# Evaluation of Mask and Mask Material Suitability for COVID-19 Transmission Protection and Influence of Face Velocity and Exhaled Breath Condensate on Filtration Efficiency

by

Emily Quecke

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in Environmental Engineering

Civil and Environmental Engineering
University of Alberta

# Abstract

Facemask use has been a key public health measure in response to the SARS CoV-2 pandemic; they are used to reduce airborne transmission of the disease amongst the public. The facemasks used by the public are non-medical in nature and therefore are not regulated like medical masks. Cloth masks, both commercially sourced and homemade have been used throughout the pandemic. Cloth mask suitability for protection from transmission of SARS-CoV-2 is still being determined, while new research is emerging, knowledge is limited on this topic, especially due to the variety in materials and use scenarios. Understanding filtration efficiencies of different materials in different use scenarios is key for public health during this and potentially future respiratory infectious disease outbreaks.

A testing line using NaCl challenge aerosol is used to evaluate the filtration efficiency and pressure drop for a variety of materials, commercially sourced non-medical masks, and medical masks. The testing line and procedure is closely adapted from the ASTM F2299 testing method used for testing medical masks. Materials and masks were tested individually as well as in various combinations. Four mask types were also tested at four different face velocities, three within the acceptable face velocity range allowed for ASTM F2299 certification and the other masks and materials were tested at two face velocities. Masks were also exposed to aerated simulated exhaled breath condensate (EBC) for 1 to 24 hours and their filtration efficiency was tested immediately following exposure. Both hygroscopic and hydrophobic masks were tested after exhaled breath condensate exposure. Statistical analysis was used to identify correlation between breath condensate exposure duration and filtration efficiency and pressure drop.

Filtration efficiencies at 0.15 µm at a face velocity of 25 cm/s for commercial cloth masks, disposable non-medical masks, medical masks, commercial mask combinations and homemade combinations were, 16-29%, 39-76%, 91-97%, 51-95%, 45-94% respectively. The quality factors (QF) for this data ranged from 2.3 to 36 $kpa^{-1}$. On average, the filtration efficiency decreased as face velocity of the challenge aerosol stream increased. The only masks that did not follow this trend were the woven and knitted materials and two of the commercial masks made with cotton. Filtration efficiency decreased by up to 20% after EBC exposure. Two masks had statistically significant correlations between filtration and EBC exposure time at 1.0 µm; other masks showed similar trends but were not statistically significant. There was no strong correlation between EBC exposure and pressure drop.

With proper layering, household materials can achieve high filtration efficiency and breathability requirements similar to medical masks. More regulation of disposable and cloth masks are needed considering the large variety in masks quality. The velocity range allowed for medical mask testing as per ASTM F2299 is too large and should be revised. Filtration efficiency varies within this range which means masks that are all certified under this standard can be inconsistent. Cloth masks should be removed and cleaned after an 8-hour workday. If possible, removal after 4-hours would be preferred. Medical and non-medical disposable masks are not largely impacted by breath condensate and therefore should be worn according to manufacturer's specifications. Further research should be conducted on the subject of how filtration mechanisms are impacted by breath condensate and on the subject of mask maintenance and lifespan which was not included in this scope.

# Dedication

*I dedicate this thesis to my late father, Glen. Unfortunately, he will not be able to see the finished product, but I know he was with me every step of the way. It is because of his encouragement and love along with my remarkable and resilient mother, Kim, and my amazing brother, Oliver, that I have been able to achieve all these accomplishments.*

*I would also like to dedicate this work to my supportive partner, Ty. He has been my rock through this process; his faith, love and inspiration has helped motivate and ground me. Him and my two study buddies Luna and Houdini helped my working from home over the last year.*

*I also want to recognize all the supportive teachers from my youth that set me on the academic path and home science experiments with my mom.*

# Acknowledgement

Firstly, I would like to acknowledge my supervisors, Dr. Zaher Hashisho and Dr. Bernadette Quemerais. Their support, guidance and knowledge were integral for my success in this project. Particularly their flexibility and patience during the challenges of the pandemic was greatly appreciated.

My peer, Dr. Arman Peyravi was instrumental to the completion of this project. I want to recognize his assistance and guidance, his work in setting up this project as well as his willingness to let me join the project.

The experiments from this thesis were conducted in the Air Quality Characterization and Control Lab of the Civil and Environmental Engineering Department at the University of Alberta. I appreciate all my peers with whom I shared this space. I am also indebted to the Natural Sciences and Engineering Research Council (NSERC) which funded a large portion of this project; Alberta Health Services (Dr. Stephanie Smith) as project partner on the Alliance grant; and the co-principal investigators (Dr. Patricia Dolez and Dr. Alexander Doroshenko) for their contribution to the project.

# Table of Contents

# List of Tables

# List of Figures

# List of Equations

# List of Acronyms

| | |
|---|---|
| ACF | Cabin Air Filter |
| ASTM | American Society for Testing and Materials |
| EBC | Exhaled Breath Condensate |
| FE | Filtration Efficiency |
| FG | Firm Grip (brand) |
| L2 | Level 2 surgical masks |
| L3 | Level 3 Surgical masks |
| MPR | Microparticle Performance Rating |
| QF | Quality Factor |

# 1. Introduction

Amidst the COVID-19 pandemic which began in late 2019, one common, worldwide public health measure is the use of face masks in public spaces to reduce infection rates. Facemasks have long been used in the medical field to prevent transmission of respiratory infectious diseases and other inhalation hazards. However, due to the high demand for masks, there are now new mask materials, such as cloth masks, mask reuse, and lengthened single mask use. These new scenarios have not been fully researched and the suitability of these mask materials and scenarios are not well established. Mask suitability, referring to both breathability and filtration efficiency, in different scenarios needs to be understood to protect public health and to inform public health measures.

Governments and agencies around the world have implemented some form of mandatory facemask use in public spaces. The World Health Organization first published a document in June of 2020 which encouraged the public use of facemasks as one way to help prevent SARS-CoV-2 (COVID-19) transmission [1]. Guidelines vary across countries; generally, non-medical masks are suggested for healthy individuals in public spaces, especially where a safe distance cannot be maintained. For potentially infected individuals or those who are at a high risk of serious complications from COVID-19, medical masks are recommended whenever in a public space [1]. Homemade masks are encouraged to have 3 layers, and factory made non-medical masks should meet filtration, breathability, and fit requirements [1]. Despite these guidelines, non-medical mask quality varies, and medical masks have been in shortage due to elevated use. Furthermore, medical masks and disposable non-medical masks create a significant amount of waste. It is estimated that 89 million masks have been used per month during the COVID-19 pandemic [2]; if all these masks are disposable there will be significant environmental effects from the production and disposal of masks.

SARS Cov-2 virus can be transmitted through inhalation of aerosols as well as through saliva droplets. Droplets (>5 μm) and aerosols (0.1-5 μm) generated by sneezing, coughing, breathing (especially elevated when exercising), and talking can transmit infectious respiratory diseases [1], [3], [4], [5], [6]. Saliva droplets are greater than 5 μm in size and are easily captured by masks, this route of transmission is also addressed through thorough cleaning and handwashing. Aerosol transmission prevention, however, presents more of a challenge; smaller particles can penetrate masks and the respiratory system more easily as well as they can remain suspended in the air for longer periods [7], [8], [9]. Aerosol transmission is more important for COVID-19 transmission than originally thought. Multiple studies have detected COVID-19 in aerosols at great distances from their origin. Baboli et al. (2021) found COVID-19 in aerosols greater than 3 meters from the beds of infected patients in a hospital COVID-19 ward [10]. Guo et al. (2020) similarly found that COVID-19 spread exceeded 4 meters from infected patients in hospitals [11].

### 1.1. Objectives

This research aims to provide practical knowledge on the topic of public mask use for the prevention of transmission of SARS-CoV-2. Through literature review on the topic of fabric mask suitability and public use to reduce airborne transmission of infectious disease, presented in a later section, a set of recommendations for further research were developed. From these recommendations three clear objectives were chosen for this study. The first objective was to quantify the suitability for COVID-19 transmission control of various commercially available materials for masks and cloth masks and to compare them to medical masks and disposable non-medical masks. Suitability will be quantified in terms of filtration efficiency of aerosols 0.1-5µm in size and pressure drop. The second objective is to compare the suitability of these same fabric masks and non-medical masks at different low range face velocities. The final objective is to investigate the impact that exhaled breath condensate accumulation has on fabric mask efficiency over time. This final objective will also be used to make recommendations on suitable duration of wear to maintain a reasonable filtration efficiency.

## 1.2. Outline

This dissertation presents a detailed literature review in chapter 2 on the topic of mask use and suitability for the prevention of respiratory infectious diseases. This review in chapter 2 also includes background information on the topics of filtration mechanisms, mask testing, mask regulations and mask use parameters such as wear time and washing. Through the analysis of this review recommendations were made for further research in this area in the conclusions section of the chapter. After the literature review the methods developed to address the outlined objectives is presented in chapter 3, followed by analysis of data in chapter 4. Chapter 5 includes conclusions, recommendations based on the data analysis and applications of the findings.

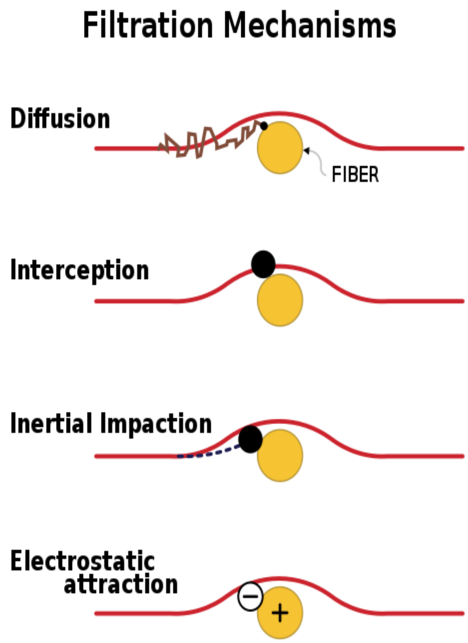
# 2. Literature Review and Background

## 2.1. COVID-19 Aerosols and Droplets

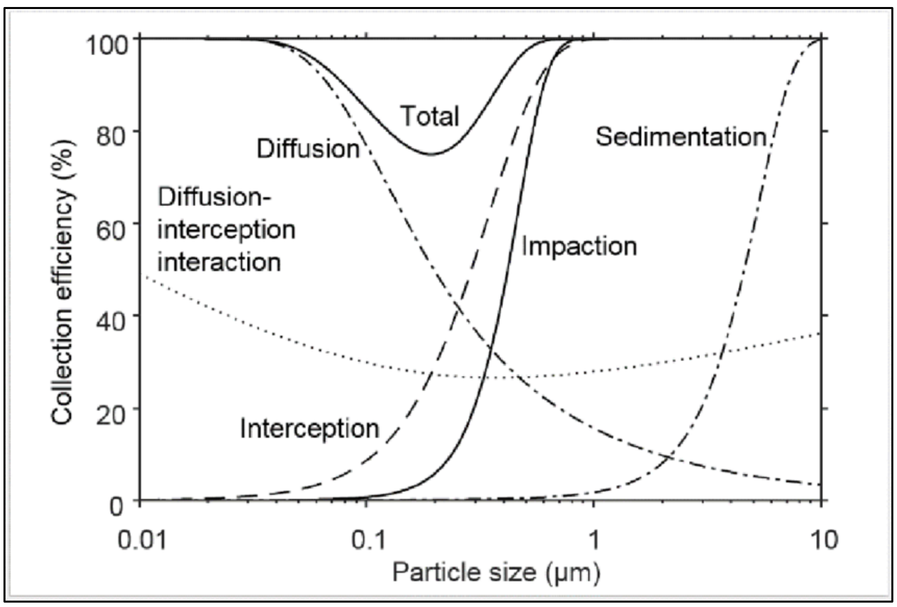
Aerosols is a term referring to liquid or solid particulates that are suspended in the air or other gases [12]. Aerosols can be visible, biological in nature (bioaerosol), monodisperse or polydisperse [12]. The term droplets refer directly to accumulated liquid particulates [3], [12]. In terms of COVID-19, the coronavirus particles can be transmitted both as an aerosol as well as inside respiratory droplets. Respiratory droplets are accumulated respiratory fluid and therefore have a larger size (> 5 μm) and mass and therefore do not remain suspended in air as long as aerosols do [3]. Coronavirus particles have a spherical shape and are reported to be 0.125 μm in diameter [13]. Other sources have estimated coronavirus particles to be anywhere from 0.06-0.15 μm [14]. Because these particles are very small, they can remain suspended in the air for significant time and distance. It has been generally assumed that infectious particles remain in the air for 1-2 m [3]; while this may be true for some of the larger droplets containing COVID-19, there is increasing data that the smaller aerosols travel farther, even up to 8 m [5], [7], [8], [9], [10], [11]. Theoretically based on their size these aerosols could likely travel even further. Studies suggest certain individuals have a heightened ability to virally shed and aerosolize the virus, creating superspreading events [13]. Social distancing can help reduce transmission of the virion but due to the large distances that infectious aerosols can travel after expulsion other means need to be employed to reduce transmission from infected individuals. Both facemasks and proper ventilation can work to do this through different mechanisms. For the purposes of this research, only facemasks as protection from transmission will be discussed. Facemasks work to both contain exhaled contaminants by a potential disease carrier as well as to protect the wearer from inhalation of airborne disease [15].

### 2.2. Filtration Mechanisms

In principle, face masks prevent transmission through collecting airborne aerosols on the mask fibers. This collection is primarily done through 4 mechanisms: inertial impaction, interception, diffusion (due to Brownian motion) and, electrostatic forces. These mechanisms are illustrated in Figure 2-1 a). As seen in Figure 2-1 b), inertial impaction and interception are the primary mechanisms for collection for large droplets, 1-10 µm [3], since the efficiencies of these mechanisms are directly related to weight and size of the particles. Diffusion, however, is the result of the random motion of gas particles, and only has a significant impact on collection efficiency of particles < 0.3 µm in diameter [16]. Electrostatic forces are also important for collection of small particles [3], [16]. Electrostatic mechanisms of collection rely on the charging of particles, through either field charging or diffusion charging. Once the particles themselves are charged they are attracted toward the charge of the collection surface [16]. The importance of electrostatic forces and electrostatic recharge after mask disinfection has been a common topic of facemask research and will be discussed in more detail in section 0.




*a) Four primary filter collection mechanisms [Taken from NIOSH [17]]*




*b) Effect of Particle Size on Filtration Mechanism Efficiency [Taken from Hinds [12]]*

***Figure 2-1*** *Filtration Mechanisms and Their Interaction, a) Four primary filter collection mechanisms [Taken from NIOSH [10], b) Effect of Particle Size on Filtration Mechanism Efficiency [Taken from [12])*

## 2.3. Types of Masks

There are many types of masks and respirators that can be used for protection against a variety of inhalation hazards. In context of the COVID-19 pandemic, masks could be classified into 4 types: medical masks, disposable non-medical masks, reusable commercial masks, and homemade masks.

The medical mask category includes level 1, 2 and 3 surgical masks, as well as N95 masks, pictured in Figure 2-2, and are considered a form of personal protective equipment (PPE). These masks are tested according to ASTM standards and are proven to be suitable for protection against COVID-19. Medical masks provide a high level of filtration efficiency and are also breathable. N95 masks are particularly efficient; however, they must be fit tested prior to use and the wearer must be clean shaved. The N95 designation means the mask has a 95% filtration for particles of 0.3 µm, the standard size for filtration testing, with a maximum inhalation pressure drop of 35 $mmH_2O$ and exhalation pressure drop of 25$mmH_2O$ [18]. N95 approval and requirements are set by NIOSH according to document 42 CFR Part 84 [18]. Level 1, level 2, and level 3 surgical mask designations refer to ≥95%, ≥98%, ≥98% filtration efficiencies for both bacterial and sub-micron filtration (0.3 µm) and <5.0 $mmH_20/cm^2$, <6.0 $mmH_20/cm^2$, <6.0 $mmH_20/cm^2$ pressure drops, respectively. All three level surgical masks are certified according to ASTM F2100 [19]. N95 masks are made to prevent transmission as well as protect the wearer; surgical masks do somewhat protect the wearer but are primarily designed to prevent transmission to others. While medical masks are suitable for protection against COVID-19 airborne transmission, they are both disposable and in limited supply. Due to limited supply, healthcare workers have been prioritised for N95 mask use. Though medical masks are the most suitable for healthcare workers and should be used in these scenarios, the increased global use of these masks creates significant amounts of waste. There has been increased research on the topic of disinfecting medical masks for reuse [20] [21] [22] [23]. This topic is discussed in greater detail is section 0. Though there is some indication that some reuse does not significantly affect mask efficiency, any reuse from medical masks should be limited and is not recommended. Furthermore, with the increased global demand for facemask there have been shortages of medical masks since the beginning of the pandemic [2]. Due to their high efficiency, quality assurance and breathability, it is logical that medical masks should be saved for front line healthcare workers and those who are most at risk.


*a) Surgical Mask* *b) N95 Mask View 1* *c) N95 Mask View 2*

***Figure 2-2*** *Medical masks, a) Surgical Mask, b) N95 Mask View 1, c) N95 Mask View 2*

Disposable non-medical masks appear to be very similar to surgical masks in terms of design and material. The primary differences between medical and non-medical masks, pictured in Figure 2-2 and Figure 2-3, are the testing requirements, target removal efficiency requirements, purpose, sterility requirements and availability [24]. For example, Levitt Safety supplies level 3 surgical masks, level 2 surgical masks and what are described as disposable barrier masks. The disposable barrier masks, unlike the surgical masks, do not have ASTM certification; they have manufacturer approval by the International Organization for Standardization only [25]. Some non-medical disposable masks claim to have ≥95% or ≥98% filtration efficiencies, while some do not advertise their targe removal efficiencies. Generally, disposable masks, as well as fabric/cloth masks, are used for source control rather than as a form of PPE [26]. Considering medical professionals need to use approved masks, non-medical masks are more available to the public. One thing both non-medical masks and some medical masks (surgical masks) have in common is their fit. Both kinds of masks include an adjustable nose clip and come in a generic size. While the nose clip does aide individual fit, the masks can gape at the sides of the face and seal is not guaranteed [27] [28]. Disposable non-medical masks present the same sustainability concerns as medical masks.

