Development of a Chamber Platform for Evaluating Indoor Dust Contact Transfer and Resuspension in Infant Near-Floor Microenvironments

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ABSTRACT

During the key motor development stages for infants that occur between the ages of 6 and 18 months, the act of crawling over a surface disturbs settled dust particles by the impact of the infant's hands and limbs. The disturbed settled dust can then either be resuspended and inhaled by the infant or contact transferred and then ingested during mouthing events, entering their system regardless. The contents of settled dust in a given environment are reflective of the socioeconomic disparities of services in cities. Settled dust in indoor environments can contain health-relevant materials, such as per- and polyfluoroalkyl substances (PFAS), metals, microplastics, flame retardants, plasticizers, allergens, and microorganisms. Given the significant potential for inhalation and ingestion of disturbed settled dust, it is critical to understand the size-dependent fate and transport of these particles during crawling events. Doing so will help identify how to mitigate health risks for infants during their key motor development stages. Experiments will be conducted within an Inert Controlled Environmental Chamber (ICEC) such that environmental conditions, maintained by a ventilation system, are representative of infant occupied dwellings and intentionally resuspended particles are isolated for detection by filtering supply air. Infant contact dynamics will be simulated with a linear stage motor to perform impact tests between samples of simulated skin and indoor surfaces of interest. Information about the velocity and forces of infant crawling styles and their associated development stages will be determined through the New York University Databrary database of laboratory and home recordings of infant locomotion. This data can then be replicated with the linear stage and stepper motors through specified contact impulses on surfaces to mimic infant locomotion.

Experimental data collection will distinguish between resuspended and contact transferred particles from each event of interest. The Wideband Integrated Bioaerosol Sensor (WIBS) utilizes single particle fluorescence spectrometry to count and measure the equivalent diameter of airborne particles, which will be used to determine the size-resolved (j) dust resuspension fraction, r_j, of each event of interest using a single-zone material balance model. For the dust particles that underwent surface transfer during the event of interest, microscopic imagery will be used for identifying the particle count of dust that transferred from the experimental surface at impact, and a Laser Diffraction Particle Sizer (LDPS) will be used to determine size distributions of the transferred particles. These processes will be used to determine the size-resolved surface contact transfer fraction, c_j, of each event of interest. In the existing literature, the factors for dust inhalation and ingestion, as well as the processes themselves, have been studied and examined individually and exclusively of each other. The aforementioned dust resuspension and surface transfer fractions will provide insights into the dust inhalation and dust ingestion potential of our interactions of interest, respectively. This novel examination of both fractions simultaneously allows for new mechanistic insights into the size-resolved behavior of settled indoor dust particles, removing the limited perspective of analyzing these processes individually.

1. INTRODUCTION

The progression from the crawling stage to the walking stage is defined by rapid development in the motor skills of an infant (Adolph and Hoch, 2019). An infant's size and the nature of their mobility plays a role in their exposure to significant quantities of dust and other particulate matter (PM) in their near-floor microenvironment during an important period of their biological and motor development. The settled dust disturbed by the infant's locomotion can then either be resuspended and then inhaled or surface contact transferred and then ingested during mouthing events, entering an infant's system either way (Wu *et al*., 2021). Before addressing the mechanistic behavior of settled indoor dust disturbed by infant locomotion, the composition of indoor dust must be examined to understand the potential health implications of dust inhalation and ingestion. The settled dust found in indoor environments contains both chemical components, such as per- and polyfluoroalkyl substances (PFAS), metals, melamine, organophosphates, microplastics, phthalates and other plasticizers, pesticides, and biological components, such as bacteria, fungi, pet allergens, mite allergens, squames, and pollen. PFAS substances are known to stunt childhood development (Zheng *et al*., 2020a). Another study found melamine-based compounds in the settled dust of childcare facilities, which when combined with cyanuric acid, can cause the formation of crystals in kidneys and renal failure (Zheng *et al*., 2020b). Exposure to microplastics through inhalation of indoor dust is also shown to potentially be a higher risk than through ingestion of food (Song *et al.*, 2023). Even with an equal quantity of particulates in an indoor environment, environments with animals are responsible for higher concentrations of bacteria and viruses than environments without animals (Tan and Zhang, 2004). While not limited to these compounds, the danger of infant exposure to excessive quantities, as well as potential inhalation and ingestion, of indoor dust during their early development is established.

