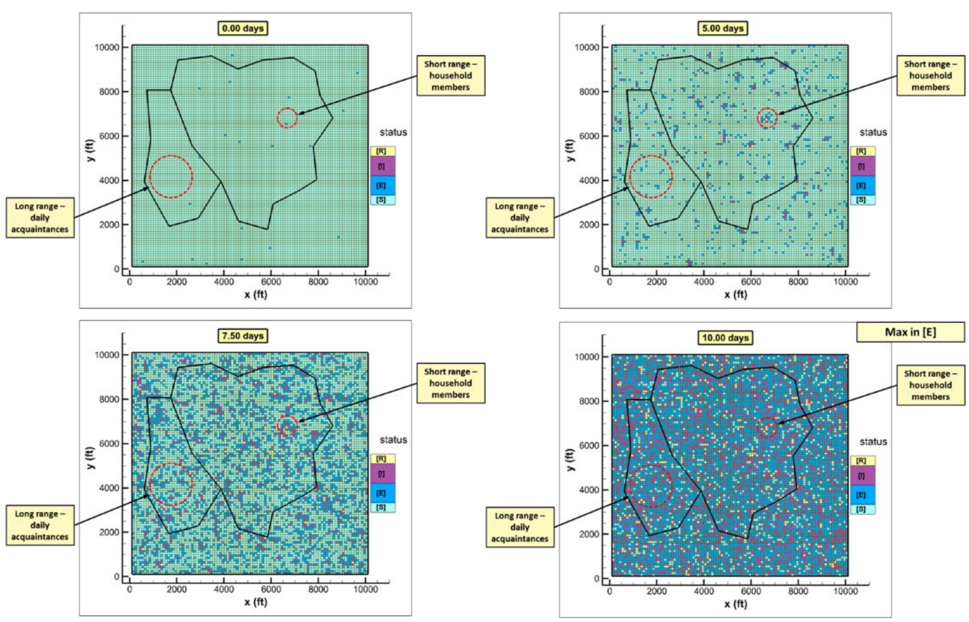

Figure Caption: Extended-SEIR status on the nodal network, time = 0 days (top left), 5 days (top right), 7.5 days (bottom left) or 10 days (bottom right).

At time zero (0 d), two observation regions are highlighted by dashed-red circles. One watches to see how household contacts behave (one on the right), while the other one watches to see how long-range contacts behave (one on the left). Prior to time zero, all individuals are set to [S]. As can be seen in the figure, one initial [E] seed in placed within the right one, while no [E] seeds are placed in the left one. After 5 days have past, multiple household contacts have generated local pockets of activity, while long-range contacts have distributed activity throughout the small world. Infectious individuals are showing up in both sewersheds, as well as in the surrounding areas. By 7.5 days a significant number of exposed [E] and infectious [I} individuals are seen. At day 10, a maximum level of totally exposed [E] individuals is reached where their distribution is pretty uniform over the entire small world domain. As the above example clearly illustrates, even for a single realization a very dynamic process of evolution occurs. To reach a converging stochastic-based response many realizations have to be executed (numbers in the 1,000s in many cases).

Genomic Sequencing of SARS-CoV-2 in Wastewater

Goals:

- To assess the feasibility of using the wastewater microbiome as an indicator of community-wide SARS-CoV-2 surveillance
- To establish SARS-CoV-2 genomic variation's association with mortality rate of COVID-19 and correlation with WWTF genomic analysis.

Summary:

Since the start of the pandemic, public health officials, researchers, and epidemiologists have turned to sewage systems across the country (and the globe) to strategically detect the presence and gauge the prevalence of SARS-CoV-2 RNA signatures. Sampling at specific effluent sewage sites equates to testing up to thousands of potential human shedders at one time. Thus, SARS-CoV-2 viral loads can be compared from one community to another to "triage" which populations need critical resources more than others. While SARS-CoV-2 detection methods have principally relied on molecular amplification of partial viral genomes (e.g., N1 and N2 markers) via qPCR, one significant drawback of this method is the loss of whole genomic information that can identify genomic mutations and critical variants. Genomic variations from the original (wild type) Wuhan strain have been proposed to either increase virulence and/or decrease vaccine efficacy. Therefore, it is vital to concurrently detect / quantify SARS-CoV-2 in the population and identify key genomic variations that may lead to phenotypic alterations.