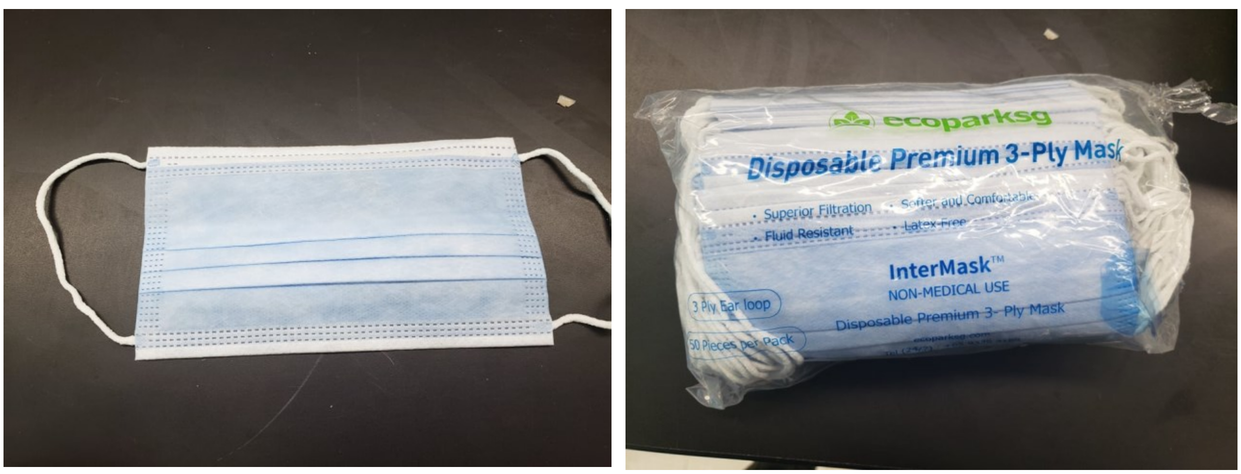



***Figure 2-3*** *Disposable non-medical masks*

Reusable commercial masks, pictured in Figure 2-4 are commonly used by the public. There is a large variety of materials, designs and fits among commercial reusable face masks due to a lack of regulation [1], [23]. Reusable face masks sold as source control have disclaimers which identify them as not being a direct replacement for medically certified masks [26]. Generally, these masks are made from 3-5 layers of cotton or other woven fabrics; there is often a pouch built into the design to allow insertion of filters during use. These masks are reusable and therefore must be decontaminated. Generally, it is suggested that the mask be decontaminated after one day of wear or as soon as it is damp or dirty and that they should be washed with warm water and soap [1]. Often time, the packaging of commercially available fabric masks will provide suggestions for when and how to wash the face mask.


***Figure 2-4*** *Commercial reusable cloth mask example*

Homemade masks are similar to reusable commercial masks; however, the quality of homemade masks is even more variable than similar commercial masks. Homemade masks were particularly popular in the early stages of the COVID-19 pandemic as reusable masks were not yet commercially available and medical masks were in shortage. As the pandemic has continued, homemade masks became much less popular and are therefore less important towards future research. Generally, it has been recommended that homemade masks have 3 layers of non-woven fabrics [1], these masks were often made from bedsheets, t-shirts, and other household woven fabrics.

### 2.4. Mask Testing Methods

Materials used for medical grade and regulated masks are tested for a variety of parameters according to standard procedures. Masks are tested for their ability to resist fluids, combustibility, differential pressure to represent breathability and their filtration of both bacteria and particles [29]. In relation to public everyday use for the prevention of disease transmission, breathability and filtration are the most important parameters. ASTM standard F2100 "Standard Specification for Performance of Materials Used in Medical Face Masks" [19] details the testing requirements for materials to be used in medical face masks as well as the details for classification of a medical mask. ASTM F2100 details the performance requirements for level 1, 2 and 3 surgical masks, in the categories of bacterial filtration efficiency, sub-micron filtration efficiency, pressure drop, flammability and resistance to synthetic blood, and refers the reader to different standards for the determination of these performance metrics. ASTM F2100 refers to ASTMF2299/F2299M for determination of sub-micron filtration efficiency, ASTMF2101 for bacterial filtration efficiency and EN14683:2019 Annex C for the determination of differential pressure. Table 2-1 summarizes the three standards that ASTM F2100 refers to.

ASTM standard F2299/F2299M "Standard Test Method for Determining the Initial Efficiency of Materials Used in Medical Face Masks to Penetration by Particulates Using Latex Spheres" [30] is used for the preliminary testing of filtration efficiency of materials to be used in medical masks. ASTM F2299/F2299M uses a light scattering particle counter for particle detection, monodispersed latex sphere aerosols, sized 0.1-5.0 µm at an airflow of 0.5-25 cm/s; this standard also details mechanisms for the recording of pressure drop, temperature and relative humidity. ASTMF2101 involves preparing a bacterial challenge and running a test apparatus at an airflow of 28.3L/mm (1ft$^3$/min) [31]. Breathability performance is tested by determining the differential pressure of a mask. The European standard EN14683:2019 Annex C is the standard commonly used for the determination of breathability of a mask [32]. This standard calls for the use of a differential manometer to measure the pressure drop across a specimen 25 mm in diameter at a flow rate of 8 L/min. This standard calls for 5 replicates on separate samples; the final differential pressure found is normalized per cm$^2$ of fabric.

***Table 2-1*** *Summary of Standard Mask Testing Methods*

| **Test Method** | **Conditioning step** | **Challenge Aerosol** | **Flow rate (l/min)** | **Sample size** | **Velocity (cm/s)** | **Replicates** |
|---|---|---|---|---|---|---|
| ASTM F2299 | RH: 30-50%<br>T: 21C | PSL spheres (100-5000nm) | N/A | N/A | 0.5-25 | 5 |
| ASTM F2101 | RH: 85%<br>T: 21C<br>For 4 hrs | Staphylococcus aureus (3000nm) | 28.3 | 40cm$^2$ | 11.8 | 1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| EN 14683 (Annex C) | RH: 85%<br>T: 21C<br>For 4 hrs | N/A | 8 | 25mm diameter (~5cm$^2$) | 26.3 | 5 |
| TEB-ARR-STP-0059 | RH: 85%<br>T: 38C<br>For 25 hrs | NaCl, RH: 30%, T: 25C, Median :0.075 µm, C: 200mg/m$^3$ | 85 | N/A | N/A | 20 |

Some research projects have used ASTM F2299/F2299M to evaluate the filtration efficiency of materials for fabric masks or have referenced one of the above ASTM standards for guidance. Chen et al. [33] and Nallathambi et al. [34] used ASTM F2299/F2299M as a basis for their methodology; however, instead of using a monodisperse latex particle they used a polydisperse salt. Considering SARS-Cov-2 can be transmitted via aerosols of various sizes [3], [35] this is a logical approach for this context. NIOSH also has a standard method to test filtration efficiency of respirators with sodium chloride salt that is commonly used or adapted [36]. The NIOSH test method is used for approving N95 masks. This method, known as procedure TEB-ARR-STP-0059 is referenced in 42 CFR 84. It utilizes an automated filter tester with a neutralized NaCl challenge aerosol. The challenge aerosol needs to be at a RH of 30 ± 10% and 25 ± 5°C, with a median particle size of 0.075 ± 0.02 µm and concentration less than 200 mg/m$^3$. The filter should be preconditioned prior to testing and the flow rate during testing should be 85 ± 14 lpm [36], [37].

### 2.5. Breath Condensate and Masks

As humans breathe, they exhale breath condensate (EBC), a mixture of water, ions, and proteins. This breath condensate will be captured by face masks and will accumulate over length of wear time. Humidity and accumulated moisture can have a significant effect on mask filtration efficiency, breathability, and bacterial lifespan. Breath condensate properties can vary; one study found EBC to have a total ionic strength of ~500 µM [38], this same study found protein content in respiratory fluid but not in breath condensate. Scheideler et al. [39] assessed EBC for protein content, finding between 0.76 µg/ml and 107.7 µg/ml in the EBC of 8 out of their 10 subjects. Another study found an average EBC protein content of 6 µg/mL which is within the previously stated range [40]. This same study found EBC to have an average pH of 6.3 and EBC volumes expelled in a 6-minute period to be 0.627, 1.019, and 1.358 mL at flow rates of 7.5, 15 and 22.5 L/min, respectively. This is similar to the findings of Winters et al. who reported 0.71-0.91mL of EBC over a 6-minute collection period and 1.2-1.62mL of EBC over a 10-minute period, depending on collection method [41]. Volume of EBC exhaled by individuals is also variable and dependant on both individual health and activity state (resting, walking etc.). PH of EBC is highly dependent on individual health, individuals with asthma tend to have more acidic EBC [38].

Most conventional mask recommendations include that a mask should be removed once it is wet or dirty [1], [42]. This is a logical recommendation, however; it is also very vague and subjective. The mask may be damp from breath condensate long before someone deems it is too wet for wear. It is important to determine experimentally at what point is a mask no longer suitable for purpose due to wetting. There are a few ways that breath condensate could negatively impact the filtration performance of a mask. The electrostatic properties of a filter are compromised when wet or in an environment with high relative humidity [12]. Also, the fibers of the filter when wet can matte or bind creating a barrier for gases, thus decreasing the breathability [16].

## 2.6. Review of Mask Related Research

Due to the urgent and widespread nature of the pandemic, considerable time and money has been invested in the past year in COVID-19 related research.

### 2.6.1. General Suitability Studies

Prior to the COVID-19 pandemic there has also been various attempts to quantify mask efficiency and other related parameters for mask use in health care settings and as prevention for the spread of influenza and other past diseases of concern such as H1N1. Some of these previous facemask-related studies looked at the viability of using cloth masks for the potential future case where there would be a need for widespread protection against a respiratory infectious disease [43], [44], [45], [46]. Many of these studies were generic in their approach; the consensus of these early studies is that cloth masks do reduce exposure to potentially harmful aerosol, but they are significantly less efficient than medical masks. These results are in line with the current research that is being produced on the topic of cloth face masks for use in the pandemic. However, much of the emerging research on this topic is looking at ways to increase the suitability of cloth masks for use against transmission of infectious diseases. This includes research into different fabric materials, layering, coatings, designs and other ways that can increase filtration efficiency and functional use of cloth masks by the public. Due to the testing requirements and other regulations regarding medical mask, the filtration efficiencies and breathability parameters of medical masks are well understood and in themselves do not need to be furthered researched. Mask design and fit is exceedingly important for mask performance, poor fit significantly reduce filtration efficiency [47]. Despite this being an important factor for mask efficiency, for the purpose of this scope the influence of fit will not be furthered investigated. A few significant studies on the topic of cloth mask filtration efficiency are presented in Table 2-2. The results of these studies are varied considering the number of parameters that can be adjusted.

***Table 2-2*** *General cloth mask use studies*

| **Reference** | **Objectives** | **Types of masks/ materials used** | **Notable Results** |
|---|---|---|---|
| Konda et al., 2020 [3] | Evaluate FE of particles in 10 nm-10 μm range at 1.2 and 3.2 CFM. | Cotton, silk, chiffon, flannel, synthetics, and combinations | Individual materials had filtration efficiencies of 5-80 % found for particles < 0.3 μm with an increase to 5-95 % for > 0.3 μm. These results increased with layering, layering can well approximate medical masks. |
| Li et al., 2020 [48] | Evaluate particle concentration at 3 different distances from a mask wearer while coughing | Face shield, cloth mask, surgical mask, N95, and combinations | Face shield provided essentially no source control. Cloth mask reduced particle count by 77-89 % depending on distance and the surgical mask were > 94 % efficient. Also studied coughing particle size distribution and a peak coughing flow of 20.5 l/min. |
| Rengasamy et al., 2010 [44] | Compare penetration through cloth masks and other fabrics to N95 Performed tests with polydisperse and mono disperse aerosols at 5.5 cm/s and 16.5 cm/s | Cloth mask, other fabrics (sweatshirt, t-shirt, towel & scarf), and N95 | Penetration of 40-90 % through materials with polydisperse aerosols, significantly higher than the N95. Penetration increased marginally with the increase in face velocity for tests with the monodisperse aerosol. |
| Hao et al. 2020 [49] | Evaluate FEs and breathability of various household materials for use as homemade masks. Tests done at 232., 15.3 and 9.2 cm/s. | N95, KN95, air filters, vacuum bags, coffee filters, activated carbon, bandana, scarf, pillowcases + combinations (43 in total) | Fibrous filters (household air filters) performed significantly better than common fabrics. Fibrous filters could come close to N95 performance. Increasing thread count increased efficiency. As face velocity was increased the FE decreased for fibrous filters and both increased and decreased with fabric filters, depending on particle size. |

| | | | |
|---|---|---|---|
| Zangmeister et al. 2020 [50] | Different materials were evaluated in terms of filtration efficiency and breathability. The two factors were considered simultaneously using a quality factor. Face velocity at the filter holder was 6.3 cm/s. | 32 materials (14 cotton, 1 wool, 9 synthetic, 4 synthetic blends, 4 synthetic/ cotton blends) and combinations of those materials | The 5 materials with the best performance were all woven with moderate thread counts, 3 cotton and 2 synthetics. They also found that as number of layers were increased, so did filtration efficiency and pressure drop. The minimum filtration efficiencies reported are well under 50% for all fabrics. |
| Lustig et al. 2020 [51] | Using fluorescent nanoparticles, they compared the filtration efficiencies of household fabrics to a 5-layer N95 at a flow rate of 14 l/min. Breathability was not considered. | N95 and 70 different household fabrics (such as terry cloth, different cottons, flannel, denim, polypropylene, etc.) | 14 of the fabric combinations were found to have transmission rates similar or better than the 5-layer N95 mask. Another conclusion from this data is that an ideal mask has both and absorbent and barrier layer. |
| Zhao et al. 2020 [52] | Tested the FE of household materials using a modified NIOSH approach. Also looked at possibility of enhancing performance with triboelectric charging | Cotton, polyester, nylon, silk, polypropylene, paper-based fabrics. | All individual fabrics had FEs between 5% and 25%. Charging increased FEs for most fabrics, especially polypropylene. Concludes that an unknown number of layers of some of the materials tested could meet or exceed medical grade filtration. |

### 2.6.2. Mask Use Studies

Most COVID-19 mask related research has focused on suitability of different mask and methods for enhancing filtration efficiency or fit. While these are important topics, mask use can have just as important of an impact on mask efficiency and should also be a topic of focus. Because masks are being reused, washed at home, and used over longer time periods in new circumstances, such as at the gym, these elements must be researched and understood. Wang et al. (2021) [15] performed a review of mask use in terms of COVID-19 transmission mechanisms, mask case studies, regulations, and research. Their review included a section on the topic of proper mask use and reuse to address this important topic. This section provides a summary of some disinfection techniques and reuse options for medical masks. Other than the recommendations by the American Center for Disease Control that cloth masks should be washed to avoid contamination, there is little information on reuse of cloth masks. The French government, however, has included specific recommendations for mask reuse and washing as part of their mask requirement documentation. They require manufacturers certify that masks can maintain their properties through 5 to 20 wash cycles of minimum 30 minutes at 60°C washing temperatures. They recommend that masks are washed separately and dried thoroughly and inspected after every wash for damage [42]. These requirements, however, are not extended to homemade masks. Though reuse is one of the main features of reusable cloth masks, there are few studies that evaluate the impact that reuse and prolonged single use has on filtration efficiency.

Mask washing and disinfection research is beginning to increase and the effect of disinfection on mask filtration efficiency is beginning to be understood. These topics are important for all mask types. Though medical masks are well regulated in terms of filtration efficiency, due to higher demand for masks, people are using medical masks in ways that were previously not recommended or under-researched. One approach to improving mask use is the concept of applying antiviral coating to face masks. Both Pemmada et al. (2020) and Bezek et al. (2021) investigated the possibilities of different coatings for their ability to inactivate COVID-19 viruses [53], [54]. This could help ensure that cloth masks are better disinfected and more suitable for long term wear during the day. While this is a promising concept it still needs to be tested. Table

2-3 summarizes some notable studies that have investigated topics related to appropriate mask use and mask reuse.

***Table 2-3*** *Studies on topic related to mask reuse (disinfecting, wettability, length of wear, etc.)*

| **Reference** | **Objectives** | **Types of masks used** | **Notable Results** |
|---|---|---|---|
| Ou, 2020 [55] | The effect of different decontamination methods on filtration efficiency. Methods tested: ultraviolet germicidal irradiation (UVGI), oven heating, steam heating, and isopropanol soaking. | Respirator, surgical mask, procedure mask and two new respirator materials | Found that certain methods worked better with the electret versus non-electret materials and vice versa. UVGI method preserved the efficiency of the masks tested to an acceptable level for 10 full treatments. |
| Zhao et al., 2020 [20] | Studied the effect of sterilization using UV-C irradiation at specific wavelengths on filtration efficiency. | N95 and non-rated surgical masks | Found that disinfection with UV-C irradiation of specific wavelengths (254 and 265 nm) at a certain specific energy can disinfect masks with no reduction in filtration efficiency and no alteration of the mask's physical characteristics. |
| Lu et al., 2020 [56] | Studied the effect of gentle washing and air drying on filtration efficiency after 30 washes. | mask that uses PTFE as the membrane in the filter layer | Found that after 30 wash cycles filtration efficiency was reduced by 10-20 %. For comparison, a surgical mask was washed once, this resulted in a 60 % reduction in filtration efficiency. |
| Wang et al., 2020 [23] | Studied the effect of soaking masks in hot water and then drying with a hair dryer on filtration efficiency. | Disposable medical, surgical, and KN95-grade masks | Found that while filtration efficiency dropped, the masks were still suitable for purpose after up to 10 decontamination/wear cycles. |
| Hossain et al., 2020 [21] | Investigated a method to regenerate filtration capacities of degraded masks. | N95 | Found that recharging the electrostatic characteristic of masks possible and increases filtration efficiency post decontamination. With this method, after decontamination by ethanol and washing machine and recharge, filtration efficiencies met N95 requirements. |

| | | | |
|---|---|---|---|
| Carnino et al. 2020 [57] | Tested pre-treating materials for use as face mask filters with salt solution. | Paper towel (2 brands), Surgical mask filter layer | Found a significant increase in filtration efficiency of nanoparticles. Found that the salt solution alone is sufficient to produce this increase. |

### 2.7. Conclusions

From the available literature there is a clear understanding of the filtration efficiency and

Based interpretation of the literature reviewed in this section, generally:

- Cloth masks do filter a significant amount of potentially contagious particles [48], [3], [44], [45], [43], [58]
- Cloth masks are significantly less efficient and consistent compared to medical masks [44], [45], [43], [48], [58]
- More layers increase mask efficiency [3]
- Higher face velocities seem to often result in lower efficiencies, especially for woven fabrics, but there is no consistent correlation between face velocity and filtration efficiency at this time [3], [44]
- Medical masks can be disinfected but only to a limited extent and only with certain methods [20], [21], [23]

Based on the available research, there are a few clear areas for increased study. The first area is the effect that face velocity can have on mask efficiency. Most studies that included multiple face velocities investigated only 2 at most. The ASTMF2299/F2299M include a range of face velocities; some studies such as Rengasamy et al. (2010) [44], used 2 face velocities within the acceptable standard range and found the face velocity to have noticeable effects on filtration efficiency. Better understanding of the impact of testing face velocities on filtration efficiencies will help comparisons of results at different face velocities.

Another area that requires more research is the proper use and reuse of cloth masks. Cloth mask washing and use limits are often cited as being important to the suitability of these masks to prevent disease transmission however at this time this is not well understood or quantified. Most studies that consider duration of wear time do so in terms of virus accumulation and the need for disinfection. While this is important it fails to consider the potential decrease in filtration efficiency due to wetting of mask over time from collection of breath condensate. The effect of breath condensate on filtration efficiency for mask wear has not been quantified at this time. Konda et al. (2020) also indicated this as an area for future study.