Additional substances of concern are presented when considering that the contents of settled dust in a given indoor environment are reflective of the socioeconomic disparities of services in cities and the differences in lifestyle choices of individuals. While modest compared to the direct inhalation from the act of smoking, tobacco constituents found in settled dust in the homes of smokers can contribute to involuntary exposure if disturbed (Hein *et al*., 1991). Even if a smoker is not present in the immediate environment, traces of tobacco-related particles can infiltrate and be found in neighboring spaces (Zhang *et al*., 2021). Suburban and urban areas create unique environments that determine potential contaminants for any given home, where the particulates can enter by transmission, such as wearing shoes indoors, or through gaps in the building envelope (Tan and Zhang, 2003). These studies further acknowledge the potentially dangerous composition of settled dust in indoor environments and emphasize the need for diversity in the examination of settled dust samples.

The previously acknowledged variability in conditions and contributing factors of settled dust samples prompts that further research accounts for variability in indoor surfaces, including material types and cleaning frequency, from which samples are collected from for consideration when evaluating dust loadings disturbed by infant locomotion. In the United States, carpets make up roughly half of the country's flooring market due to commercial appeal from their noise reduction and comfort qualities, but when compared to hardwood flooring of a similar area, carpet flooring is more likely to have higher concentrations of microbiological and chemical components and a higher dust loading (Haines *et al*., 2020). On top of the higher dust concentrations found in carpets, infant locomotion, specifically the act of crawling, generates significantly higher levels of microbial PM in their breathing zone than the act of walking does for adults (Hyytiäinen *et al*., 2018), thus inducing higher exposure to PM inhalation in infants and nearly 4-fold higher deposition of fluorescent biological aerosol PM in infant respiratory tracts (Wu *et al*., 2018). By simulating the act of crawling with a robotic infant across various carpet samples, this study recognized that such a device does not accurately replicate every act of infant locomotion that causes resuspension (Wu *et al*., 2021), thus prompting further development into methods that can reliably replicate other forms of infant locomotion, as well as additional tests on other typical flooring materials with representative dust loadings.

Given the significant potential for ingestion and inhalation of disturbed settled dust and the health concerns that it presents, it is critical to understand the size-dependent fate and transport of these particles during infant locomotion events such as crawling. To evaluate the mechanistic behavior of settled dust particles in infant near-floor environments, we developed an Inert Controlled Environmental Chamber (ICEC) platform to conduct resuspension and surface contact transfer experiments simulating infant locomotion. Doing so will help identify how to mitigate health risks for infants during their key motor development stages between the ages of 6 and 18 months.

2. MATERIALS AND METHODS

This research will mechanistically evaluate the size-dependent behavior of settled dust disturbed by infant locomotion. To accomplish this objective, experiments will be performed within an ICEC utilizing a robotic platform to simulate infant locomotion. The evaluation of disturbed settled dust behavior will account for variable indoor surfaces, environmental conditions, and indoor dust deposit structures, as illustrated in Figure 1. The settled dust disturbed by the events of interest will be classified as the result of one of two mechanisms, either resuspended particles or surface contact transferred particles. This distinction in mechanisms will be used to define the size resolved (j) resuspension fraction, r_j, and the surface contact transfer fraction, c_j, of particles in a single-zone material balance model.