For the goal of sequencing SARS-CoV-2 genomes from wastewater, our VFT-WW team collaborated with Drs. Raul Gonzalez and Jim Pletl from Hampton Roads Sanitation District (HRSD) in Virginia. HRSD has been performing molecular based / qPCR wastewater monitoring for human respiratory diseases for several years. Our discussions with HRSD targeted nine wastewater facilities from which HRSD extracts DNA/RNA to perform their state dashboard reporting of COVID-19 cases. Upon completion of the sequencing efforts, HRSD would send the data to LANL to perform genomic analysis and mapping of the reads to the SARS-CoV-2 Wuhan genome reference strain (NC045512.2) using EDGE Bioinformatics platform (https://edgebioinformatics.org/).

Using the Wuhan strain as the reference to map Illumina reads sequenced, none of the individual data sets completed a SARS-CoV-2 genome, as each sample uniquely covered varied regions of the genome. By looking at which areas of the reference genome had representation, it appears that there is no amplification or sequencing bias involved. Rather, targeted amplification across the genome during the library preparation step was random. This could be the result of several events, either alone or in combination: (1) the [dominant] SARS-CoV-2 genome in the extract may have been degraded; (2) there may be inhibitory compounds present in the extract that limited the amplification efficiency during library preparation; (3) insufficient amount of high quality SARS-CoV-2 RNA template; and (4) low quality products were derived during the library preparation.

From the data sets derived from all the WW sites, we surmised that if the collective data were combined, a significantly greater coverage of the SARS-CoV-2 genome would be achieved, albeit short of a complete genome. Another assumption is that, if "assembled", the collective data would reveal no strain variant of the reference Wuhan strain. To address this, we used five data sets that, individually, gave the most coverage of the reference genome: York River (YR), Williamsburg (WB), Atlantic Beach (AT), and unassigned reads (P1 and P2) that possessed sequence data, but were not identified via demultiplexing based on the assigned barcodes. This collective analysis did greatly improve genome coverage to nearly 60%, but still fell short of a complete mapped genome with no detection of SNPs, see figure below. Our analyses of each of these sites strongly suggests that much more effort on the wet lab operations must be improved.

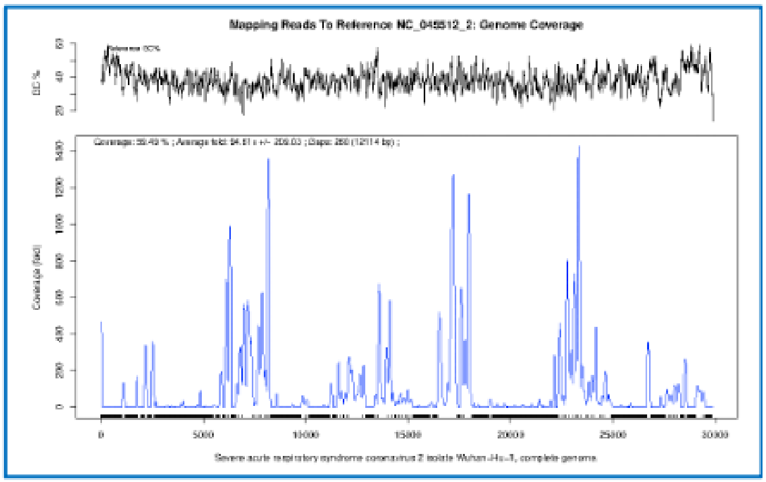

Figure Caption: Combining Reads from Select Data Sets. We utilized data sets with the most resultant, individual coverage. These sites are York River (YR), Williamsburg (WB), Atlantic Beach (AT), and unassigned reads (P1 and P2). Although this improved genome coverage to 59.5%, again, a complete genome was not obtained.

RESULTS: Topic 2

SARS-CoV-2 viability in groundwater and implications for the current outbreak and potential resurgence

- Effects of Virus Load, Filtration, Inactivation, and Dilution on Virus Transport
- Effects of Hydrogeologic Factors (Permeability, Hydraulic Gradient, Depth to Unconfined Aquifer, and Fractures)
- Effects of Inactivation Rate and Attachment
- Results of Stochastic Modeling and Effects of Uncertainty of Attachment Rate
- Assessment of the Worst-Case Scenarios

Submitted and planned publications:

- Saavedra Cifuentes, E., R.T. Mills, R. Nichols, H. E. Torres, Brian Viner, E. Yan, A. Packman. "Assessing the transport of SARS-CoV-2 in groundwater." *Water Research*, submitted.
- Saavedra Cifuentes, E., R.T. Mills, R. Nichols, H. E. Torres, Brian Viner, E. Yan, A. Packman. "Evaluation of controlling factors for virus transport in groundwater." Journal TBD
- Saavedra Cifuentes, E., R.T. Mills, R. Nichols, H. E. Torres, Brian Viner, E. Yan, A. Packman. "The impact of CSO flow events on virus transport in surface water." Journal TBD

Effects of Virus Load, Filtration, Inactivation, and Dilution on Virus Transport

Goals:

- To provide a current understanding of the factors influencing transport of SARS-CoV-2 through groundwater.