# 3. Methods and Materials

## 3.1. Experimental Design

A testing line was built in the air quality control and characterization lab at the University of Alberta for use in testing particle capture efficiency and pressure drop of materials for use as protective masks.

The design of this experiment was closely modeled according to ASTM standards F2299/F2299M [59]. This standard provides a test method for assessing the particle capture efficiency and pressure drop of a material to be used for a face mask. The only significant difference between the experimental design used in this dissertation and the standard test method is the type of particles used. After using the set up with both latex spheres and NaCl aerosols in preliminary experiments, NaCl aerosol was used for all final tests as this provides more consistency and precision to inlet particulate concentration. Furthermore, there are a few other challenges when using monodisperse latex spheres including, their susceptibility to clumping or forming clusters [12]. NaCl is a polydisperse aerosol while latex spheres are a monodisperse aerosol. The NaCl aerosol, while polydisperse has sufficient concentration of the particle sizes that we are interested in for this research and therefore is an appropriate alternative. NaCl has been used very frequently in many other recent research on the topic of face mask suitability [33], [34]. The test set up suggested by ASTM is presented in Figure 3-1. The ASTM set-up was used as a general guide to design a test set-up that would work for the needs of this testing.

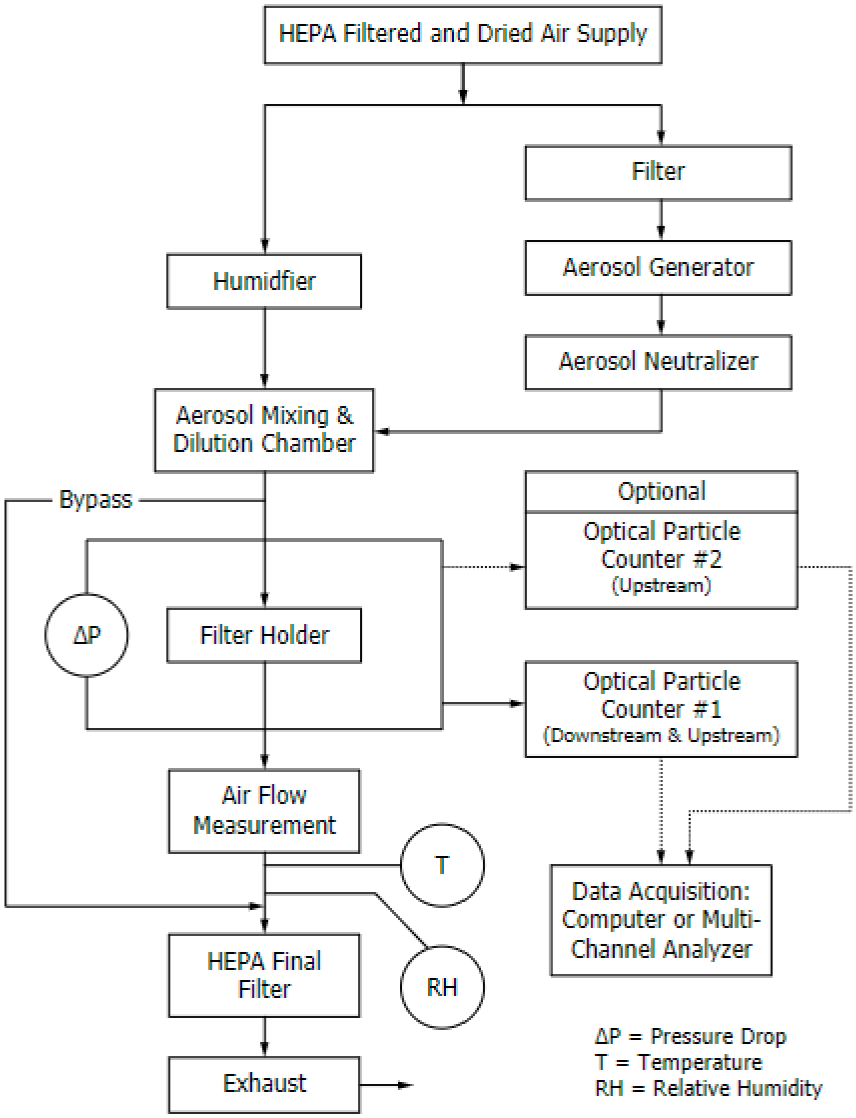



***Figure 3-1****. Schematic of suggested ASTM test setup (ASTM F2299-F2299M-3 [59])*

The actual test set-up used a single, multi-channel optical particle counter (OPC) and did not include an aerosol neutralizer as suggested in the ASTM schematic. The OPC sampling lines were controlled by a valve switching machine and the upstream sampling line for the OPC was diluted by a factor of ten to protect the OPC. A schematic of the test set up used and a photograph of the in lab set up can be found in Figure 3-2.

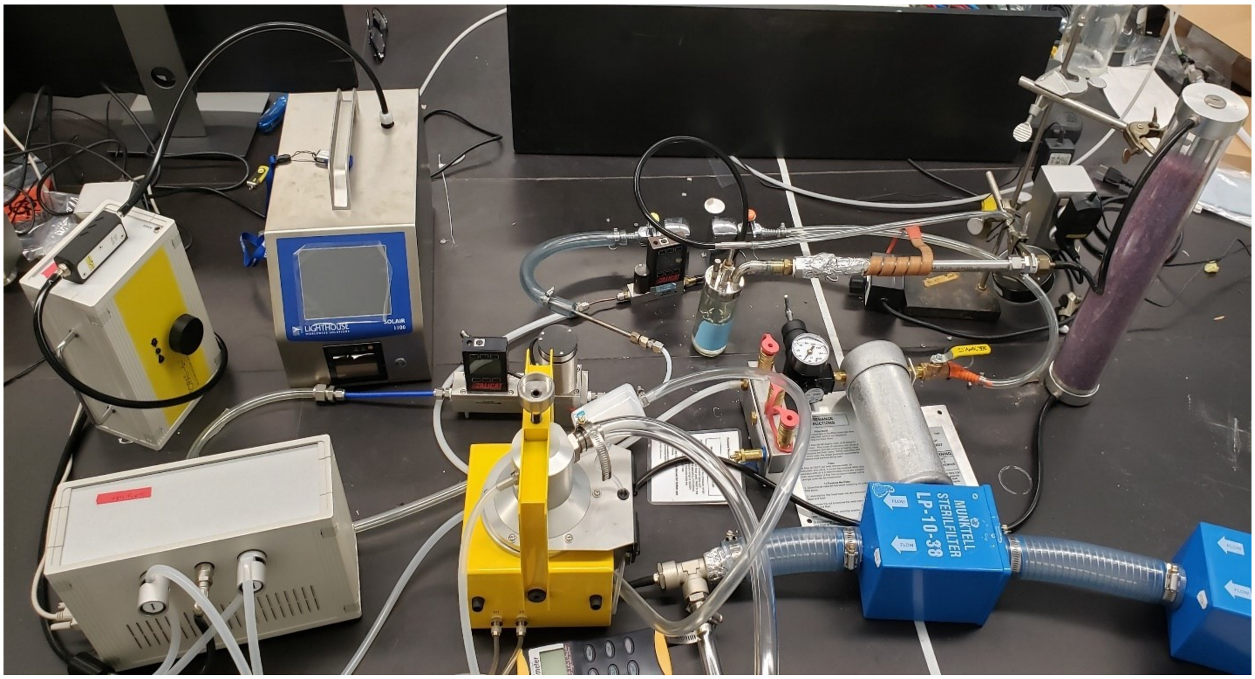
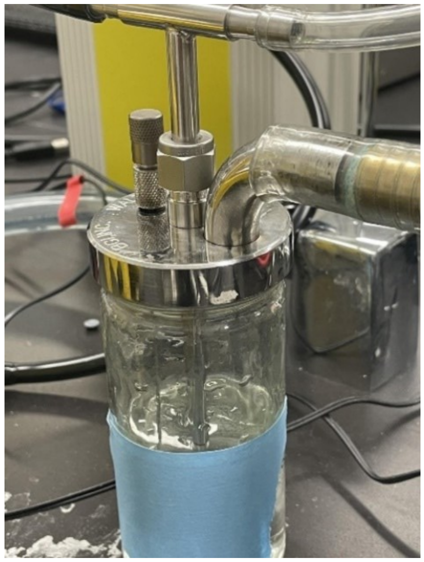



***Figure 3-2**. Set-up for Testing of Filtration Efficiency and Pressure Drop of Masks and Mask Materials*

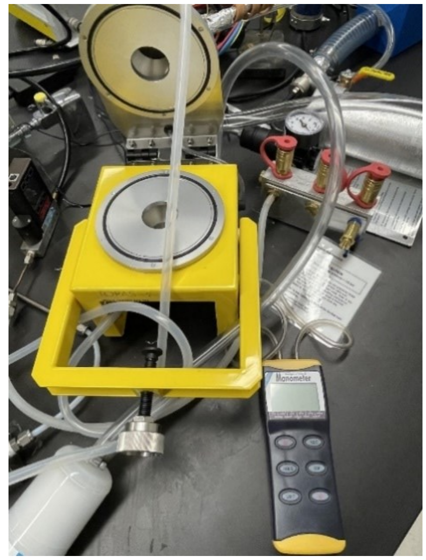
As presented in the overall schematic, this test set-up uses an aerosol generator, seen in Figure 3-3, a), to create the aerosol stream which is then dehumidified before being combined with filtered air. This combined air then flows through a filter holder, Figure 3-3, b), under vacuum pressure. A manometer, seen in Figure 3-3, c), measures the pressure drop across the filter in the filter holder when flow is active. There are two lines, one connected to upstream, and one connected to downstream of the filter in the filter holder. These lines are connected to a valve switching machine which is then relayed to a dilution chamber before they are connected to the optical particle counter, Figure 3-3, d), for measurements. The OPC used measures particles in a set volume according to bin size, the particle sizes measured are >0.1, <0.15, 0.2, 0.25, 0.3, 0.5, 1 and 5 μm. The aerosol used for this test did not have any significant amounts of 5 μm particles and was therefore not included in results. The OPC takes measurements every 5 seconds, and this data is saved in CSV format on a USB drive. All part components are described in detail with manufacturing numbers in Table 3-1.

***Table 3-1*** *Components used in mask suitability tests*

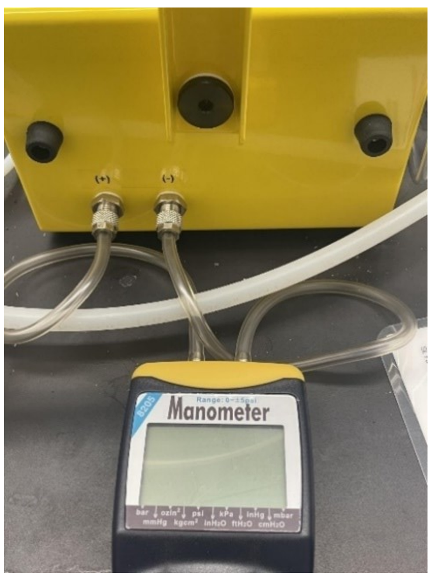
| **Component** | **Manufacturer** | **Model Number** |
|---|---|---|
| Optical Particle Counter | Lighthouse Worldwide Solutions | SOLAIR 1100 |
| Switching Valve Machine | TOPAS | SYS 520/S |
| Dilution Machine | TOPAS | DIL 550 |
| Manometer | OMEGA | HHP 8205 |
| Filter Holder | TOPAS | AFS 153 |
| Humidity Meter | OMEGA | OMEGAETTE HH311 |
| Mass Flow Controllers | Alicat | MCR-100SLPM-D/5M |
| Aerosol Generator | BGI, INC. | N/A |



a) *Aerosol Generator*



b) *Filter Holder*

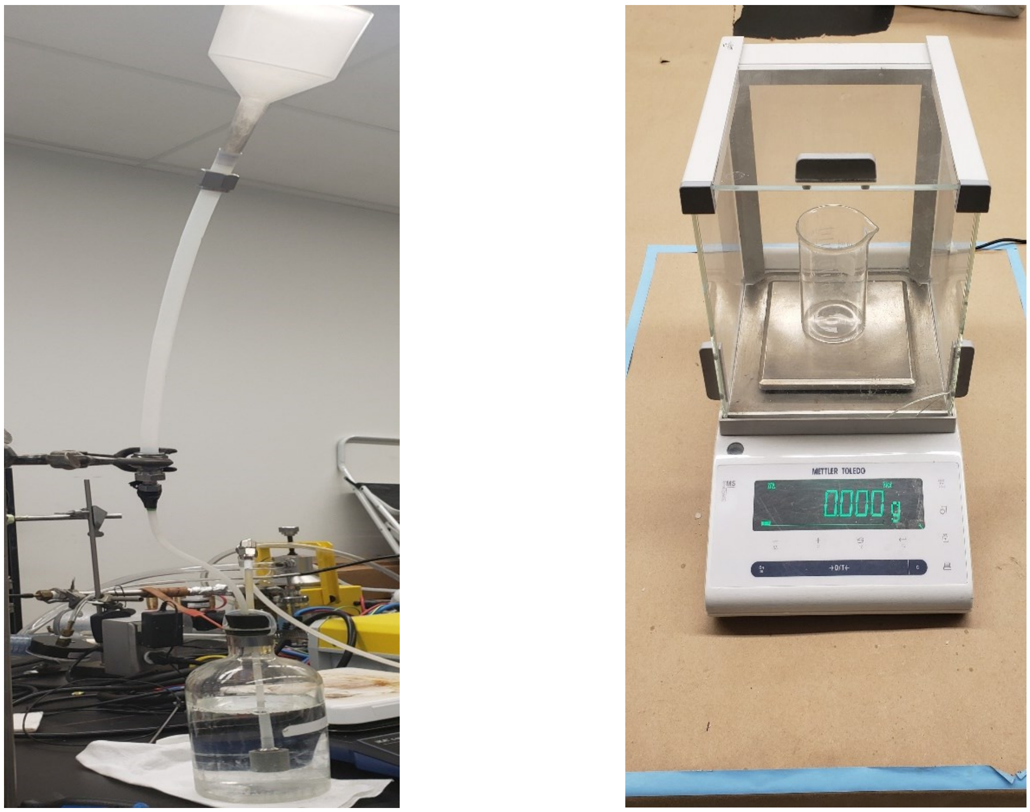



c) *Manometer*


d) *Optical Particle Counter*

***Figure 3-3***. *Test Set-up individual components, a) Aerosol Generator, b) Filter Holder, c) Manometer, d) Optical Particle Counter*

An apparatus was used to expose the masks to EBC in a way that mimics real life exposure. This set up consisted of a porous stone bubbler connected to a funnel with a diameter greater than the filter holder opening at the outlet. The inlet of the bubbler was connected to a MFC drawing filtered air. The MFC was set to a flow rate that was both attainable with the compressed air source as well as a flow rate that is within the acceptable range for ASTM mask testing standards [59]. This exposure set up is pictured in Figure 3-4, as well as the scale used to weigh the masks before and after exposure.




*a) EBC exposure bubbler set-up* *b) Scale used to weigh EBC collection on masks*

***Figure 3-4*** *EBC exposure test devices a) EBC exposure bubbler set up, b) Scale used to weigh EBC collection on masks*

## 3.2. Method

The procedure used for testing the performance of masks and mask material is adapted from ASTM standard F2299/F2299M to fit with the exact specifications of the test set up used for this research. The experiments consisted of an initialization period and a testing period. During initialization, the OPC and the test lines were purged. During the testing period of the experiments, a mask or mask material was placed in the filter holder and air flow with the challenge aerosol was routed through the filter holder. The manometer measured the pressure drop across the filter holder while the OPC was set to purge. When set to purge both the inlet and outlet lines are closed and are not measuring. To test filtration efficiency, the inlet and outlet lines were opened one at a time, and the measurements were taken for 3 minutes for each line. All measurements are done in triplicate on one sample, multiple samples were tested for the different scenarios. The inlet and outlet concentrations were averaged over a 3-minute sampling time and used to determine filtration efficiency. The masks were tested with their technical inside facing upwards toward the inlet concentration. For more details, please see Appendix A.

## 3.3. Materials

### 3.3.1. Simulated EBC

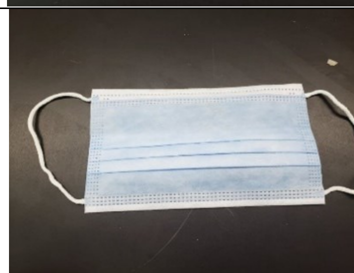
EBC simulation was created based on average protein, ionic strength, and pH values. The values for protein content, pH and volume determined by McCafferty et al. were used considering EBC was analyzed by McCafferty et al. at flow rates of 15 L/min and 22.5 L/min which are similar to the flow rates used in the experiments in this paper. Furthermore, the values determined by McCafferty et al. were similar to other studies. The ionic strength values used were determined in Effros et al. Protein content used was 6 µg/mL, ionic strength used was 500 µM and the volume of EBC corresponded to 1.2 mL / 6 minutes of regular breath [38], [40]. For more details on solution preparation and calculation see Appendix B. This simulation was made with deionized water, salt as the ion and albumin as a protein.

### 3.3.2. Masks Materials

Four commercially available non-medical masks were chosen for this experiment, three of these are cloth and one disposable. The masks chosen are sourced from various manufacturers and all with different designs. One mask is designed with a pocket for filters; for the first objective of this experiment, publicly available filter materials were used with this mask to investigate the impact that this design feature could have on mask suitability. These masks and filter materials are pictured in **Table 3-2**.