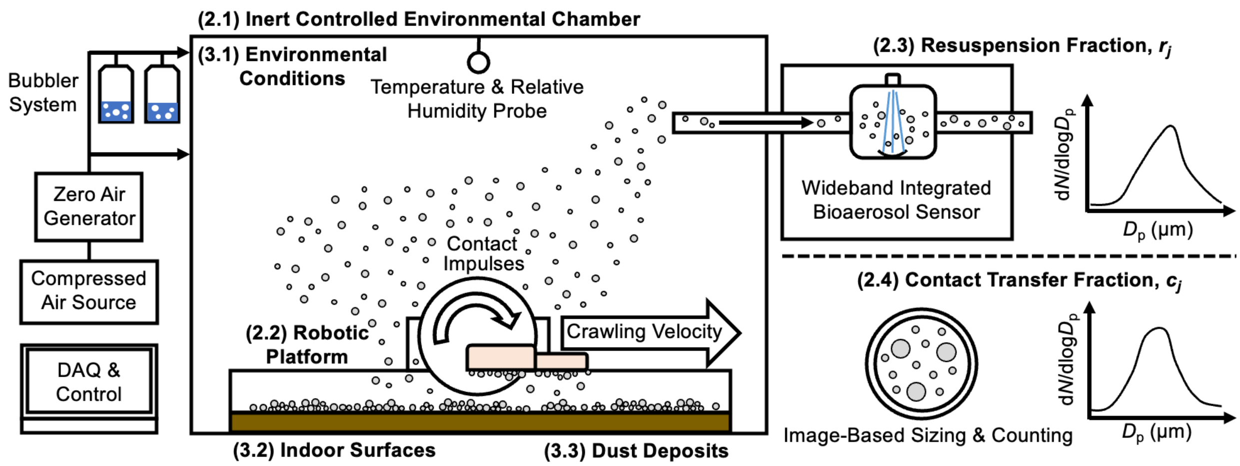

Figure 1: Mechanistic evaluation of indoor dust resuspension and contact transfer during infant locomotion.

2.1 Inert Controlled Environmental Chamber for Indoor Dust Transport Experiments

The nature of these experiments requires the use of an environmental chamber to provide a sealed volume to perform experiments within and collect samples from. The chamber itself must be inert to prevent reactions with any substance introduced into the chamber and to prevent emissions from the surfaces during experiments (Magnuson *et al*., 2023). Thus, 304 Stainless Steel sheet metal was selected as the material of choice for the walls of the chamber, with Tungsten Inert Gas (TIG) welding used to form permanent connections between sheets. Additional hardware used in the fabrication of the chamber and its ventilation system was restricted to either 8-18 or 316 Stainless Steel.

To further minimize the possibility of deposition of particles on the interior of the chamber that could lead to contamination between experiments, the surface roughness of the Stainless Steel would need to be reduced by non-mechanical methods. The 304 Stainless Steel sheet metal was factory polished with a #2B finish, which is defined by ASTM A480 as a smooth finish with a surface roughness between 0.3 and 1.0 μm. Following the completion of the fabrication process, the chamber was then sent to Elkhorn Electropolishing in Elkhorn, WI, to electropolish all surfaces to reduce the surface roughness even further to the range of 0.1 to 0.8 μm, as defined by ASTM B912.

To ensure minimal contamination of the interior environment from additional suspended particles and to allow for the removal of suspended particles in between experiments, the chamber was fitted with a ventilation system to provide a clean supply of air and to purge the interior of suspended particles through the exhaust (Magnuson *et al*., 2023). As illustrated in Figure 2, compressed air is first passed through a carbon filter and a HEPA filter to remove PM, and then the system utilizes a Zero Air Generator that reduces the relative humidity of the supply air to roughly 0% before passing through a second HEPA filter. The HEPA filters remove 99.97% of particles greater than or equal to 0.3 μm, and the activated carbon filters remove volatile organic compounds. This system does not utilize any return air to prevent reintroduction of suspended particles during experiments.

Since water content is known to impact dust resuspension from indoor surfaces, the relative humidity within the ICEC is maintained by a LabView control platform paired with mass flow controllers that is responsive to the conditions within the chamber. As LabView measures RH values in real-time, it communicates with the two mass flow controllers, with one connected to a bubbler system. With a constant total flow rate into the chamber, LabView will direct more of the flowrate into the bubbler system if the RH is below the desired value or direct it away from the bubbler system if the RH is too high. These controls can maintain the desired RH with minimal oscillation. Mixing fans prevent air stagnation in the chamber to thoroughly mix the chamber air before it is exhausted.