Summary:

A new module named "BIOPARTICLE" was developed for PFLOWTRAN to simulate virus transport. The conceptual model used for the development of BIOPARTICLE is shown in Figure 23 and include virus activation and particle filtration. The combined effects of dilution, inactivation, and filtration on SARS-CoV-2 breakthrough are presented in the figure below. Since filtration and inactivation are both modeled as first-order reactions, they have a similar effect on the relationship between SARS-CoV-2 breakthrough and travel time: longer travel times result in greater removal of infectious viruses. The attachment rate was quantified in our experiments using an intermediate value for the collision efficiency = 0.01. Consequently, accounting for filtration resulted in a minimum log-removal that was 0:5 higher than when considering only virus inactivation. While this minimum occurs at a slightly higher water table gradient (I ~1 x 10-2), a wide range of I (5 x 10-3< I < 5 x 10-2) still yields a SARS-CoV-2 removal that is less than 4 log-reductions.

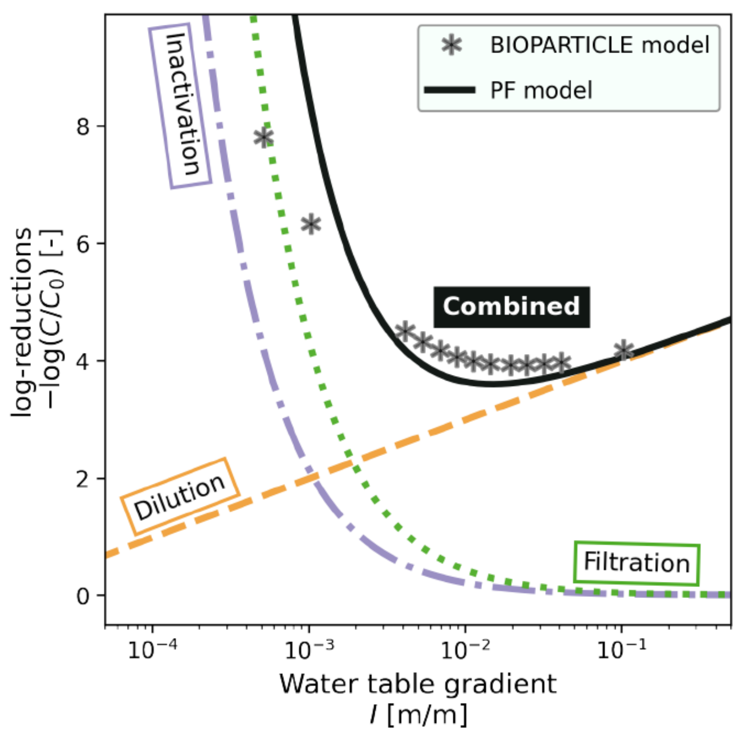

Figure Caption: Reduction in SARS-CoV-2 concentration between source and receptor due to the combination of filtration, dilution, and inactivation predicted by PF and BIOPARTICLE model simulations. Results are shown for the effect of filtration only, dilution only, inactivation only, and the combined effect of all three processes.

Effects of Hydrogeologic Factors (Permeability, Hydraulic Gradient, Depth to Unconfined Aquifer, and Fractures)

Goals:

- To provide a current understanding of the factors influencing transport of SARS-CoV-2 through groundwater.
- To provide estimates for virus concentrations at drinking water wells in unconfined alluvial aquifers and identify the conditions leading to potentially concerning scenarios.

Summary:

A finite-volume numerical model was utilized to solve the governing equations for non-conservative transport in three-dimensional, variably saturated porous media, as an attempt to investigate the effects of hydrogeologic conditions on virus transport. In order to identify the impact of hydrogeologic factors on the virus concentration at the domestic well, and the combinations leading to potentially concerning scenarios, 54 scenarios or model variations were defined. These scenarios were built considering variations in three main hydrogeologic factors: 1) The permeability of the aquifer, 2) the hydraulic gradient and 3) the thickness of the unsaturated zone. Six different permeability values were tested, with three representing homogenous gravel, coarse sand and fine sand aquifers, and three representing heterogeneity and preferential flowpaths within the aquifer through fractures. To model flow through the unsaturated zone relative permeability and saturation functions had to be associated with each soil material.