***Table 3-2***. *Facemasks used in this research*

| Mask Brand | Shorthand | Photo | Mask details |
| --- | --- | --- | --- |
| Firm Grip (sourced from Home Depot) – Design 1 | FG-d1 |  | 3 Layers, 100% cotton, no pocket |
| Firm Grip (sourced from Home Depot) – Design 2 | FG-d2 |  | 3 Layers, 1 – 100% polyester nano mesh, 2 – 100% polyester, 3 – 65% polyester and 35% cotton. Also has water-repellent (unspecified) |
| Old Navy | ON |  | 100% Cotton, layers not specified, no pocket |

| | | | |
|---|---|---|---|
| Tilley (sourced from Costco) | Tilley |  | 3 Layer Woven with filter pocket |
| Ecoparksg brand disposable mask | Disp (E) |  | Disposable Mask – 3ply |
| Hui Lin brand disposable mask | Disp (HL) |  | Disposable Mask - 3ply, non-woven |
| NLT brand level 3 surgical mask | L3 SM |  | Non-woven, 3 layers: polypropylene filter, soft internal layer, hydrophobic layer |
| Levitt-Safety brand level 2 | L2 SM |  | Disposable Mask – 3ply, non-woven |
| N95 (Dasheng DTC3Z) | N95 |  | Mold compression 5 layers of non-woven and melt blown materials. |

| | | | |
|---|---|---|---|
| Filtrete furnace air filter MPR AF2200 | AF2200 |  | Electrostatic high-performance TM 2200, non-woven, 100% polypropylene |
| Filtrete furnace air filter MPR 1500 | AF1500 |  | Electrostatic high-performance TM 1500, non-woven, 100% polypropylene |
| Facemask filtration material | Filti |  | Non-woven, polypropylene/polyester |
| Cabin Air Filter Fram | ACF |  | Non-woven, polypropylene/polyester |
| Bed sheet Home TrendsTM | BSH180 |  | Woven, 100% cotton, low thread count |

| | | | |
|---|---|---|---|
| Bedsheet MainstaysTM | BSH300 |   | Woven, 100% cotton, high thread count |
| T-shirt Hanes | T-shirt |   | Knitted, 100% cotton |

The masks and materials were chosen to represent a variety of parameters and attributes present in homemade and commercial masks. Four different types of cloth masks were chosen from three different brands. Three of these cloth masks are made of 100% cotton, these three styles are woven and represent three different, commonly seen designs: pleated/square, non pleated, non-pleated with a pocket. The other cloth mask has a blend of material and is from the same manufacturer as one of the cotton masks. This was included to evaluate the impact of fabric type as well as the difference in quality among a single brand through different designs. Two different non-medical disposable masks were included to investigate the difference in quality among similar designs, especially considering these designs are also similar to the surgical mask design. In terms of materials, two bed sheet materials were used so that the impact of thread count on performance could be investigated. The bed sheets and t-shirt material represent different easily available cloth material, the bedsheets are both woven while the t-shirt was knitted. This was used to investigate how cotton behaves differently when fabricated differently. The Filti material was investigated since it is being advertised as a filtration option for masks. The inclusion of the

ACF and the furnace filters was to compare the mask filters to other household filters. Two furnace filters with different MPR ratings were tested to investigate the impact of this parameter on filtration performance in the COVID-19 context.

### 3.4. Calculations

The inlet and outlet concentration data from the OPC are reported as particulates per a set volume of 0.08 cubic feet and it is diluted by a factor of 10. Inlet and outlet data from the OPC was normalized into particulates/m$^3$. Once the data is in proper units Filtration efficiency based on number **Equation 1** is used to determine filtration efficiency, based on number, for each size distribution category. The mass flow controllers used have units of standard liters per minute. To convert the liters per minute shown on the MFC to the desired face velocities in cm/s the conversion equation shown in Face Velocity

**Equation 2** was used. Quality factor (QF), Quality Factor

**Equation 3**, is a metric that can be used to compare filtration media in terms of both filtration efficiency and pressure drop (ΔP) at the same time. The opening of the filter holder used is 2 cm in diameter.

*Filtration efficiency based on number* ***Equation 1***

$$\text{Filtration efficiency}(\%) = \eta = \frac{\text{Inlet Concentration} - \text{Outlet Concentration}}{\text{Inlet Concentration}} * 100$$

*Face Velocity* ***Equation 2***

$$Face\ Velocity(cm/s) = \frac{Flow\ rate(slpm) * \frac{1000}{60}}{A(cm^2)}$$

*A = area of filter holder opening = 12.56 cm$^2$*

*Quality Factor* ***Equation 3***

$$QF\ (kpa^{-1}) = \frac{-ln(1 - \eta/100)}{\Delta P}$$

ΔP = Pressure drop in kpa

# 4. Results and Discussion

The chapter is divided into three sections, each section corresponding to an objective of this experiment. The first section presents data and analysis on mask suitability in terms of filtration efficiency and breathability, for the purpose of protection against COVID-19 transmission. This section includes filtration efficiency and breathability data from 7 different individual fabrics, 4 different commercially available cloth masks, 5 types of commercially available disposable masks (3 medical and 2 non-medical) and combinations of these masks and fabrics. The second section discusses and presents data on the influence of face velocity on filtration efficiency of commercially available masks. The last section discusses the influence of exhaled breath condensate on performance of commercially available masks.

## 4.1. Mask and Fabric Suitability for COVID-19 Transmission Protection

### 4.1.1. Pressure Drop and Filtration Efficiency Results Across Fabrics

Findings in this section have been organized according to the type of mask or material. Filtration efficiency data was calculated using Equation 1 from Chapter 3. All inlet and outlet data measurements were averaged over a collection period and done in triplicate on the sample. Some tests were run in duplicate or triplicate depending on the materials required for the test, this data is specified in more detail throughout the results. All the pressure drop data was taken at a face velocity of 25 cm/s because this is the closest face velocity within the range of ASTM F2299 to the face velocity requested in EN 14683 Annex C. The pressure drop data presented is the average of 5 samples and has been normalized across the area being tested as to compare the results to the ASTM requirements. Pressure drop data as well as the unit conversion used for pressure drop data is available in Appendix C. As discussed in Chapter 2, level 1 surgical masks require a pressure drop of less than 5 $mmH_20/cm^2$ while level 2 and 3 surgical masks have a less stringent requirement of 6 $mmH_20/cm^2$ [1]; the N95 requirements are <32 $mmH_2O$ and <25 mmH2O for inhalation and exhalation [2]. For this work the pressure drop data will be compared to the more stringent of the two surgical mask maximum allowable pressure drop of 5 $mmH_20/cm^2$ [1]. The pressure drop per area metric is a better comparison for the test set-up being compared to the N95 total pressure drop metric.

The first few figures present the results from testing the individual fabrics as materials for use in masks at face velocities of 10 cm/s and 25 cm/s. These materials were tested in a preliminary way to inform decisions for fabric combinations, and thus were tested with only one sample. Inlet and outlet measurements were averaged over three minutes for the first measurement, after channel values had stabilized measurements were averaged over two minutes for the other two measurements. The inlet concentrations, the concentrations upstream of the sample, recorded during testing are presented on the filtration efficiency graphs for reference. The relative humidity (RH) for these tests was checked periodically and found to be around 30% during this portion of testing. The influence of RH is discussed further in 4.1.3. The pressure drop for these fabrics at 25 cm/s are included in Figure 4-1; this figure also includes the pressure drops measured for Level 3 surgical masks and the N95 mask tested, for reference.

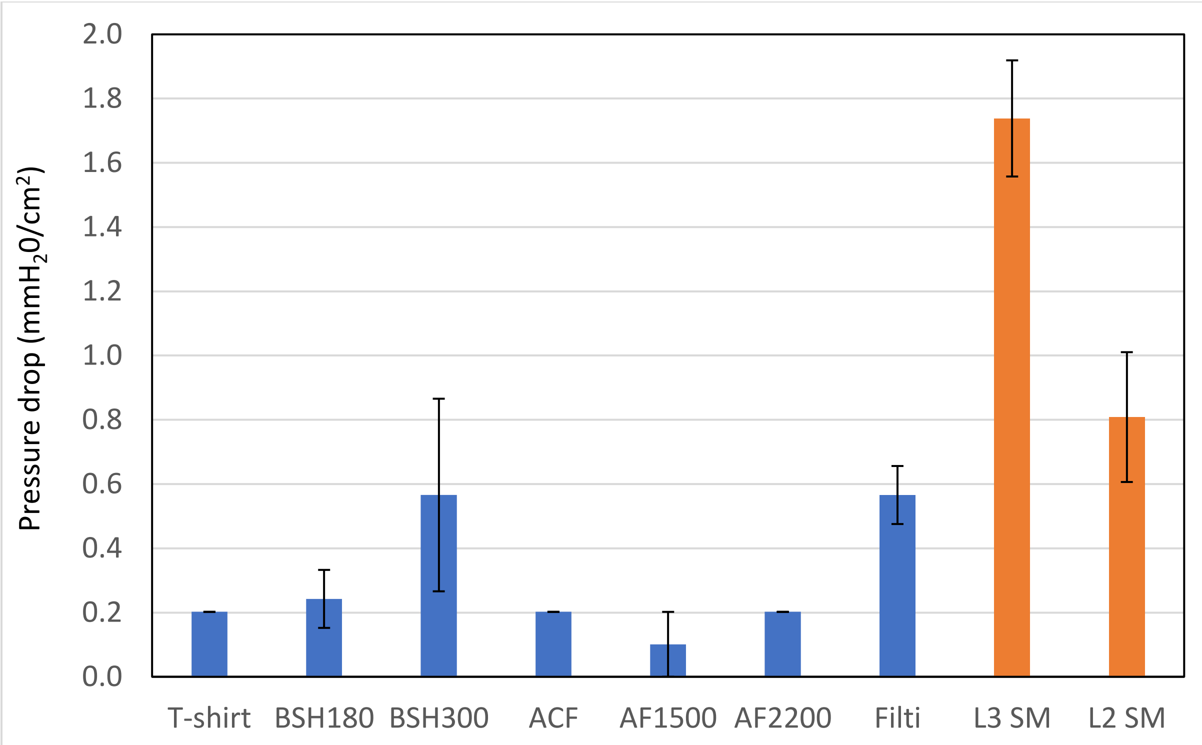
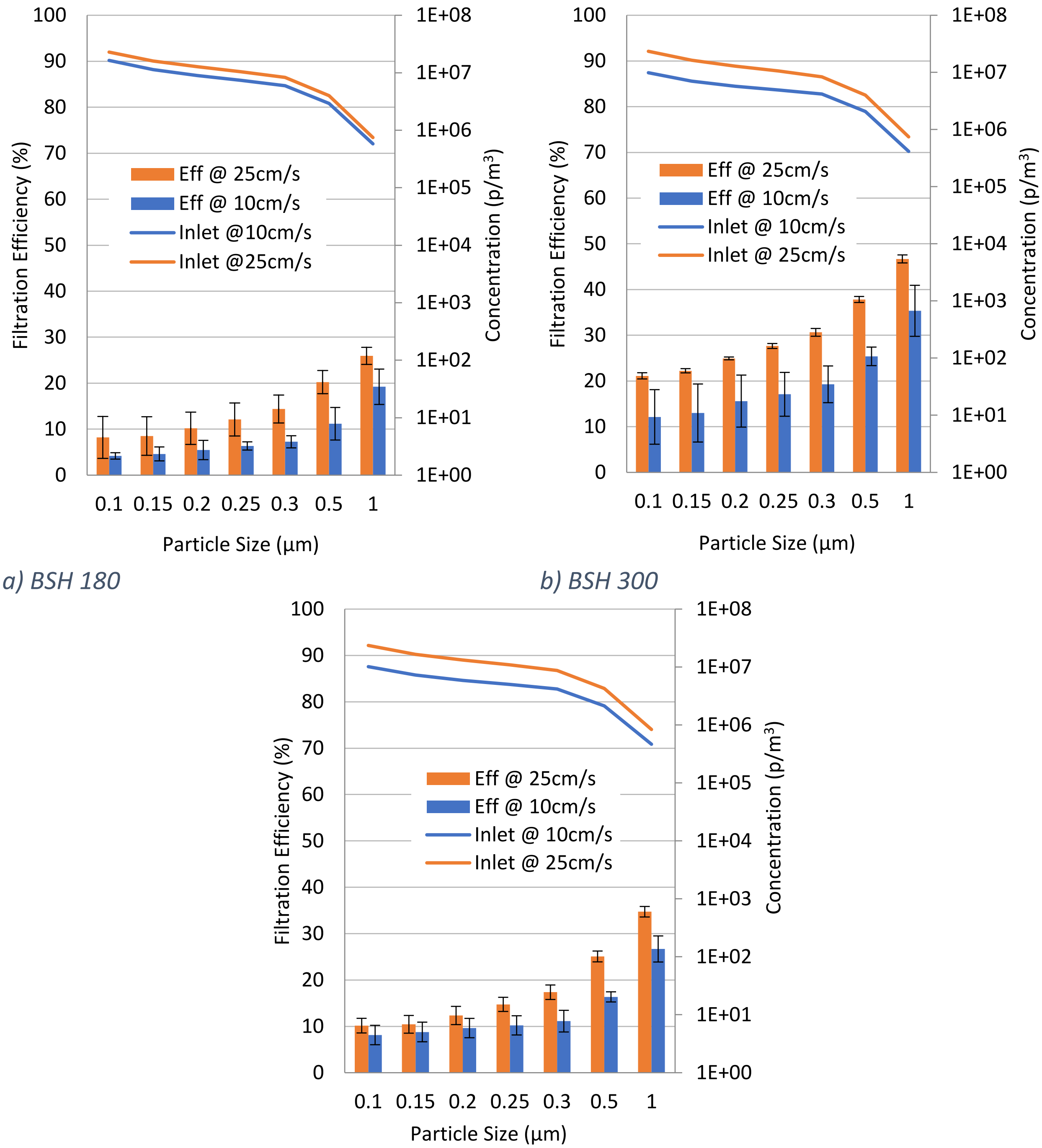



***Figure 4-1** Pressure drop results for individual fabrics at a face velocity of 25 cm/s. Error bars represent standard deviation of 5 measurements, except N95, which was based on 2 measurements*

Figure 4-2 presents the results from filtration efficiency testing of individual woven and knitted fabrics. This includes both the high and low thread count bedsheet material as well as the knitted cotton t-shirt. Figure 4-3 presents the filtration efficiency tests for non-woven individual fabrics; Filti, the cabin air filter and both furnace air filter materials.




*a) BSH 180* *b) BSH 300*

*c) T-shirt*

***Figure 4-2*** *Filtration efficiencies of woven and knitted individual fabrics and inlet particle concentration during testing at two face velocities, a) Filtration efficiency of BSH 180, b) Filtration efficiency of BSH 300, c) Filtration efficiency of T-shirt. Error bars represent standard deviation of 3 measurements on one sample.*

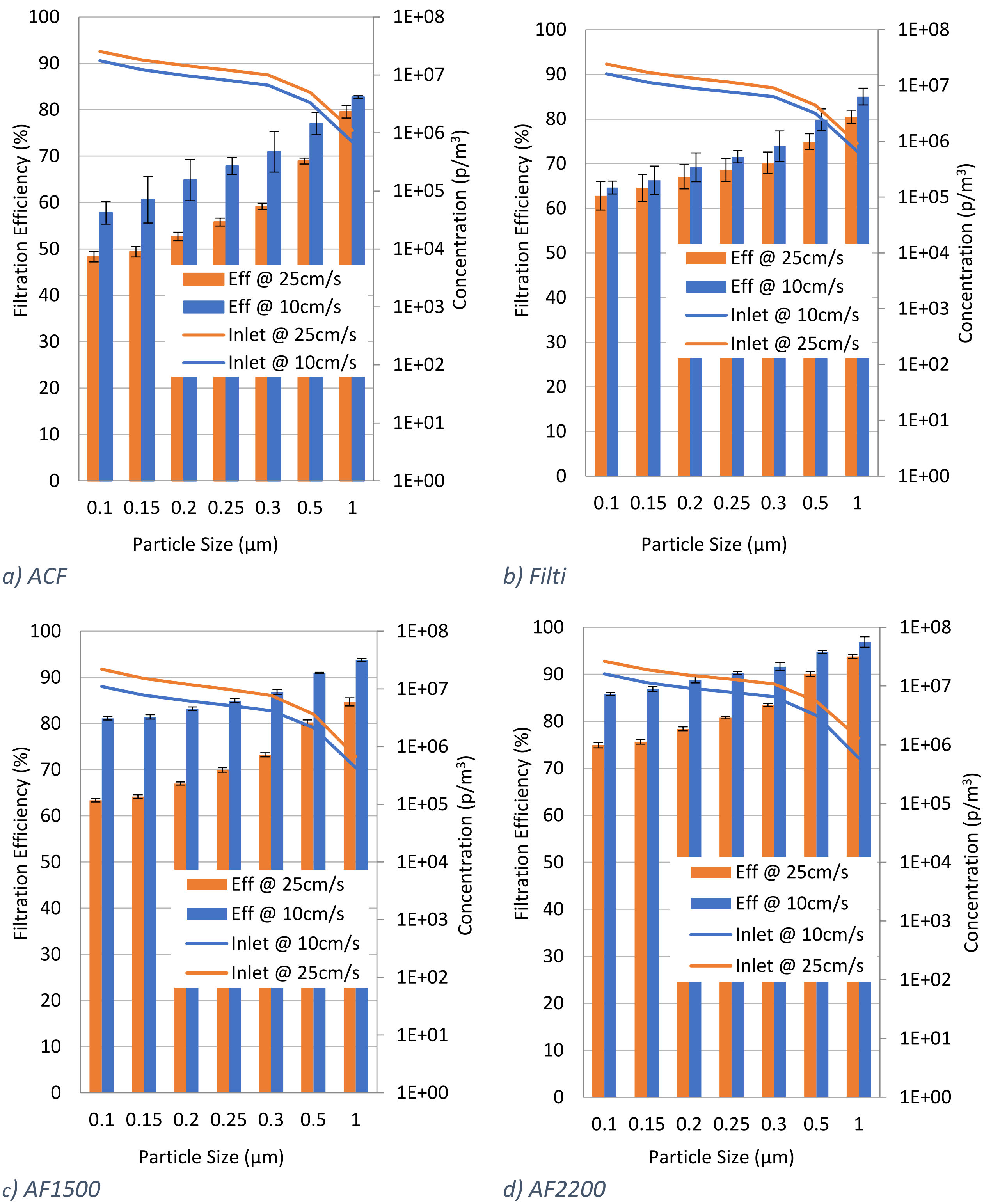



***Figure 4-3*** *Filtration efficiencies of non-woven individual fabrics and inlet particle concentrations during testing at two face velocities, a) Filtration efficiency of ACF at two face velocities, b) Filtration efficiency of Filti, c) Filtration efficiency of AF1500, d) Filtration efficiency of AF2200. Error bars represent standard deviation of 3 measurements on one sample.*

### 4.1.2. Pressure Drop and Filtration Efficiency Results Across Commercial Masks

The performance results of commercially available disposable and reusable masks are presented in Figures 4-4 to 4-7 for both face velocities of 10 cm/s and 25 cm/s. The pressure drop results for the reusable and disposable masks at 25 cm/s are presented in Figure 4-4. The RH was measured daily during this round of filtration efficiency testing, testing was only done within the 30-50% RH range as specified by ASTM F2299. The daily lab conditions, including RH, are included in Appendix D. The influence of RH is discussed further in 4.1.3.