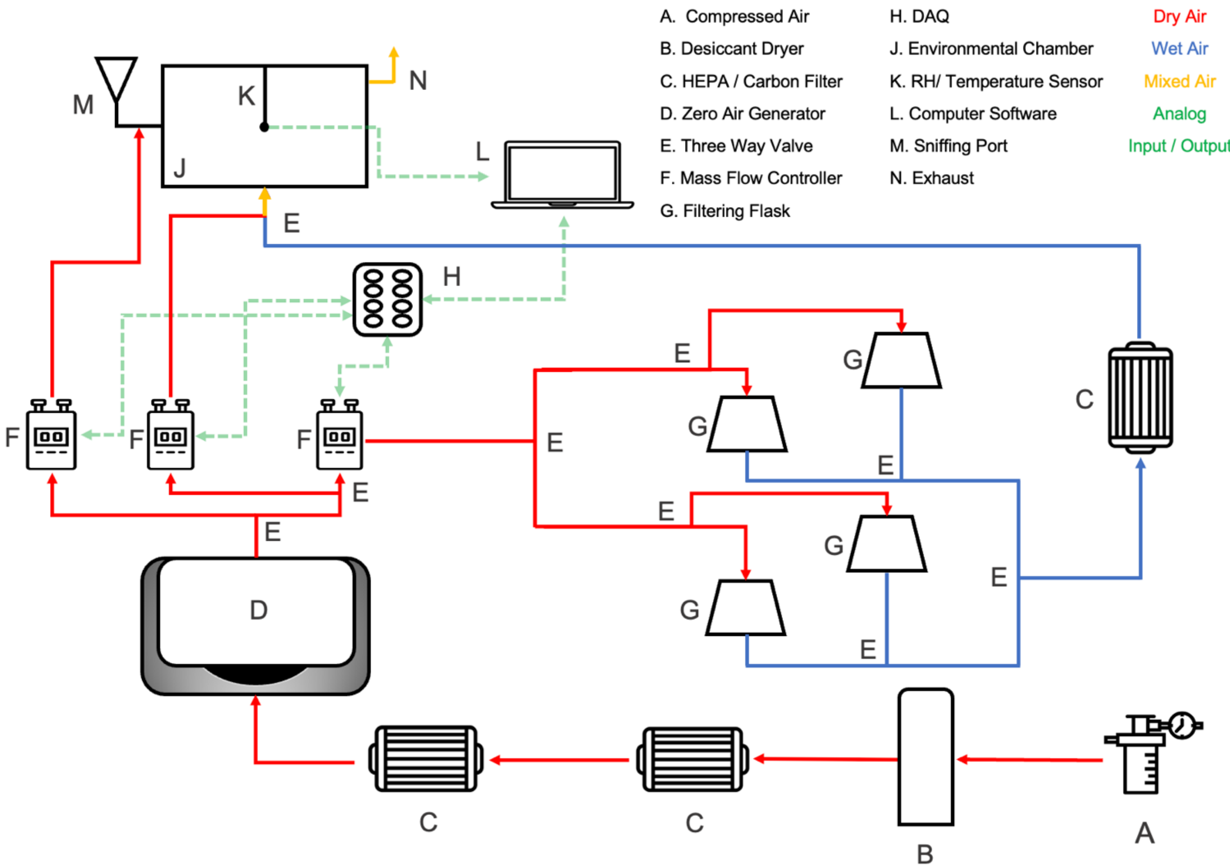

Figure 2: System schematic of the inert controlled environmental chamber.

2.2 Robotic Platform for Simulating Infant Locomotion

Infant contact dynamics will be simulated with a linear stage and a stepper motor to perform impact tests between samples of simulated skin and indoor surfaces of interest. Simulated skin will be used to model infant limbs, with artificial saliva and skin oil being added to simulate different conditions. Infant locomotion milestones will dictate what motions are simulated while also recognizing the increased control that infants have over their movements as they mature (Adolph and Robinson, 2015). Information about the velocity and forces of infant crawling styles and their associated developmental stages will be determined through our psychology collaborators at Purdue University and New York University (NYU), utilizing the NYU Databrary database of laboratory and home recordings of infant locomotion. This data can then be replicated with the linear stage and stepper motors through specified contact impulses on surfaces to mimic infant locomotion.