The models representing gravel aquifers were found to achieve lower virus reductions below the threshold value among all the tested aquifer materials (gravel, coarse and fine sands). However, the least log10 reductions observed in the gravel models were achieved under the lower hydraulic gradient (1 x 10-4 m/m) consistently, regardless of the thickness of the unsaturated zone (as shown in the figure below A). This result supports that the combination of high permeability and high hydraulic gradient actually allows for more dilution of the virus, resulting in increasing virus reduction with faster flow systems, given that the leakage rate is constant. In contrast, for a less permeable aquifer materials (e.g. coarse sand), the less virus reduction is achieved with the higher hydraulic gradient. This suggests that increasing the flow velocity (combination of the permeability and hydraulic gradient) in the system raises the virus concentration at the receptor up to an inflection point (as shown in the previous section) controlled by the leakage rate, and after which increasing the flow velocity only leads to greater dilution and lower viral loads.

Fine sand models were found unable to achieve potentially concerning concentrations at the domestic well for t = 102 days, even under fully saturated conditions with the higher gradient value (figure below A). Since these experiments represent the slower flow systems and would be affected the most by the virus removal processes, fine sand models were not investigated for further analyses under inactivation and filtration scenarios. Increasing the thickness of the unsaturated zone was found to consistently lead to greater virus log10 reductions at the receptor, with a more significant impact on lower permeabilities since these more effectively reduce the virus leakage into the vadose zone and enhance dilution.

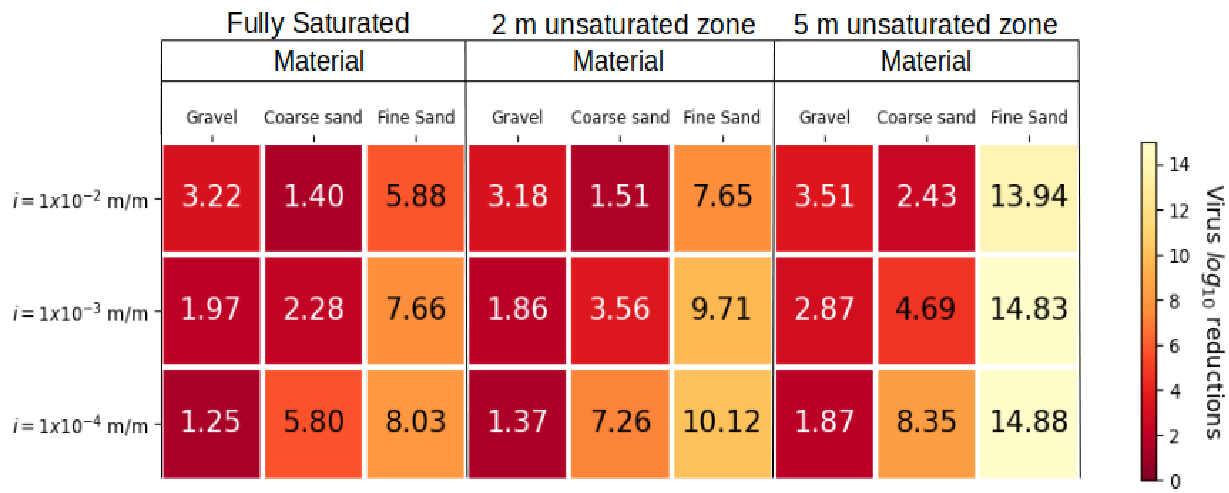

Figure A: Virus relative concentrations and $\log_{10}$ reductions at the domestic well for the models with homogenous media. Potentially vulnerable scenarios are indicated with a white font.