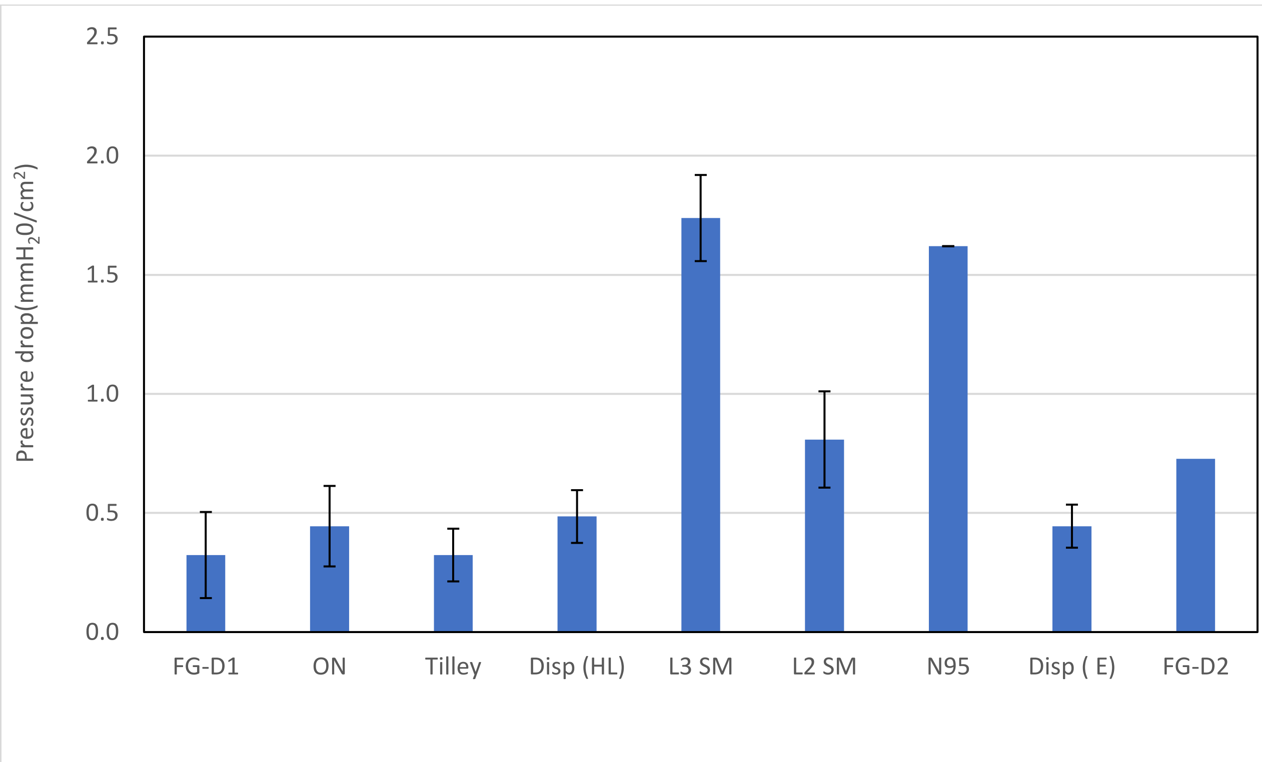
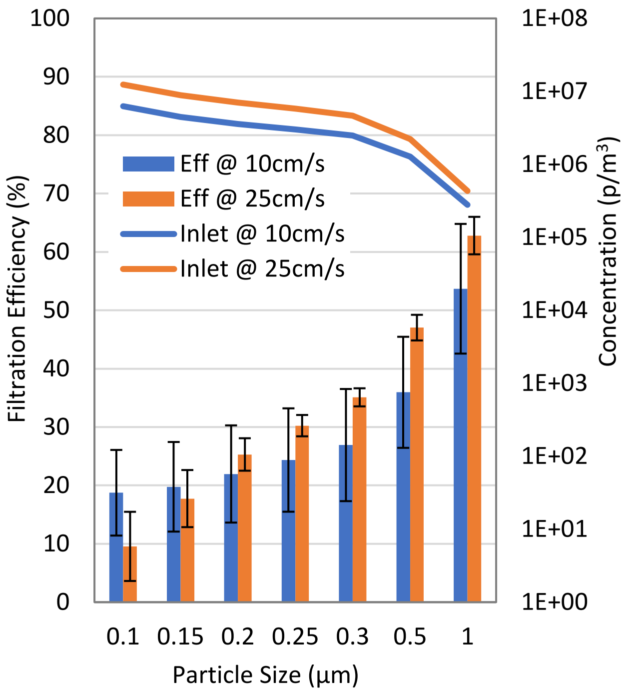
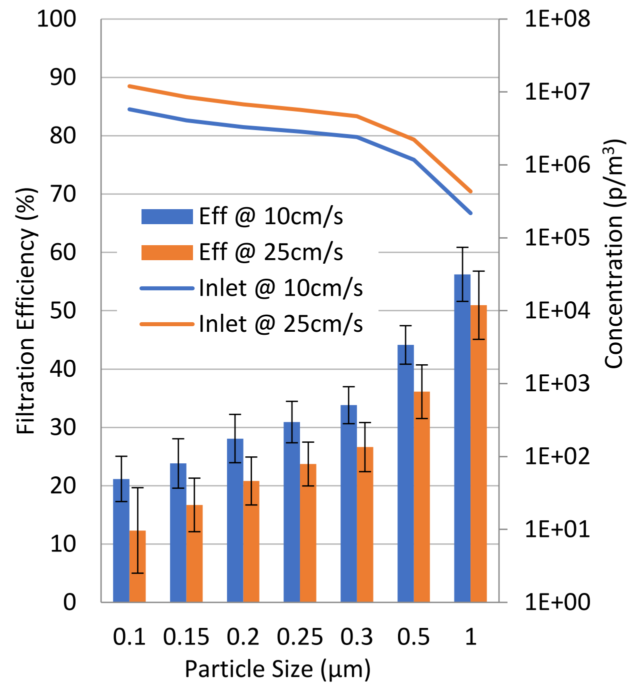



***Figure 4-4** Pressure drop results for commercial masks (reusable and disposable). Error bars represent standard deviation of 5 measurements.*

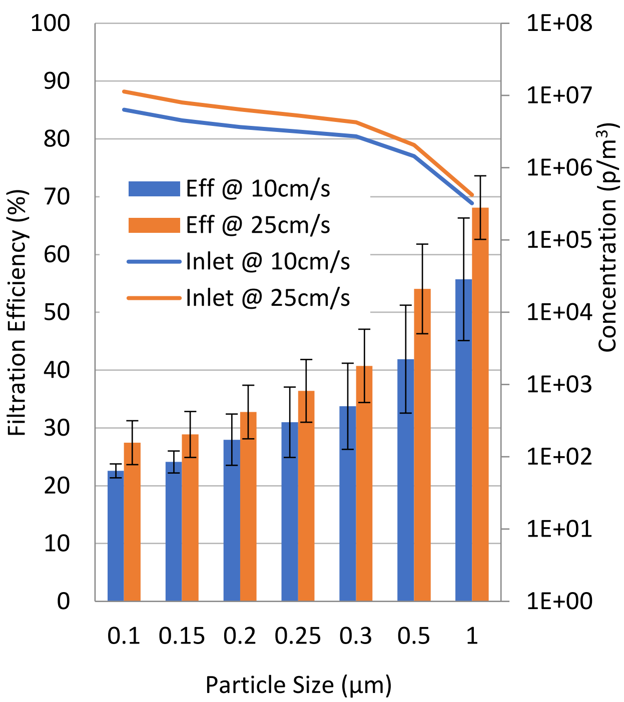
The results from testing reusable masks sourced from Old Navy, Tilley, and Firm Grip (with two different designs) are in Figure 4-5. Figure 4-6 and Figure 4-7 illustrate the results from testing medical and non-medical disposable masks respectively; this includes N95 masks, Level 3 surgical masks, Level 2 surgical masks and both brands, Hui Lin (HL) and Ecoparksg (E), of disposable non-medical masks. The results presented here are the average of the measurements done on two different samples, except for the N95 masks at 10 cm/s, due to the scarcity of N95 masks. Each sample has upstream, and downstream measurements averaged over 3 minutes done in triplicate.



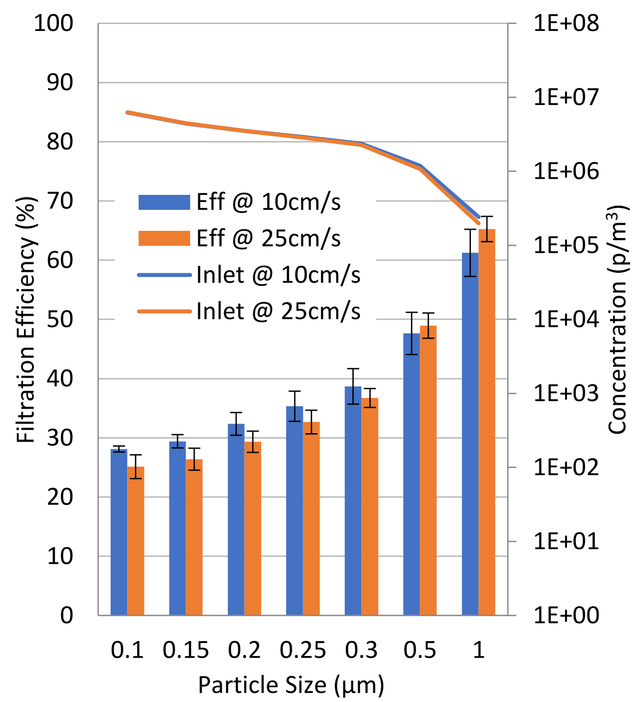

*a) Old Navy*




*b) Tilley*

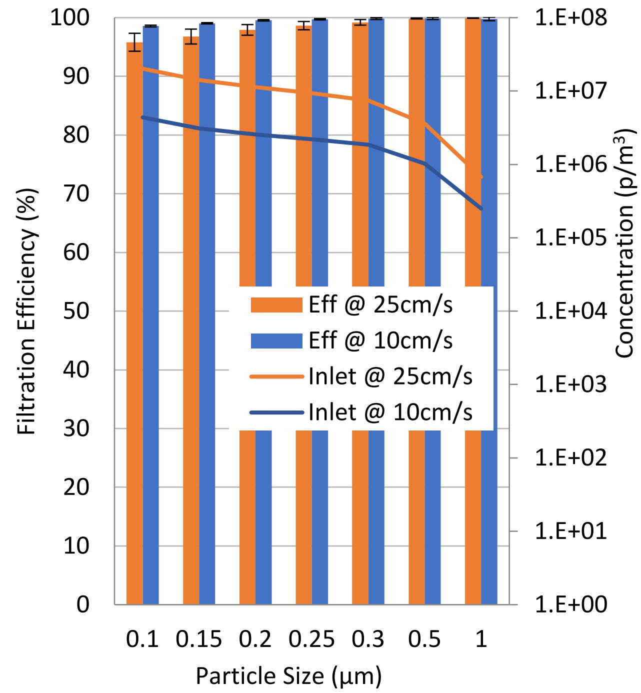



*c) Firm Grip – Design 1*

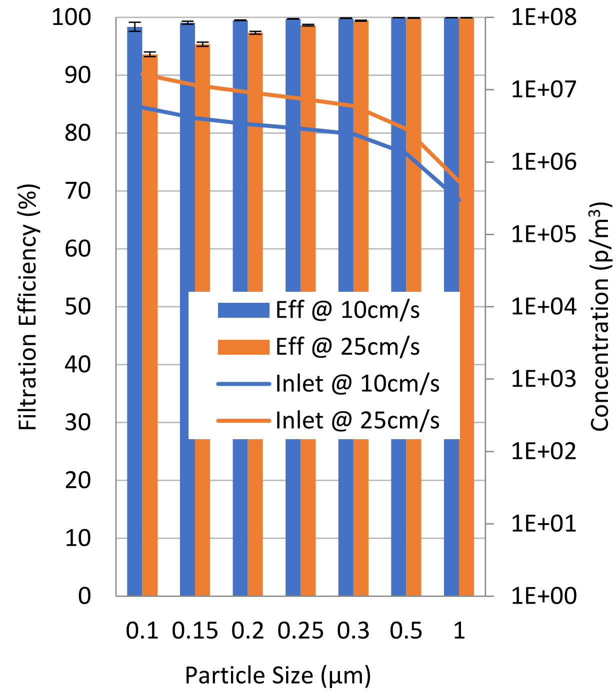



*d) Firm Grip – Design 2*

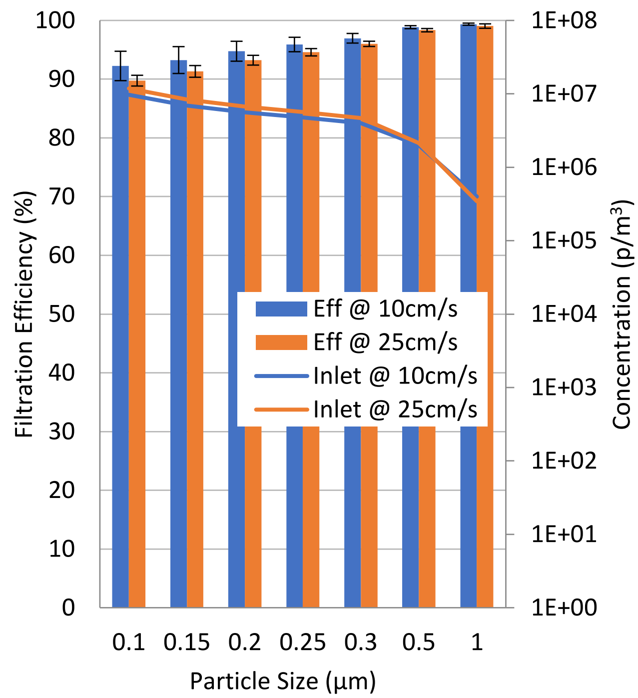
***Figure 4-5*** *Filtration efficiencies of commercially available reusable cloth masks and initial particle concentrations during testing at two face velocities, a) Old Navy, b) Tilley, c) Firm Grip – Design 1, d) Firm Grip – Design 2. Error bars represent standard deviation of 6 measurements (two samples).*




*a) N95 Mask*

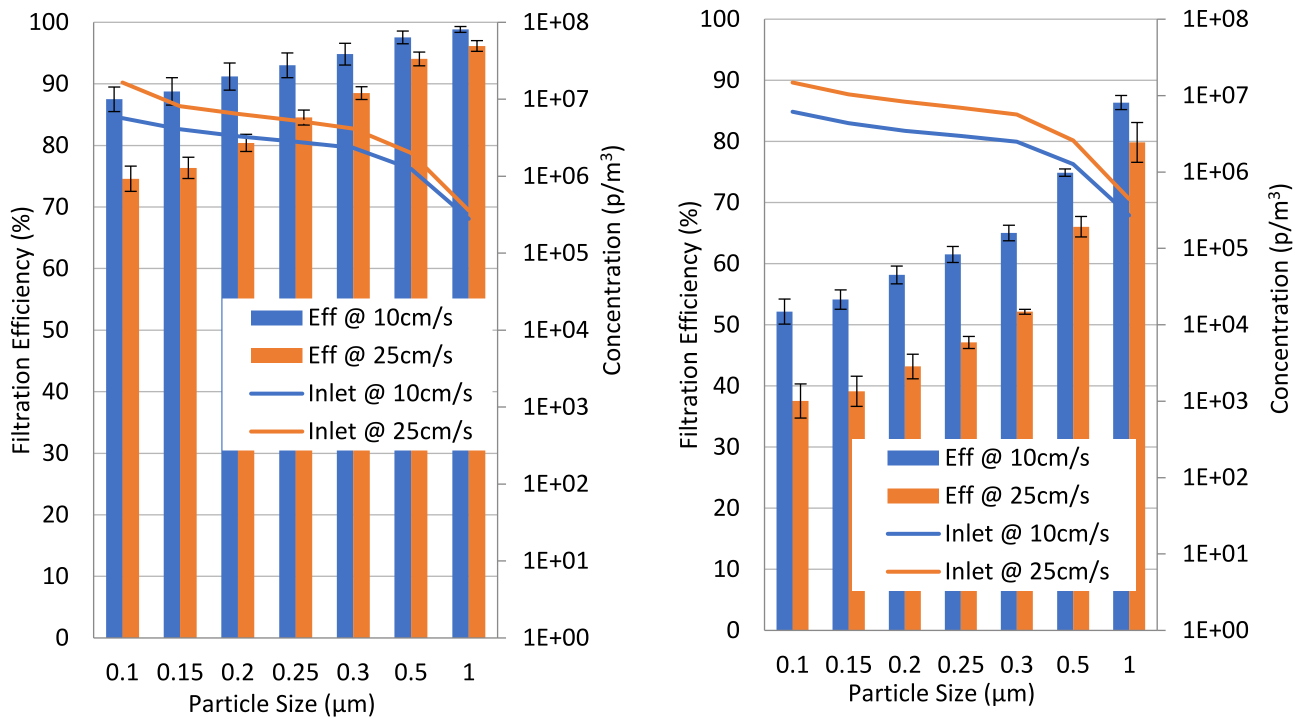



*b) Level 3 Surgical Mask*




c) *Level 2 Surgical Mask*

***Figure 4-6*** *Filtration efficiencies of disposable medical masks and initial particle concentrations during testing at two face velocities, a) N95, b) Level 3 Surgical Mask, c) Level 2 Surgical Mask. Error bars represent standard deviation of 6 measurements (two samples), except the N95 10 cm/s is 3 measurements (one sample).*




*a) Hui Lin Disposable Non-Medical Mask* *b) Ecoparksg Disposable Non- Medical Mask*

***Figure 4-7*** *Filtration efficiencies of disposable non-medical masks and initial particle concentrations during testing at two face velocities, a) Hui Lin Disposable Non-Medical Mask, b) Ecoparksg. Error bars represent standard deviation of 6 measurements (two samples).*

Double masking has been supported as a way to increase mask performance, particularly the use of a reusable mask layered with a disposable mask [60]. After testing individual fabrics and masks, these fabrics and masks were tested in combination with each other. The fabrics were layered in ways to simulate homemade masks and the masks were tested both with filter inserts and with each other. A list of the combinations that were tested along is provided in Table 4-1. These tests were done on multiple samples with measurements done in triplicate and each measurement averaged over 3 minutes per inlet and outlet These tests were done with the higher face velocity of 25 cm/s only. The higher face velocity of 25 cm/s correlated with lower filtration efficiencies in the majority of the earlier tests and was therefore chosen as the critical velocity for these tests.

Only the mask sourced from Tilley had a pocket made for a filter insert. This mask was tested with the Filti material as an insert and the more efficient, higher MPR furnace air filter. The pressure drop at 25 cm/s from these combination tests are presented in Figure 4-8.