The simulation of the act of an infant crawling must account for the slapping motion, or the impact, of the infant's limbs and the forward movement of the infant themselves. For experimental purposes, each test will consist of 3 impact events over a stretch on a dust loaded surface, representative of 3 consecutive impacts and 2 full strides of an infant's limb. To accomplish this, a linear stage motor will be used to provide a constant velocity in the horizontal direction, while a stepper motor with a flywheel will be used to simulate the locomotion of an infant's limbs. The benefit of using radial motion for the impact events is that the stepper motor can follow through after contact with the surface to minimize contact time and maintain a higher velocity, while the options for linear stages or linear actuators that are small enough for this application have deceleration and acceleration times that reduce the impact velocity below acceptable values. To prevent merely replicating a rolling motion with the model hand or only making contact with a singular point on the surface, the model hand's fixture will be offset from the flywheel and compressible such that its impact velocity is not entirely in the horizontal direction.

2.3 Resuspension Fraction

The resuspension fraction for any given dust sample is affected by various particle and environmental characteristics, such as surface roughness, particle chemistry, surface particle concentrations, and airflow dynamics across an indoor surface (Qian *et al*., 2014), thus prompting consideration of each factor in data modeling and analysis. The Wideband Integrated Bioaerosol Sensor (WIBS) utilizes single particle fluorescence spectrometry to count and measure the equivalent diameter of airborne particles, which will be used to determine the size-resolved dust resuspension fraction, r_j, of each event of interest. The WIBS is capable of detecting fluorescent aerosol particles to identify biological components in resuspended dust (Patra *et al*., 2021). To minimize the loss of particles due to deposition on the sampling inlet manifold of the instrument, the WIBS will be placed inside the chamber such that samples are taken directly by the instrument with no additional tubing. Additionally, an Optical Particle Sizer (OPS) and a NanoScan Scanning Mobility Particle Sizer (SMPS) will provide supplemental data on particle number size distributions and will be used for running diagnostics on the ICEC. Assuming a well-mixed interior within the ICEC, a single-zone material balance for the chamber can be rearranged for the resuspension fraction, r_j, as shown in Equation (1).

$$r_j = \frac{V_{EC}}{A_o f L_j}\left[\frac{dC_{ECj}}{dt} + \beta_{ECj}C_{ECj} + \lambda_{EC}C_{ECj}\right] \quad (1)$$

For each particle size bin, j, the suspended particle concentration, C_{ECj} [# cm^{-3}], is assumed uniform throughout the well-mixed chamber of volume, V_{EC} [cm^3]. The deposited particle concentration, L_j [# cm^{-2}], is measured by a Laser Diffraction Particle Sizer (LDPS), which uses laser diffraction to analyze representative dust provided from the settled dust samples chosen for loading the sample surface area, A_o [cm^2], which is then impacted at a frequency, f [s^{-1}]. This single-zone material balance model acknowledges two main loss mechanisms for the resuspended dust particles, which are the size-resolved deposition loss rate (β_{ECj}; s^{-1}), determined by particle decay following the impact event, and the chamber's air exchange rate (λ_{EC}; s^{-1}) leading to ventilation losses.

2.4 Contact Transfer Fraction

The contact transfer fraction is known to be affected by contact pressure and surface material (McDonagh *et al.*, 2012), so the experimental conditions will need to represent various combinations of infant locomotion and surfaces. For the dust particles that underwent surface transfer during the event of interest, microscopic imagery will be used for identifying the particle count of dust that transferred from the experimental surface at impact, and a LDPS will be used to develop transferred particle size distribution curves. These processes will be used to determine the size-resolved surface contact transfer fraction, c_j, of each event of interest. The model hand of the robotic platform will be removed following each experiment to be examined by the microscopic imagery process. As the model hand will be inverted during the experiment, deposition of particles by gravitational settling would be minimal. The surface contact transfer fraction, c_j, will be calculated for each experiment with the measured size-resolved surface concentrations on both the object of interest and the flooring sample, as shown in Equation (2).

$$c_j = \frac{S_{oj}}{L_j} \quad (2)$$

The surface contact transfer fraction is a direct relationship between the adhered particle concentration on a given object's surface, S_{oj} [# cm^{-2}], and the deposited particle concentration on the sample flooring surface, L_j [# cm^{-2}].