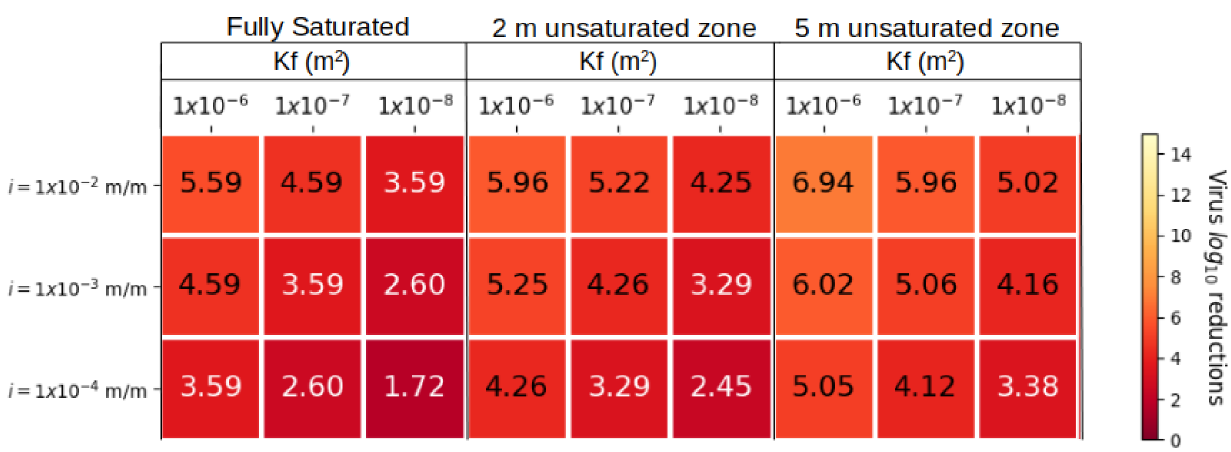

Figure B: Virus relative concentrations and $\log_{10}$ reductions at the domestic well for the models with heterogeneous media. Potentially vulnerable scenarios are indicated with a white font.

In comparison with the homogenous media models, the models with multiple continuum to represent heterogeneity due to fractures in the aquifer had permeability values equal or higher than the permeability chosen for gravel models. Therefore, dilution was more significant for these scenarios, leading to most of the potentially concerning scenarios and those with the least virus log10 reductions being found with the lower fracture permeability value (kf) of 1 x 10-8 m/d (Figure above B). Additionally, a model with this permeability value was able to achieve virus log10 reductions below the threshold value even with an unsaturated zone thickness of 5 m in combination with the lower gradient value. Overall, Figure B shows how greater permeabilities due to preferential flow paths in aquifers do not necessarily result in less virus log10 reductions at potential receptors, supporting the previous observations on permeability, gradient and unsaturated zone thickness as controlling factors for dilution.

Effects of Inactivation Rate and Attachment

Goals:

- To provide a current understanding of the factors influencing transport of SARS-CoV-2 through groundwater.
- To provide estimates for virus concentrations at drinking water wells in unconfined alluvial aquifers considering inactivation rate and attachment, and identify the conditions leading to potentially concerning scenarios.

Summary:

Two inactivation rates were simulated for the modeling systems that were identified as being vulnerable based on the combination of the permeability, hydraulic gradients, depth to the unconfined aquifer. Attachment occurring in combination with inactivation decay represents more realistic conditions for virus transport in groundwater. Therefore, several experiments were simulated considering the combination of the two inactivation decay rates with two different attachment rates intending to represent a range of possible conditions. For cold climate regions with a decay rate of 3.23 x 10-6 s-1, the lower bound attachment rate (9 x 10-7 s-1) increased the virus log10 reductions for the coarse sand model above the threshold value, while not as significantly impacting the rest of the potentially concerning scenarios (Figure below). The higher bound attachment rate (9 x 10-5 s-1) successfully mitigated all concerning scenarios except for gravel under fully saturated conditions with a gradient of 1 x 10-2 m/m. This combination of hydrogeological conditions seems to be concerning even for warmer climate regions, where the higher decay rate was found to be insufficient to achieve four or more virus log10 reductions (Figure below). Out of the homogenous media models, those representing gravel aquifers were the only ones considered as potentially concerning when accounting for both attachment and decay, with the worst-case scenario being under fully saturated conditions and with a gradient of 1 x 10-3 m/m. However, gravel aquifers with the middle and high gradient were able to achieve less than four virus log10 reductions even with a 2 m unsaturated zone.

Figure Caption: Virus relative concentrations at the domestic well for the models with homogenous media, after the addition of the decay and attachment rates. Potentially concerning scenarios are indicated with a white font.