***Table 4-1** List of combinations tested*

| Shorthand | Combination Details |
|---|---|
| Combo 1 | 3 layers BSH 300 |
| Combo 2 | 2 layers BSH 300 with Filti Insert |
| Combo 3 | 2 layers BSH 300 with AF1500 insert |
| Combo 4 | 2 layers BSH 300 with AF2200 insert |
| Combo 5 | 2 layers BSH 300 with ACF insert |
| Combo 6 | 2 layers BSH 300 with 2 layers of AF2200 inserts |
| Combo 7 | 4 layers BSH 300, 2 layers of Filti inserts |
| Tilley w AF2200 | Tilley mask with AF2200 filter in filter pocket |
| Tilley w Filti | Tilley mask with Filti filter in filter pocket |
| FGD1 w L3 | Firm Grip design 1 mask layered with a Level 3 surgical mask |
| Tilley w L3 | Tilley mask layered with a Level 3 surgical mask |
| Tilley w Disp(HL) | Tilley mask layered with a Hui Lin disposable non-medical mask |
| Tilley w Disp(E) | Tilley mask layered with a Ecoparksg disposable non-medical mask |

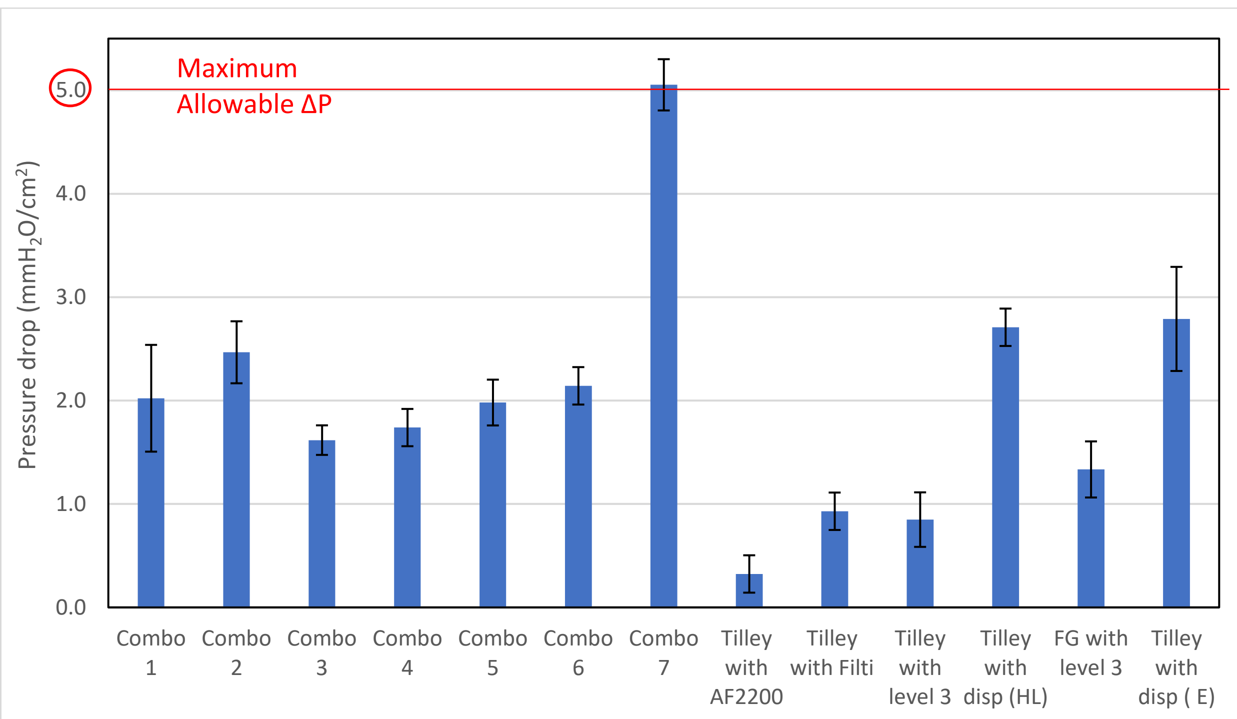
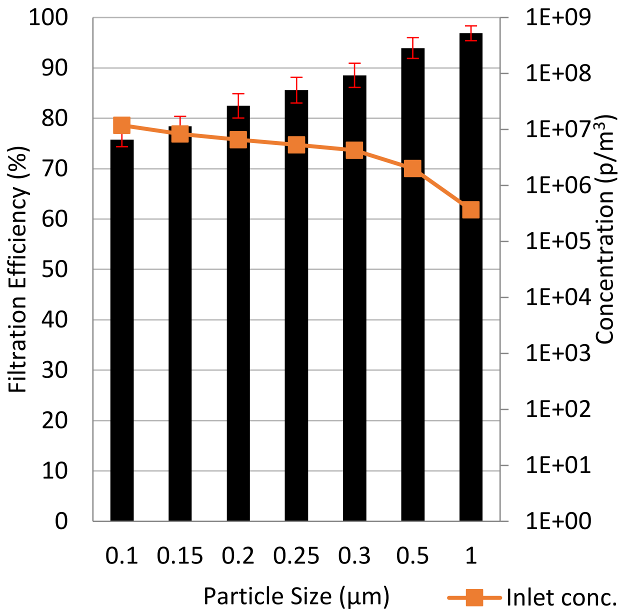
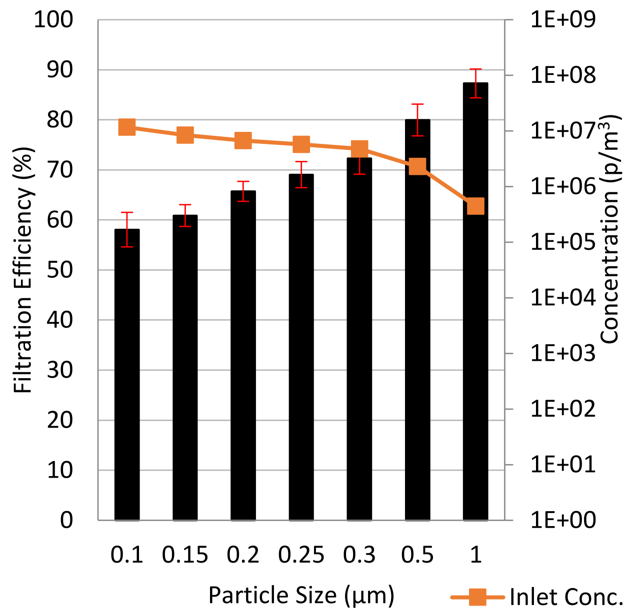



***Figure 4-8** Pressure drop results for combination tests. Error bars represent standard deviation of 5 measurements.*

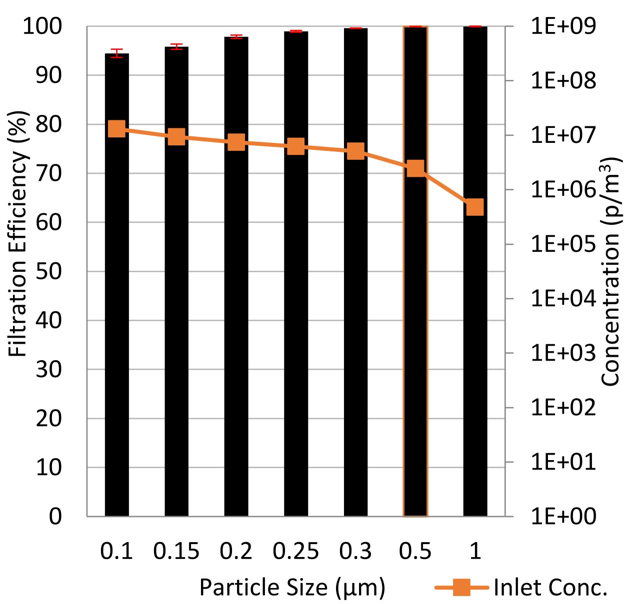
The filtration efficiencies found for these tests along with inlet concentrations are presented in Figure 4-9Figure 4-10. Figure 4-9 includes results from layering cloth masks with filters or surgical masks. Figure 4-10 includes seven different layering combinations of the individual fabrics. Since BSH 300 was the most efficient out of the three cotton fabrics presented in Figure 4-2, it was used to simulate a cloth mask. Homemade masks are suggested to have three layers; considering this, various three-layer configurations were tested. A mask with 3 layers of only cloth and then four configurations that had two layers of cloth with a non-woven center layer were tested. Since the AF 2200 was the most efficient of the non-woven fabrics, one configuration used two center layers of AF 2200 to attempt to achieve the highest filtration efficiency with a reasonable design. The last configuration included four layers of BSH 300 (two on each side) and two layers of Filti in the center. This configuration was used to evaluate a scenario where the pressure drop was at or near the more stringent maximum allowable limit for medical masks.



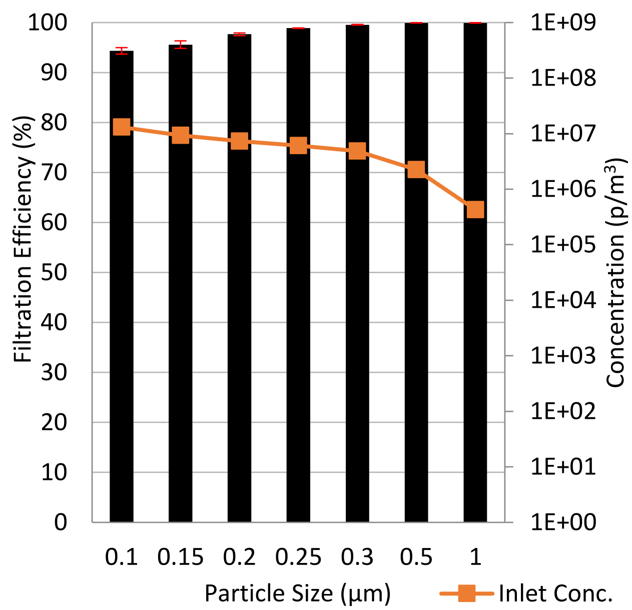

*a) Tilley w AF2200*



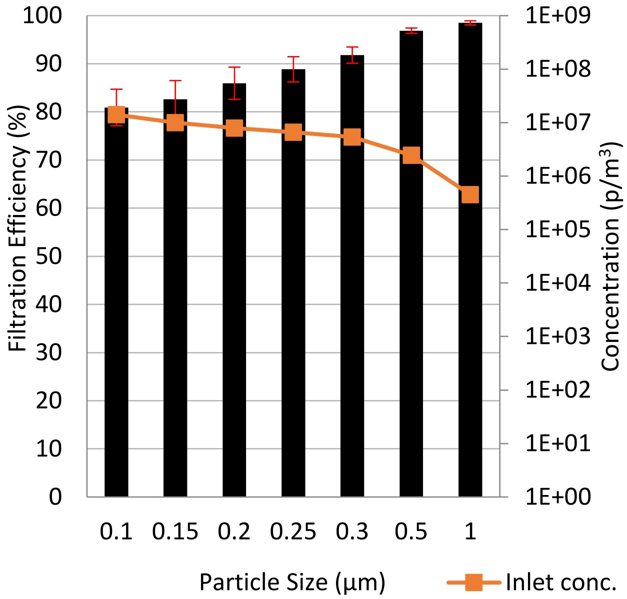

*b) Tilley w Filti*



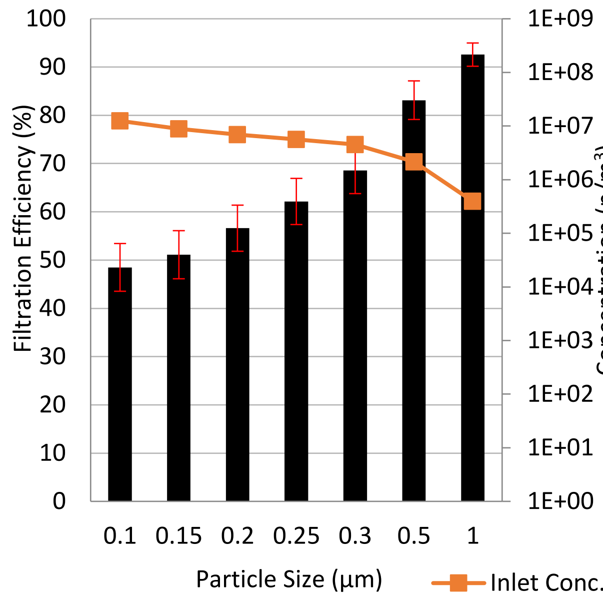

*c) FG w L3*




*d) Tilley w L3*

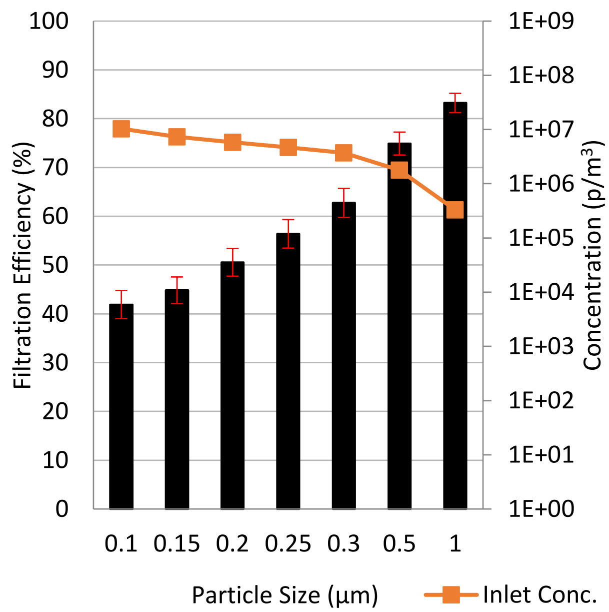



*e) Tilley w Disp (HL)*

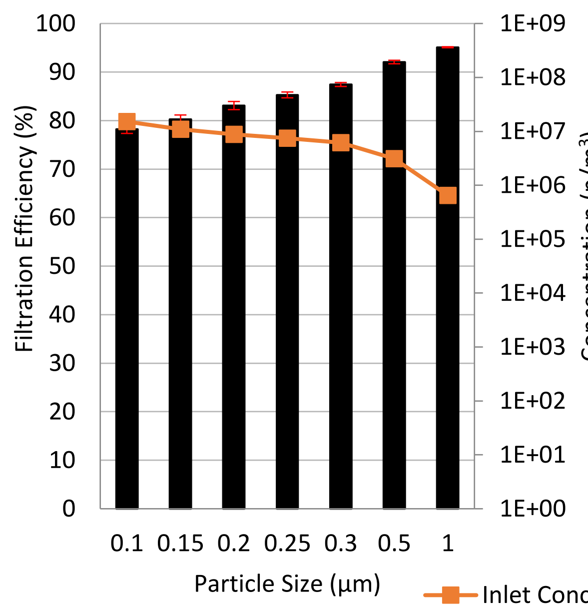



*f) Tilley w Disp (E)*

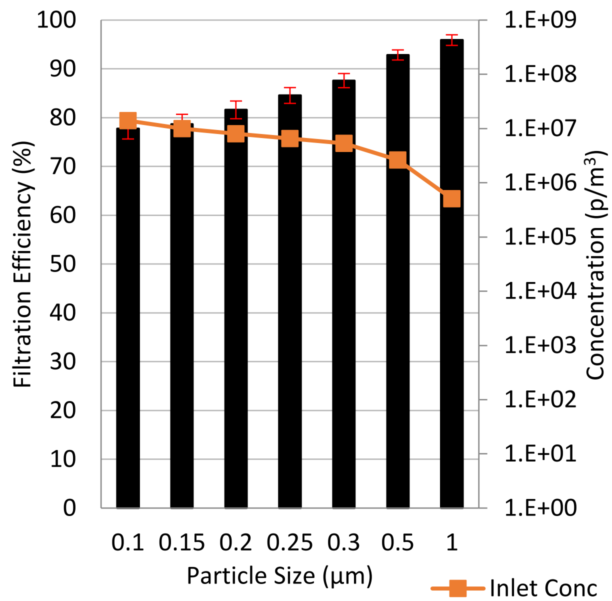
***Figure 4-9*** *Filtration efficiencies of layered commercial masks and initial particle concentrations during testing, a) Tilley w AF2200, b) Tilley w Filti, c) FG w L3, d) Tilley w L3, e) Tilley w Disp (HL), f) Tilley w Disp (E). Error bars represent standard deviation of 6 measurements (two samples).*