3. EXPERIMENTAL PLAN

For each given event of interest, the interior environment of the ICEC should be representative of the conditions that the dust samples have been collected from. The presence of moisture can drastically influence the behavior of particles as they interact with various indoor surfaces, each with different surface roughness values. Additionally, the variance in the concentration of dust deposits can play a role in the particles' mechanistic behaviors, regardless of the other two conditions. The experiments performed will adhere to the environmental conditions and parameters representative of the infant occupied residence from which the settled dust samples have been collected (Patra *et al*., 2023).

3.1 Environmental Conditions

Environmental conditions within the chamber, specifically relative humidity, will be adjusted to reflect various climates and heating/cooling conditions that will affect an indoor environment. An initial range of values to examine should include low, middle, and high percentages for the relative humidity of indoor environments. To quantify this range of values, the percentages chosen should reflect reasonable residential conditions, such as 30%, 50%, and 80%. Preliminary tests show that the LabView control platform can maintain these representative values with oscillations limited to ±1%. These initial values will help determine to what extent the presence of moisture has on the adhesion and resuspension of dust during infant crawling impact events. If initial results point towards a trend around one of the reasonably assumed values, further tests would be carried out with smaller steps between relative humidity values, such as 5%.

The ventilation system of the chamber can operate at various Air Exchange Rates (AER) in combination with the relative humidity control to even better represent the various ventilation systems found within the residential houses where settled dust samples were collected. Modeling different ventilation systems will show how different AERs affect the airborne concentrations of resuspended dust particles, and the resulting exposure rates for infant ingestion.

3.2 Indoor Surfaces

Indoor surfaces found within residences provide a variety of physical properties to be isolated and tested. Common flooring materials will be tested and compared, including wood and vinyl flooring, ceramic and stone tiles, and low- and high-pile carpets. Such surfaces need to be evaluated for differences in dust particle adhesion to each surface. The factors affecting particle adhesion for each flooring type includes the composition of the material, the surface roughness, and macroscale details of the surface.

3.3 Dust Deposits

Indoor dust deposits on a surface can be tested over a range of surface mass concentrations to reflect potential loadings of indoor surfaces. To begin, a range of 0.01, 0.1, 1, and 10 g/m^2 can be used as experimental surface mass concentrations to understand the impact of a higher presence of particles. For each of these concentrations, the coating of dust on the surface may be a monolayer or multilayer, which introduces another factor to account for in the adhesion and resuspension of particles (Boor *et al*., 2013).

4. INERT CONTROLLED ENVIRONMENTAL CHAMBER DIAGNOSTICS

To consistently detect resuspended particles during impact events of interest, the ICEC must maintain low particle counts during background conditions such that the WIBS and other equipment can differentiate particles released during experiments. Following the completion of the fabrication process for the chamber and its ventilation system, a diagnostics check was performed to confirm the system's efficiency at removing particles and maintaining a controlled environment. For diagnostic purposes, only particle number size distributions were necessary, and not fluorescent particle detection, so suspended particles within the chamber were measured by the OPS with a range of 0.3 to 10 μm, and the NanoScan SMPS with a range of 0.01 to 0.4 μm. Initially, the dry-air tests performed showed that low pressure filters were prone to degrading and releasing additional particles while also having reduced efficiency. By replacing them with high pressure filters, the overall efficiency is maintained without degradation of the filter media, allowing for virtually complete removal of particles in the chamber's supply air, as seen in Figure 3.

Following confirmation of filter performance from the dry-air tests, wet-air tests were conducted to measure the levels of particles generated by the bubbler system and the type of water used. Given the performance of the filters in the dry-air tests, the chamber ran with dry-air initially for 24-hours, followed by turning the bubbler system on for a 24-hour period, and then concluded by running solely dry-air for another 24-hours. Initial wet-air tests showed high levels of particles measured by the NanoScan SMPS during the second 24-hour period of the 72-hour test, which meant that sub-micron particles were being released by the bubbler system into the chamber. After installing an additional HEPA filter on the outtake of the bubbler system, particle emissions were reduced during periods of environmental control as shown in Figure 4. On top of successfully confirming the effective removal of particles by the ventilation system, the collected data also provided enough information to identify a standard length of time to allow for the system to reach an operational state. Regarding the experimental protocol for the ICEC, the ventilation and environmental control systems must run for at least 2 hours before any events of interest to ensure satisfactory removal of suspended particles from the chamber's interior.