Shorter travel times to the receptor could minimize the possible attenuation due to removal processes through attachment or inactivation. Therefore, several experiments were simulated to evaluate effects of attachment and inactivation on virus reduction. The low attachment rate (9 x 10-7 s-1) was found to be unable to significantly affect virus removal in any of the potentially concerning scenarios, despite the climate condition governing decay (Figure below). Contrarily, the higher bound attachment rate (9 x 10-5 s-1) was able to significantly reduce virus concentration for all the potentially concerning scenarios with a 2-m depth to unconfined aquifer, and the scenarios with the combination of the low fracture permeability and the low gradient of 1 x 10-4 m/m in the fully saturated setting (Figure below). In summation, the difference between the decay rates controlled by the groundwater temperatures is too small to result in significant differences of virus inactivation for fractured aquifers in warm and cold climate regions. Additionally, attachment could be the more important removal process for these systems, considering that the attachment rates evaluated in these experiments might not be the highest we can estimate from the range of Darcy velocities analyzed for these systems, according to colloid filtration theory. With the lower bound attachment rate, the hydrogeological conditions that lead to the worst-case scenario were found to be the lower fracture permeability value of 1 x 10-8 m/d with the lower gradient (1 x 10-4 m/m) under fully saturated conditions.

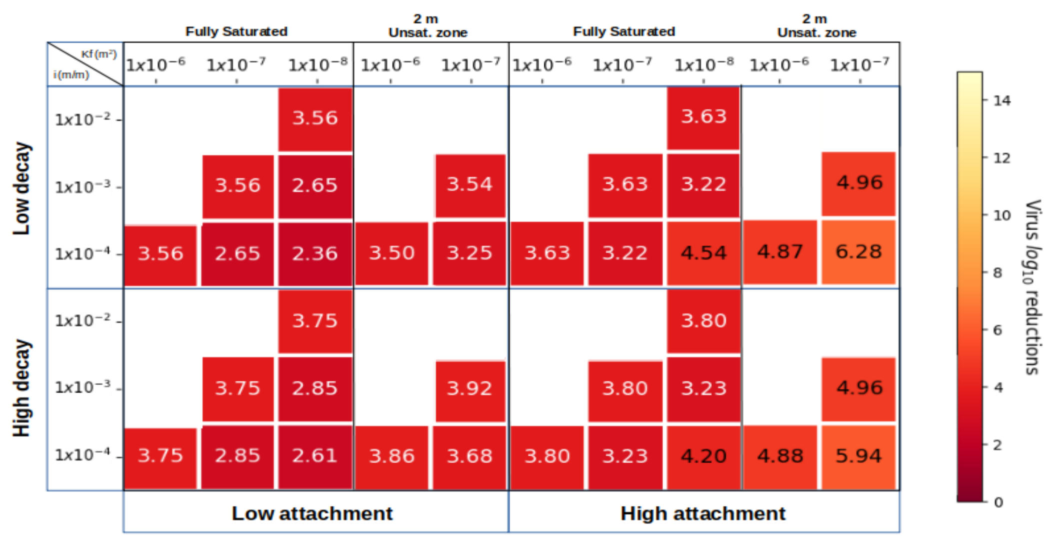

Figure Caption: Virus relative concentrations at the domestic well for the models with heterogeneous media, after the addition of the inactivation decay and attachment rates. Potentially concerning scenarios are indicated with a white font.

Results of Stochastic Modeling and Effects of Uncertainty of Attachment Rate

Goals:

- To provide a current understanding of the factors influencing transport of SARS-CoV-2 through groundwater.
- To evaluate the sources of uncertainty in the model caused by variations of the physical properties of the aquifer.

Summary:

On the basis of the colloid filtration theory, the attachment rates are controlled by both physical and chemical properties of the aquifer, groundwater, and virus. In this analysis, the physical properties that affect filtration (e.g. the porosity and grain size) are quantitatively linked to the permeability and/or flow velocity to capture the uncertainty caused by the variations of the physical properties of the aquifer. The variation of the chemical properties (i.e. the isoelectric point of the virus and pH of the groundwater controlling the charges of the virus and soil particles) is captured by the attachment efficiency (αatt), and was allowed to take any value between 0 and 1. The impact of the permeability and attachment efficiency on the attachment rate is shown in the Figure below.