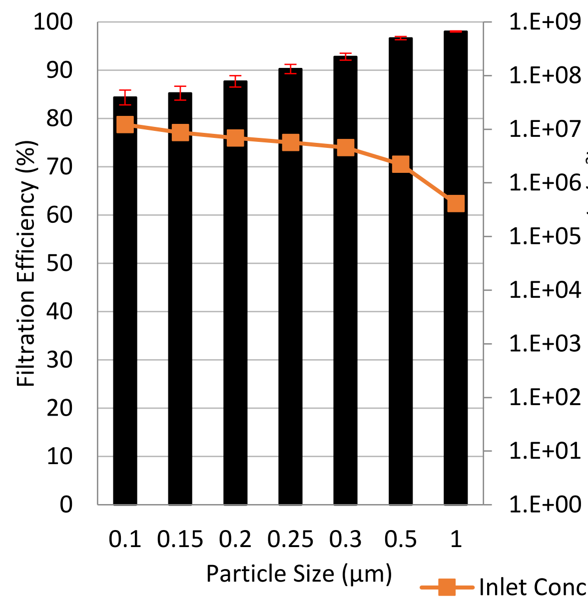

*a) Combo 1*



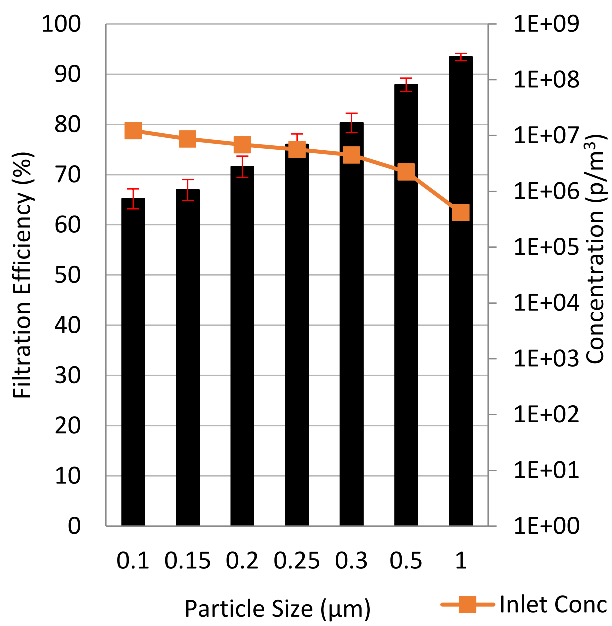

*b) Combo 2*



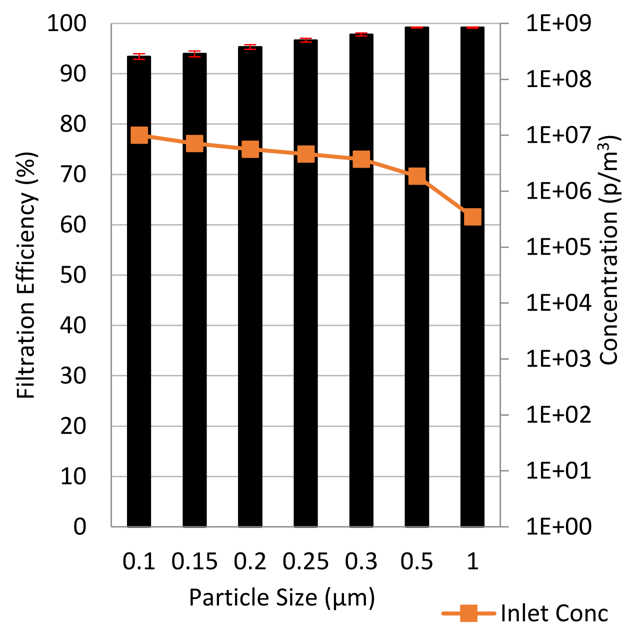

*c) Combo 3*



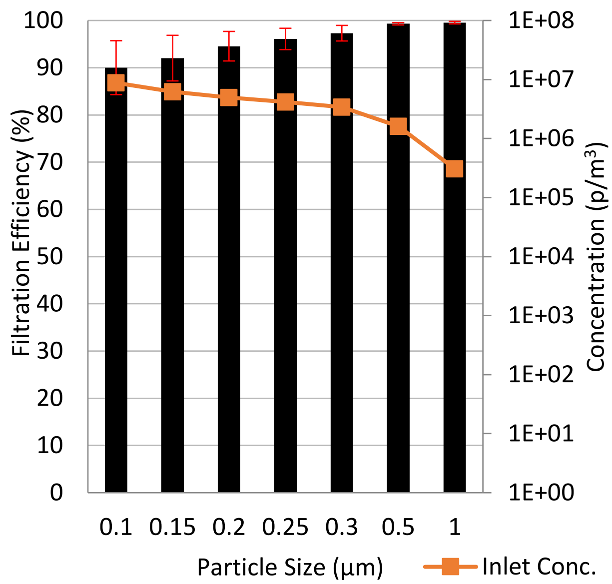

*d) Combo 4*




*e) Combo 5*




*f) Combo 6*

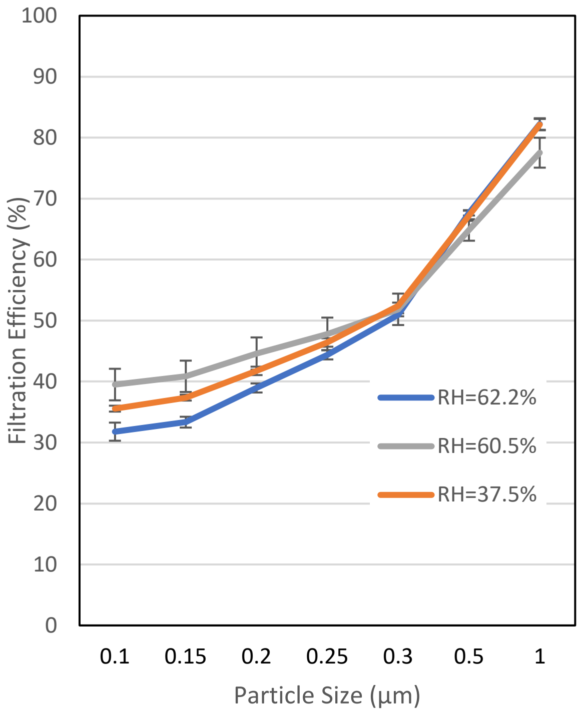



*g) Combo 7*

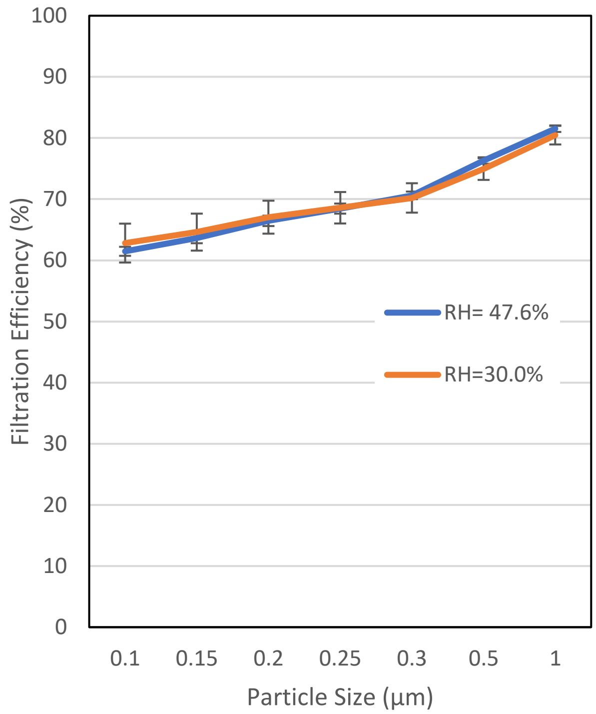
***Figure 4-10*** *Filtration efficiencies of layered materials and initial particle concentrations during testing, a) Combo 1, b) Combo 2, c) Combo 3, d) Combo 4, e) Combo 5, f) Combo 6, g) Combo 7. Note: Error bars represent standard deviation of 9 measurements (three samples).*

### 4.1.3. Filtration efficiency results based on humidity

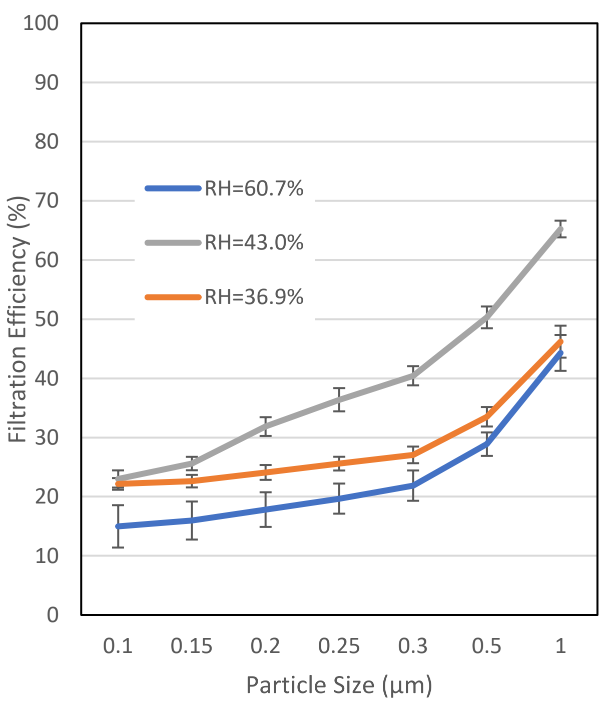
For the tests presented in 4.1, the aerosol stream of air was dehumidified however the majority of the filtered air that was combined with the generated aerosol stream was not. This means that the general lab humidity could potentially impact the filtration efficiency results. ASTM standard F2299 requires a humidity between 30-50% [30], most results presented in this chapter were tested at a lab RH within this range. A few extra tests were run at high humidity on materials of different composition to investigate the impact of humidity on FE, these tests are presented in Figure 4-11.



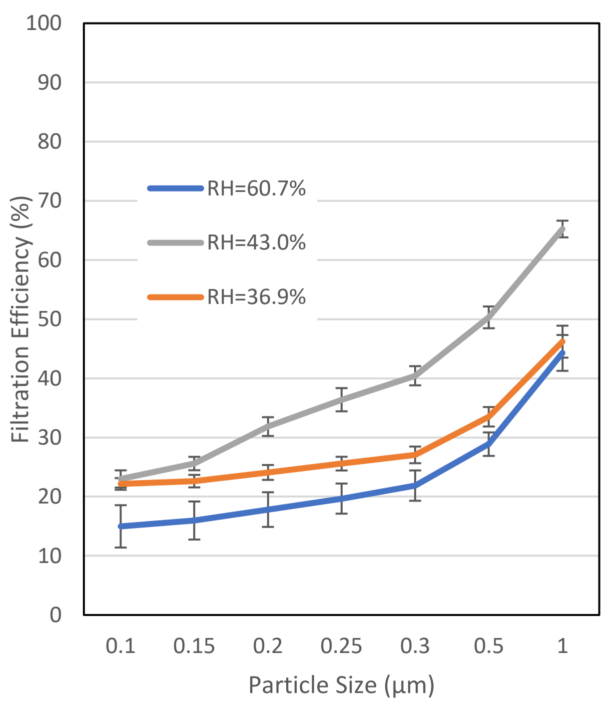

*a) Disposable (E) – 25 cm/s*



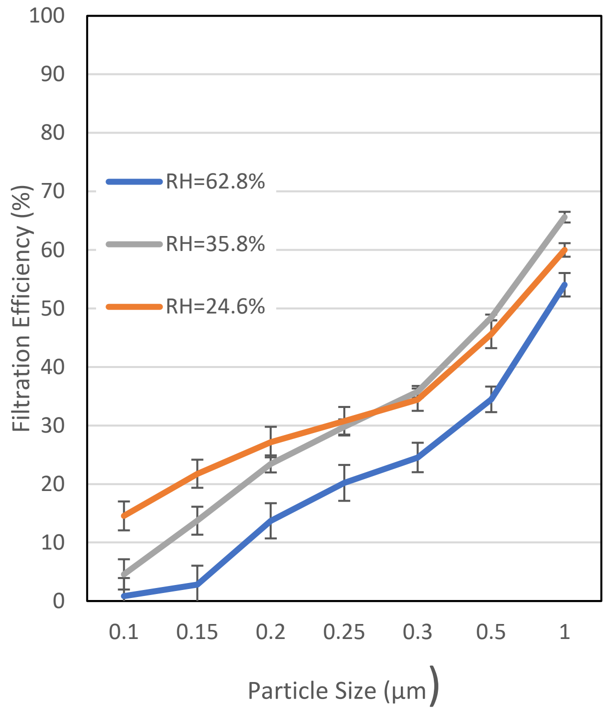

*b) Filti material – 25 cm/s*




*c) FG-D1 – 10 cm/s*




*d) FG-D1 – 25 cm/s*




*e) ON – 25 cm/s*

***Figure 4-11*** *Filtration efficiency results for select materials and masks characterized by humidity in lab, a) Disposable (E) – 25 cm/s, b) Filti material – 25 cm/s, c) HD-D1 – 10 cm/s, d) HD-D1 – 25 cm/s, e) ON – 25 cm/s. Error bars represent standard deviation of 3 measurements (one sample).*

### 4.1.4. Discussion of Mask and Fabric Performance

All of the masks and materials tested were at least somewhat able to capture particle sizes similar to the COVID-19 virus and therefore theoretically suitable to potentially reduce COVID-19 transmission. Considering COVID-19 is reported to be 0.06-0.15 µm [13], [14] in diameter, the 0.15 µm size from the tests will be the most telling for the protection against COVID-19 transmission. The 0.3 µm is the size of interest when testing medical masks according to ASTM standards and therefore is also of particular interest to this research. Filtration results for these two particle sizes of interest are summarized in Figure 4-12. The commercially available cloth masks were only marginally more effective than the woven and knitted fabrics, likely due to the multiple layers in the cloth masks. On the other hand, the disposable non-medical masks, while less efficient than the medical masks, were more efficient than all cloth masks. In terms of medical masks at the 25 cm/s face velocity, level 2, level 3, and N95 masks had efficiencies of 96.0%, 99.4%, and 99.2% at the 0.3 µm particle size and pressure drops of 0.81 mm $H_2O/cm^2$,1.62 mm $H_2O/cm^2$, and 1.62 mm $H_2O/cm^2$ (200 Pa total). Based on these results the level 3 surgical and N95 masks achieved the ASTM standard for their mask type, ≥98% and ≥ 95% efficiency at the 0.3 µm size and <6 mm $H_2O/cm^2$ and <350 Pa, respectively as per ASTMF2100 [19] and CDC regulations [18]. The level 2 surgical mask was within the ASTM standard for pressure drop and nearly achieved the required >98% efficiency at the 0.3 µm size [19]. The tested efficiency was found to be 97% at the 10 cm/s; therefore, it is reasonable to assume that at a lower face velocity, which is allowed through the ASTM testing procedure, these masks would meet the level 2 ASTM FE requirement. This is important to note because these masks were certified to meet >98% efficiency, and though that was not confirmed through these tests, it is clearly possible within the range of testing parameters allowed for ASTM certification.

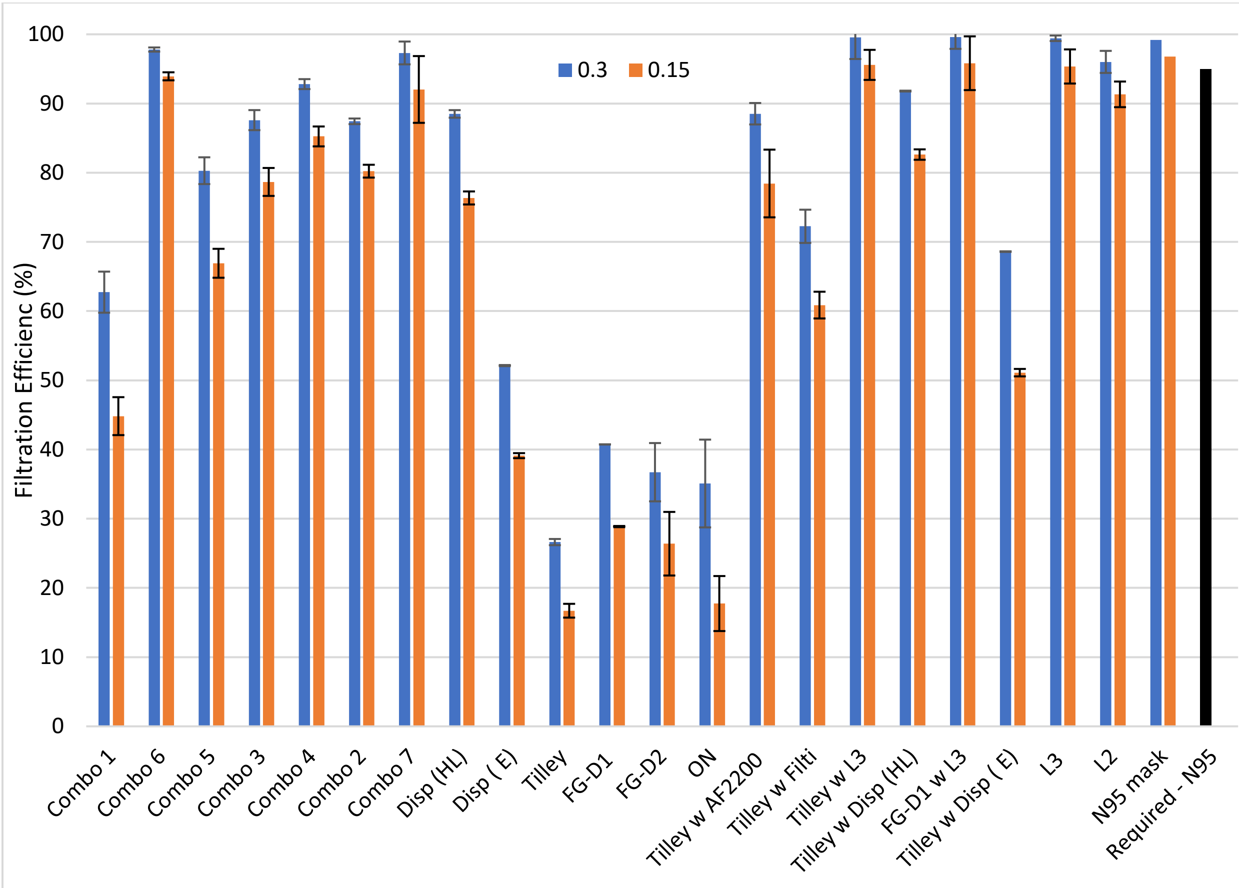



***Figure 4-12*** *Summary of filtration efficiency results for masks, mask combinations and material combinations at 0.15 µm and 0.3 µm particle sizes. Error bars represent standard deviation of 6 measurements (two samples) for commercial masks and 9 measurements (three samples) for combination masks.*

When combinations of media were tested, the filtration efficiencies of the combination were close to that of the most efficient individual mask or material involved. The filtration efficiency results from the combined media are presented in Figure 4-10. When cloth masks were paired with surgical masks, the filtration efficiencies were at or slightly higher than the filtration efficiency found for the individual surgical mask. When cloth masks were paired with Ecoparksg brand non-medical disposable masks, the filtrations were slightly higher than the disposable masks on their own. This filtration efficiency increase was more notable for larger size particles.

The use of cloth masks layered with disposable masks have been generally encouraged as a way to increase protection and reduce possibility of virus transmission [60]. Though pairing two masks did not seem to increase the overall filtration efficiency, a performance increase is still possible due to the improved fit when a cloth mask is used over top of a disposable mask [60]. The inclusion of a filter into the Tilley mask markedly increased the performance of that cloth mask. Generally, the filtration efficiency decreased when the face velocity increased. This effect seemed to be more pronounced for non-woven materials and masks (medical and disposable). This will be further investigated in section 4.2.

Generally, the cloth mask efficiencies had high standard deviation especially compared to the medical masks. This standard deviation data along with the filtration efficiencies at the 0.15 µm and 0.3 µm particle sizes are presented in Figure 4-12. Considering replicate testing of the medical masks was done with the same set up, same procedure and on the same days as the replicate testing of the cloth masks, it is reasonable to assert that the high variability in cloth mask performance is related to the cloth masks themselves. Considering the lack of testing regulations for cloth masks, variability is not surprising. In general, the standard deviation was especially high for small particle sizes (< 0.3). The OPC used has a counting efficiency of 50% for the 0.1 µm and 100% for the 0.15 µm size. This means that the OPC data for the 0.1 µm is much less reliable than all other size bins. Overall, the 0.1 µm has the highest standard deviation and this is likely partially due to the lower counting efficiency of the instrument for this particle size. This is relevant to all the data for this bin size.

The impact of relative humidity on filtration efficiency differs for different types of fabric. From Figure 4-11 it is evident that relative humidity has very little impact on performance the non-woven masks made of hydrophobic polypropylene (Filti and disposable non-medical masks). For the hygroscopic masks made of cotton; however, performance varied with variations in RH. Generally, for both the Old Navy and Firm Grip masks, the results obtained at the highest humidity showed the lowest removal efficiencies. At the 0.15 and 0.3 μm particle sizes, the difference in filtration efficiencies found at different relative humidity's varied by up to 18% difference in FE. The results found at the relative humidities within the ASTM F2299 specified range vary but less than compared to when RH >60%.

All materials and masks tested were well under the maximum allowable pressure drop for breathability of 5 $mmH_20/cm^2$. The Filti material and the higher thread count bedsheet had the highest pressure drop of the fabrics while the 1500 MPR furnace air filter had the lowest. The N95 mask had the highest pressure drop of all the tested masks (not including combinations). When looking at combinations, an increase in pressure drop did not necessarily correlate with an increase in efficiency. The high pressure drop combination (Combo 7) that was tested had similar filtration efficiency to Combo 4 or Combo 6 which both had less than half of the pressure drop comparatively. This indicates that high efficiency materials do not necessarily have high pressure drop and that it is possible to have highly efficient masks that are still breathable for the wearer.