Considering this 2 hour purging period of the ICEC, the ventilation system was able to completely remove all super-micron particles and maintain near zero concentrations of sub-micron particles. The nature of the intended experiments revolve around 3 consecutive impact events followed by a decay period, such that maintaining near-zero background concentrations allows for isolation of intentionally resuspended particles. The presence of any additional particles introduces a degree of error in the resuspension fraction calculations and limits the ability to differentiate small concentrations of resuspended particles from experiments with low dust loadings.

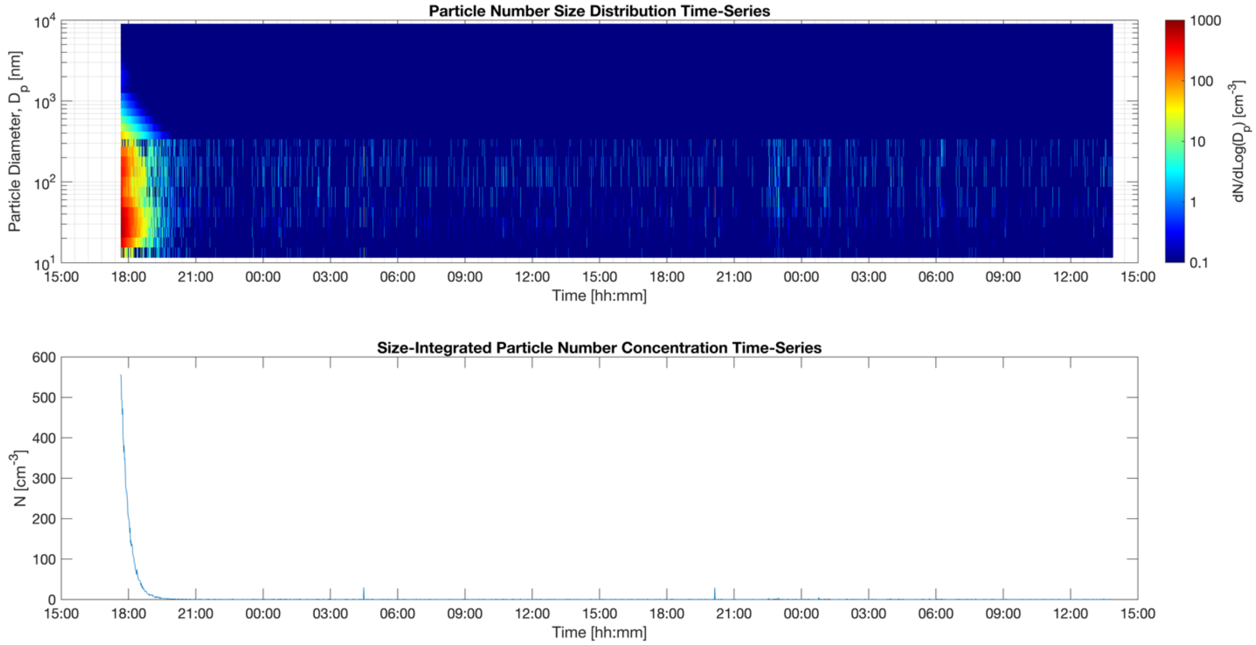

Figure 3: Size-resolved particle concentrations during dry-air tests in the ICEC. The LabView control platform maintained a 20 L min^{-1} flowrate with no relative humidity set-point for the duration of the experiment.