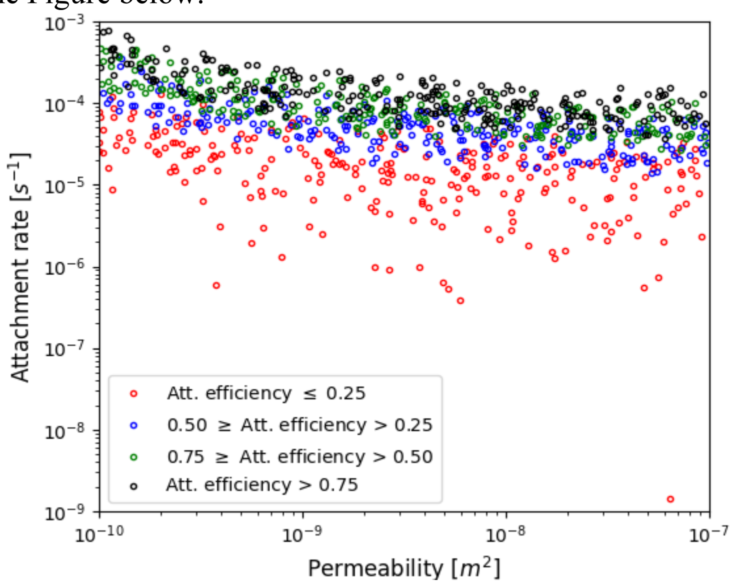

Figure Caption: Effects of a possible range of attachment efficiencies and permeabilities on attachment rate

A slightly decreasing trend in the attachment rates is observed as the permeability (tied to the porosity and grain size) increases, indicating that the effect of the permeability on the attachment rate is minimal less than one order of magnitude). Great variability in the attachment rates was observed due to the uncertainty of the attachment efficiency, especially for the group with attachment efficiencies equal or less than 0.25.

Another significant source of the variability is the hydraulic gradient, which was also randomly sampled and affects the attachment rate by increasing or decreasing the Darcy velocity of the system. To evaluate the impact of the hydraulic gradient variability, the log10 reductions derived from the 1000 ensembles were analyzed against the flow velocity, calculated from the permeability, porosity and hydraulic gradient for each of ensembles. The figure below shows that the uncertainty associated with the chemical properties of the virus and transport media has significant effects on virus reduction in slower flow systems. For a similar flow system at or less than 10-4 m/s, the differences greater than 10 log10 reductions were observed over the possible range of attachment efficiencies. Contrarily, for flow velocities above 2 x 10-3 m/s, the drastic changes in the attachment efficiency result in very small differences in terms of the log10 reductions. This suggests that the uncertainty associated with the attachment rate is not as significant for fast flow systems, as it was also observed for the inactivation decay rate. Overall, the virus reductions were found to decrease as the flow velocity increased and the number of potentially concerning scenarios significantly increased with flow velocities between 1 x 10-3 and 1 x 10-2 m/s, supporting that the certain hydrogeological conditions have minimal virus removal.

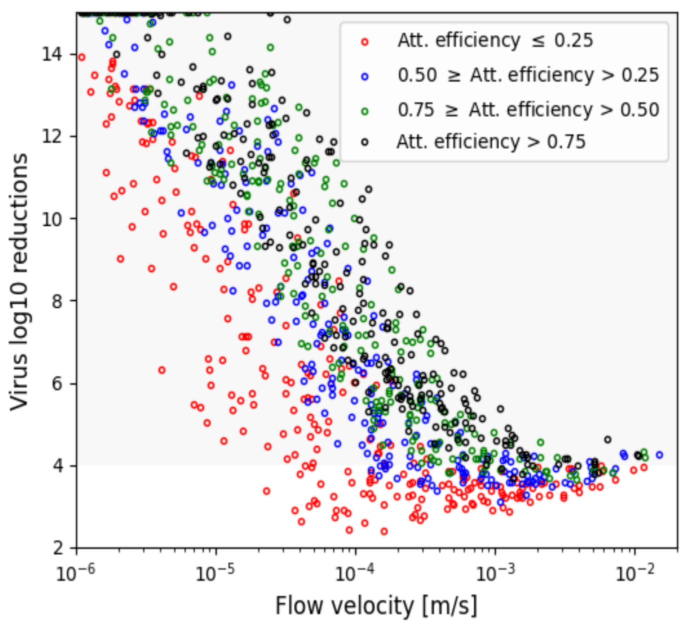

Figure Caption: Effects of a possible range of attachment efficiencies and flow velocities on virus reduction.

Assessment of the Worst-Case Scenarios

Goals:

- To assess the impact of setback difference on virus removal needed to achieve acceptable risk of transmission based on the worst-case scenarios for virus transport identified in the previous sections.