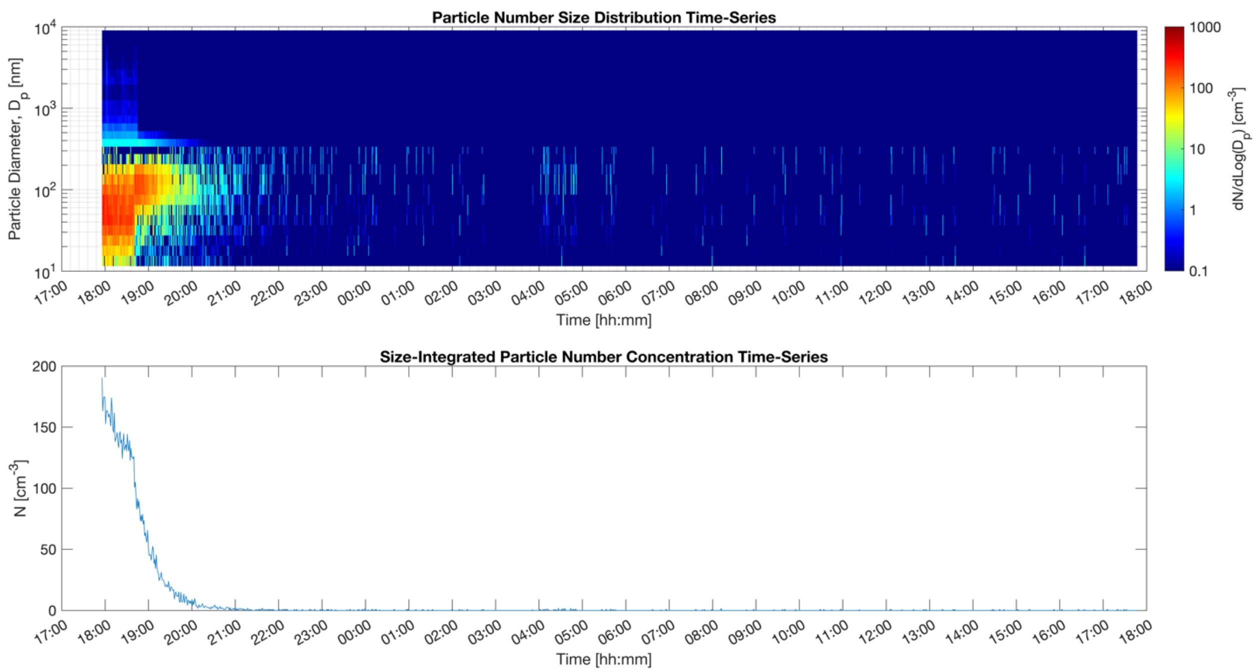

Figure 4: Size-resolved particle concentrations during wet-air tests in the ICEC. The LabView control platform maintained a 20 L min^{-1} flowrate and 55% relative humidity set-point for the duration of the experiment.

5. EXPECTED RESULTS

The preliminary results from the diagnostic tests performed with the ICEC show that the ventilation system is able to maintain near-zero particle number concentrations over long periods of time. By maintaining these particle levels, the WIBS, OPS, and NanoScan SMPS will be able to detect and differentiate resuspended particles from the background concentrations for any given event of interest. The resuspended particle data correlated to a given impact event will be recognizable as an instance of significant increase in particle number concentrations followed by a period of decay. By isolating the particle number concentration data from the instance of impact to the end of the decay period, the single-zone material balance model can be used to calculate the resuspension and contact transfer fractions.

To be used in tandem with the ICEC, the robotic platform will allow for the comprehensive experimentation of virtually any set of environmental conditions that would be representative of infant occupied spaces. By examining each representative set of conditions, the comparison of the size-resolved fractions from each set's single-zone material balance model would highlight any condition that is responsible for either relatively higher or lower fractions. This insight would help identify what environmental conditions are responsible for a higher risk of inhalation or ingestion of dust-bound contaminants in infants following impact events, and what combinations are most effective at reducing the exposure in infants. While this project will not specifically determine the effects of the identified contaminants in instantaneous exposure, the health concerns for infants from prolonged exposure can be inferred from the known health effects of the identified contaminants, whether it is a short-term infection, a disease, or a permanent condition.

NOMENCLATURE

L	flooring particle concentration	(# cm^{-2})
S	surface particle concentration	(# cm^{-2})
C	particle concentration in air	(# cm^{-3})
V	volume	(cm^3)
r	resuspension fraction	(–)
c	contact transfer fraction	(–)
f	impact event frequency	(s^{-1})
A	surface area	(cm^2)
β	deposition loss rate coefficient	(s^{-1})
λ	chamber air exchange rate	(s^{-1})

Subscript

EC	Inert Controlled Environmental Chamber
j	index of particle size bin
o	object of interest

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