Summary:

Given that gravel under fully saturated conditions was found to achieve the least virus log10 reductions at the receptor, this combination of hydrogeological conditions was selected as the worst-case scenario to evaluate the impact of additional considerations on virus reduction. Similarly, the worst-case scenarios for evaluation used the low decay rate value of 3.23 x 10-6 s-1 for cold climate regions, as it represents lower virus attenuation and results in more concerning scenarios. Four additional gradients, for a total of seven, were applied to the models constructed for the worst-case scenarios, and the virus log10 reductions achieved after 30 days of pumping and constant leakage are presented in the figure below.

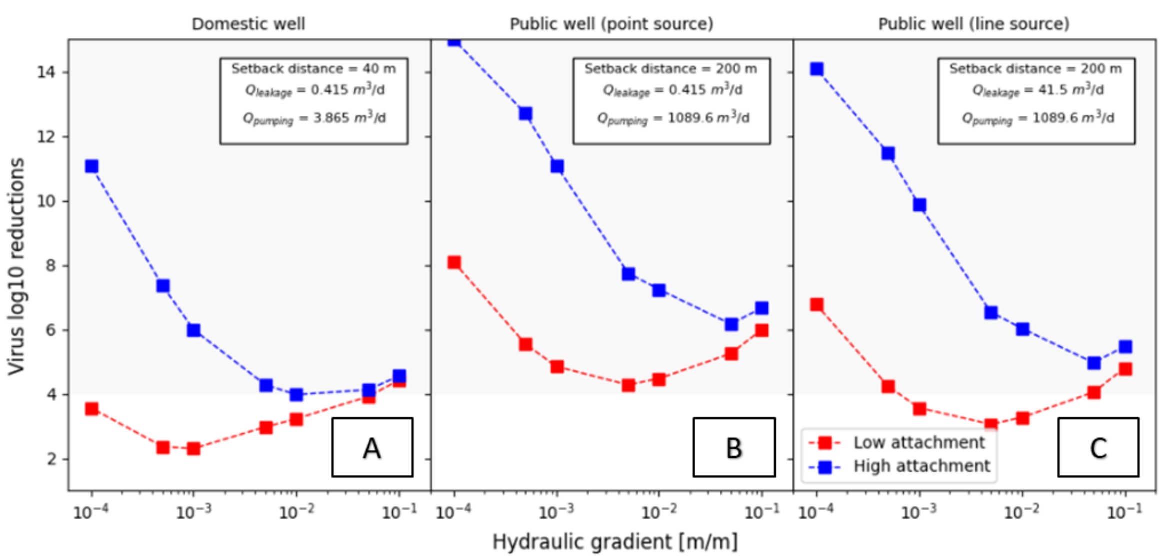

Figure Caption: Comparison of the worst-case scenario under the following configurations: (A) domestic well, (B) public well with a point leakage source, and (C) public well with a line leakage source.

Focusing on the worst-case scenario assumed for the domestic well setting, Figure 34A shows how the least virus log10 reductions are found at different hydraulic gradients depending on the attachment rate. Gradients greater than the inflection point result in greater attenuation due to dilution, while gradients lower than the inflection point result in greater virus removal. The virus reduction reaches the lowest at the inflection point. However, the inflection point in the high virus attachment environment occurs at the higher hydraulic gradient conditions (10-1 to 10-2), while the inflection point in the low attachment environment shifted to the lower hydraulic gradient conditions (10-3).

In comparison with the public well setting with point source leakage (Figure B), a greater setback distance results in significant virus removal even at high gradients. The virus reduction above the threshold of 4 log10 suggests that the worst-case scenarios would not be concerns for both low and high virus attachment environment. Combined with a greater pumping rate, the virus reductions observed were expectedly higher, since increased pumping leads to more dilution considering that the leakage rate is the same.

To assess the impact of the ratio of the leakage to pumping rates, without the influence of other factors such as different setback distances or a larger well screen, the experiments as shown in Figure C were simulated assuming increased leakage rate due to the leaking sewer lines or combined sewer overflow. Compared Figures B to C, increasing the leakage rate and, thus, increasing the ratio of leakage rate to the pumping rates, results in a shift of the virus reduction curve toward less virus reductions without changing its shape. This suggests that increasing the ratio of leakage rate to the pumping rate will raise the potential of viral loads at the receptor regardless of the conditions. However, even under this higher leaking to pumping ratio scenario, the virus removal remains significant if the system is under the high virus attachment environment. The vulnerable areas identified from the worst-case assessment could be potentially used for groundwater and surface water sampling for validation.