For a face mask to be suitable it must efficiently filter the contaminants of concern at reasonable breathing velocities and remain breathable at these same velocities. To analyze this, both filtration efficiency and breathability must be taken into consideration. To take both breathability and filtration efficiency into consideration simultaneously, a quality factor can be used to visually compare mask quality. Considering a higher filtration efficiency combined with a low-pressure drop is the most desirable combination, when this QF is plotted horizontally against FE, the most suitable mask will be found in the top right corner, and the least suitable in the bottom left. More details on quality factor calculation are available in Appendix E. The quality factors based on the filtration efficiencies for the 0.15 µm and 0.3 µm particle size at the 25 cm/s face velocity for the reusable, disposable and layered masks tested are presented in Figure 4-13 and Figure 4-14 , respectively. Using the quality factor, the N95, level 2 and 3 surgical masks and the Hui Lin disposable non-medical masks are clearly the most suitable when compared to cloth masks and possible homemade configurations. From Figure 4-13, after medical masks, or masks layered with medical masks, the next 3 highest performing options were, the Tilley cloth mask with one 2200 MPR furnace air filter, combo 6 and combo 4. Combos 4 and 6 represent 2 layers of woven fabric (bedsheet with 300 thread-count) with one or two 2200 MPR furnace air filter inserts. The least suitable masks were the commercially available cloth masks, even when compared to the combinations of household materials. The Ecoparksg brand disposable non-medical masks and the 3-layer combination of bedsheet material were only marginally more suitable than the cloth masks. The differences in both quality factor and filtration efficiency for the two brands of disposable non-medical mask are noteworthy. This illustrates the variety in quality of disposable non-medical masks that arises from the lack of testing requirements and general regulation. From Figure 4-13 it is evident that though the filtration efficiency of the Hui Lin disposable mask tested is slightly lower than the medical masks, it has advantages considering its lower pressure drop. On the other hand, pairing a Ecoparksg disposable mask with a cloth mask increases filtration efficiency while increasing the pressure drop.

The quality factors for this data range from 2.3 to 36 $kpa^{-1}$ (or 0.0023-0.036 $pa^{-1}$). Zangmeister et al. [50] found QF's of 1.8-6.2 $kpa^{-1}$, depending on layering and thickness, when testing a cloth made of cotton fiber with an aerosol with a diameter of 0.05-0.825 µm, the average being 0.252 µm. Similarly, the QF's in Figure 4-13 found for the three-layer of BSH 300 combination, the Tilley, Old Navy and Firm Grip masks, which are all made from cotton, are 2.3-8.5 $kpa^{-1}$ for 0.15 µm and 3.9-13 $kpa^{-1}$ for 0.3 µm. Zangmeister et al. also found a QF of ~100 $kpa^{-1}$ for a N95 mask and ~10 $kpa^{-1}$ for N95 fabric and the majority of the other fabrics tested had QFs between 1 and 10 $kpa^{-1}$ [50]. This is in line with the results presented in Figure 4-13; however, the N95 mask QF found in Zangmeister et al. is notably higher than the one found in this research. The face velocity in these experiments was higher than Zangmeister et al.'s, 25 cm/s versus 6.3 cm/s, which would result in a higher pressure drop, hence a lower QF.

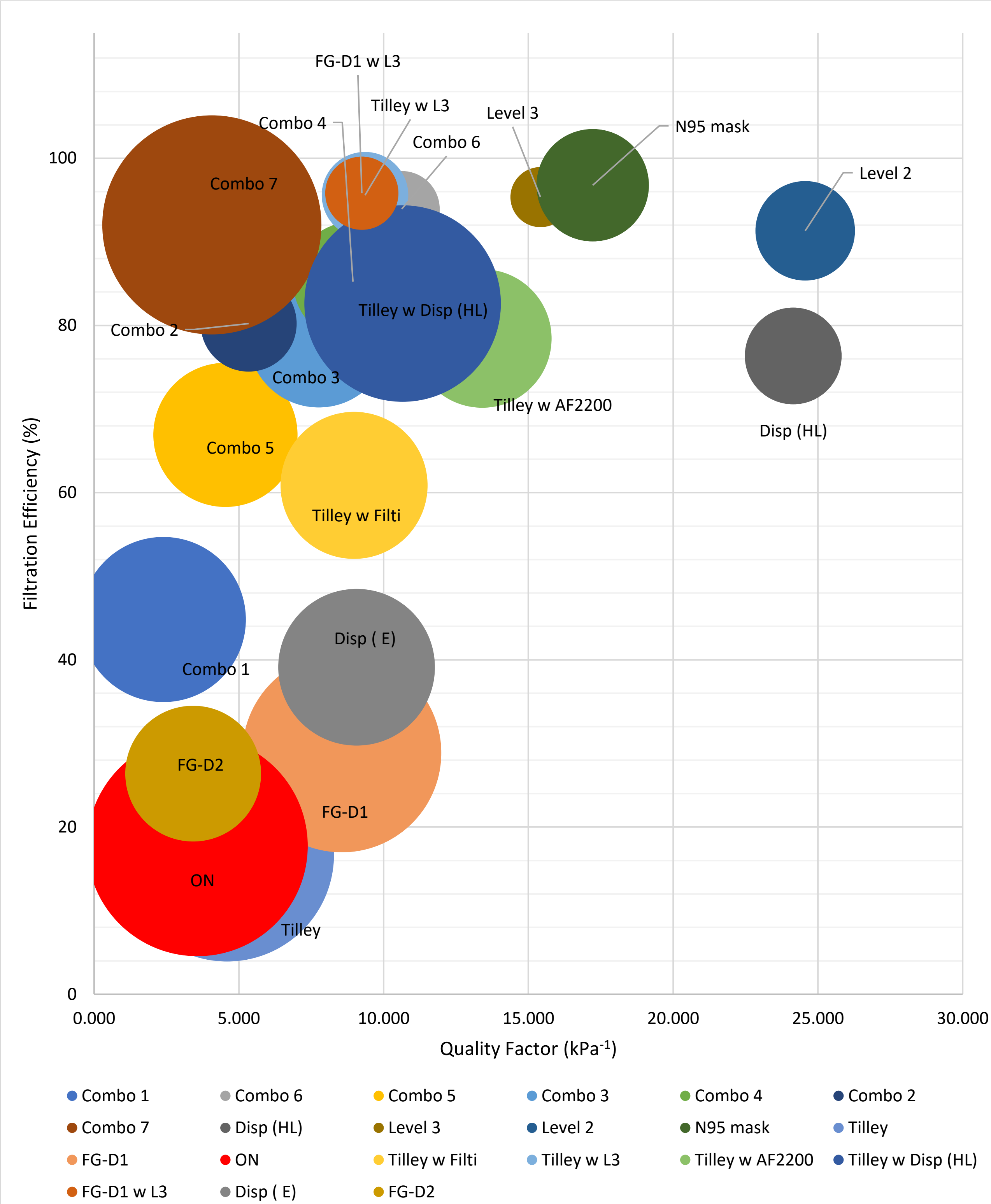



***Figure 4-13*** *Quality factor for masks, mask combinations and material combinations at 0.15 µm particle size. Size of points reflect standard deviation in filtration efficiencies of 6 measurements (two samples) for commercial masks and 9 measurements (three samples) for combination masks.*

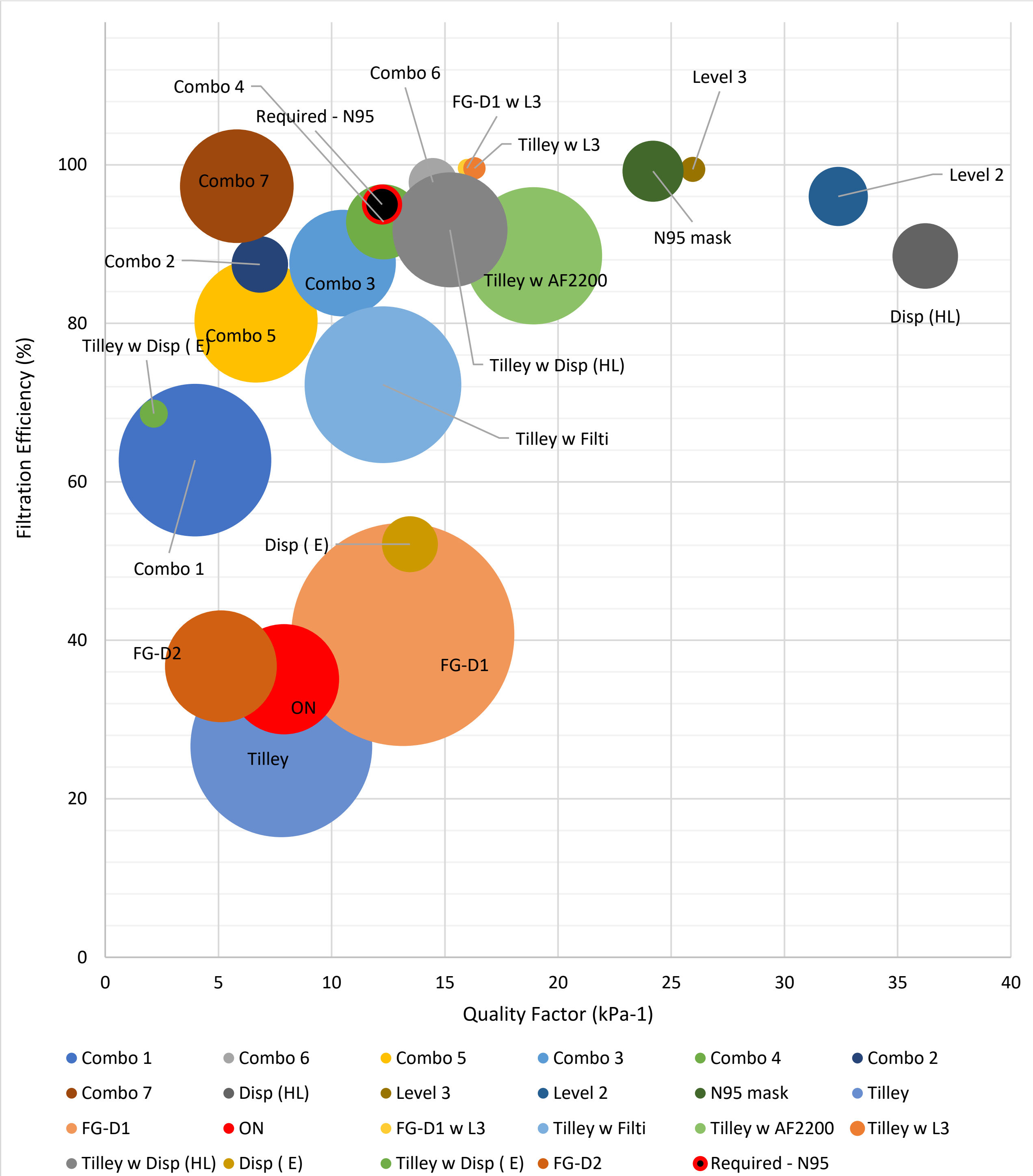



***Figure 4-14*** *Quality factor for masks, mask combinations and material combinations at0.3 µm particle size. Size of points reflect standard deviation in filtration efficiencies of 6 measurements (two samples) for commercial masks and 9 measurements (three samples) for combination masks. Note: the data point called "required" reflects the filtration efficiency and pressure drop (exhalation) requirements for N95 mask, size of "required" point is arbitrary and chosen for visibility [36].*

The 0.15 µm and the 0.3 µm QF graphs are similar in terms of relative performance to one another. The N95, L2, and L3 masks are tested at the 0.3 µm particle size so their performance at smaller sizes is not reported. One difference between the two quality factor graphs is that L2 and L3 masks are relatively more efficient and closer in performance to the N95 masks at the higher particle size. In Figure 4-13, the graph at the 0.15 µm size, the filtration efficiency of the L2 is 5.5% less efficient than the N95 and the L3 is 1.4% less efficient than the N95 but in Figure 4-14, the graph at the 0.3 µm size, the L2 is 3.2% less efficient than the N95 and the L3 is actually 0.2% more efficient than the N95. This indicates that N95 masks may have better performance for smaller particle sizes. Another difference between the QF graphs at different particle sizes is that the uncertainties are much greater for the smaller particle size. This indicates that there is more variability of performance for masks at lower particle size. Since medical masks are tested at the 0.3 µm it is expected that performance at this particle size would maintain consistency.

The benefit of including the 0.3 µm QF graph is that the standard pressure drop and filtration efficiency combination required for Level 3 surgical masks can be included for reference. From Figure 4-14 it is evident that certain masks, due to their low pressure drops, exceed the required QF but do not meet the filtration standards as seen in Figure 4-12. The Tilley w Disp(HL), Tilley w AF2200 and the Disp(HL) itself meet or exceed the QF required for L3 surgical mask certification but not the filtration efficiency. This indicates that for public use, these masks are efficient and at least comparable to surgical mask protection, while not meeting the standards completely. Comparatively the Combo 6, FG w L3, Tilley w L3, L3 and N95 masks all met or exceed both the QF and filtration efficiency as determined from the ASTM standards. This means that the Combo 6, two high thread count woven fabric layers with 2 layers of high MPR furnace filters, can reach the same standard of protection and wearability as approved surgical masks. Considering this, it is possible to make homemade masks with comparable filtration efficiency for COVID-19 virus as N95 and Level 3 surgical masks.

### 4.2. Influence of Face Velocity on Mask Performance and Testing

The filtration velocity range specified by ASTM for testing is substantial; this can negatively impact the consistency of testing using this standard [19]. It is important to investigate the influence of face velocity (FV) on filtration testing at the lower velocities as much as it is important at the higher face velocities, considering medical masks are tested at these lower velocities. To evaluate the influence of face velocity on mask performance, four face velocities, 10 cm/s (V1), 17.5 cm/s (V2), 25 cm/s (V3) and 32.5 cm/s (V4), were tested on both the reusable and disposable commercial masks. These face velocities corresponded to 7.7, 13.2, 18.9, and 24.5 SLPM, respectively. Three of these four face velocities are within the specified range for testing for the ASTM F2299 standard and one is just outside of the specified range. One velocity was chosen outside of the standard range to see if there was any noticeable change once outside of the range and therefore justifying the range itself. The velocities chosen are of equal measures from each other so that the influence of velocity can be better identified. These velocities are intended to be within general breathing and speaking velocity ranges. At the mouth or nose peak exhalation flow rates have been found to be 42 LPM for breathing, 96 LPM for talking and 360 LPM for coughing [61]. Considering these are the peak flow rates at the mouth itself and not the mask, and flow rates as low as 12 lpm for talking have been measured [61], the face velocities used in this research are reasonable. Face velocities for coughing and sneezing can far exceed the tested velocities accessible to the test setup used; they are also very unpredictable and difficult to replicate with accuracy.

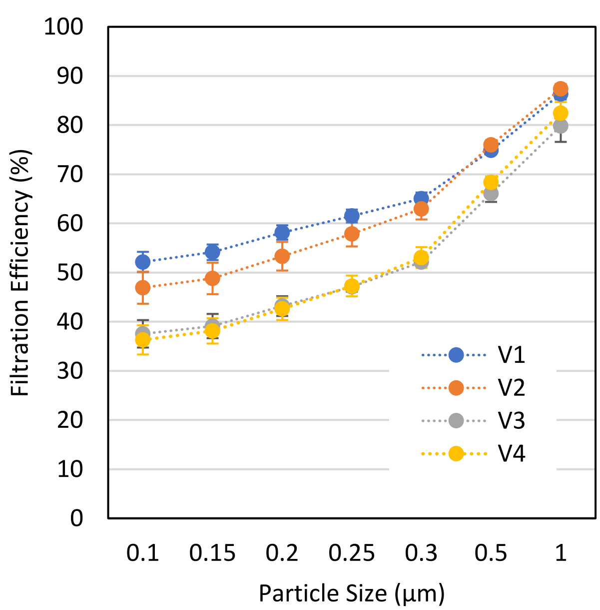
### 4.2.1. Filtration Efficiency Results in Terms of Face Velocity

Data for V1 and V3 were already found as part of objective 1. A summary of all masks and materials tested at both V1 and V3 as well as the difference between efficiencies found at both face velocities is presented in Table 4-2. In this table a positive difference between V1 and V3 indicates that efficiency is higher at the lower velocity, meaning that efficiency increases as face velocity decreases. The average difference between filtration efficiencies at V1 and V3 at both particle sizes is positive meaning the overall trend is that filtration efficiency deteriorates when face velocity is increased. Four fabrics or masks display the opposite trend for the 0.1 µm and five for the 0.3 µm sizes.

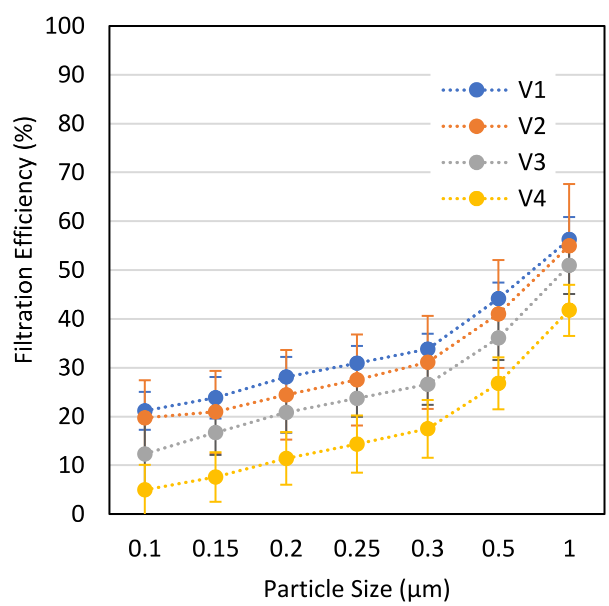
***Table 4-2** Summary of filtration efficiencies for different face velocities and particle sizes*

| Fabric/mask | At the 0.15 µm particle size | | | At the 0.3 µm particle size | | |
|---|---|---|---|---|---|---|
| | $\eta_{V1}$ | $\eta_{V3}$ | Diff ($\eta_{V1}$- $\eta_{V3}$) | $\eta_{V1}$ | $\eta_{V3}$ | Diff ($\eta_{V1}$- $\eta_{V3}$) |
| Disposable (HL) | 88.8 | 76.4 | 12.4 | 94.8 | 88.5 | 6.3 |
| Level 3 | 99.1 | 95.4 | 3.7 | 99.9 | 99.4 | 0.4 |
| N95 mask | 99.0 | 97.9 | 1.1 | 99.8 | 99.6 | 0.2 |
| Tilley | 23.8 | 16.7 | 7.1 | 33.8 | 26.6 | 7.2 |
| Firm Grip | 24.1 | 28.9 | -4.8 | 33.7 | 40.7 | -7.0 |
| Old Navy | 19.8 | 17.7 | 2.0 | 26.9 | 35.1 | -8.2 |
| Disposable (E) | 54.1 | 39.1 | 15.0 | 65.0 | 52.1 | 12.9 |
| Firm Grip-D2 | 29.4 | 26.4 | 3.0 | 38.7 | 36.7 | 2.0 |
| BSH 180 | 4.6 | 8.5 | -3.9 | 7.3 | 14.4 | -7.1 |
| BSH 300 | 13.0 | 22.2 | -9.2 | 19.3 | 30.6 | -11.4 |
| T-shirt | 8.8 | 10.4 | -1.7 | 11.1 | 17.4 | -6.2 |
| Filti | 66.3 | 64.6 | 1.7 | 73.9 | 70.2 | 3.7 |
| AF1500 | 81.4 | 64.1 | 17.3 | 86.8 | 73.2 | 13.6 |
| AF2200 | 86.9 | 75.7 | 11.2 | 91.6 | 83.5 | 8.2 |
| ACF | 60.6 | 49.4 | 11.3 | 71.0 | 59.2 | 11.8 |

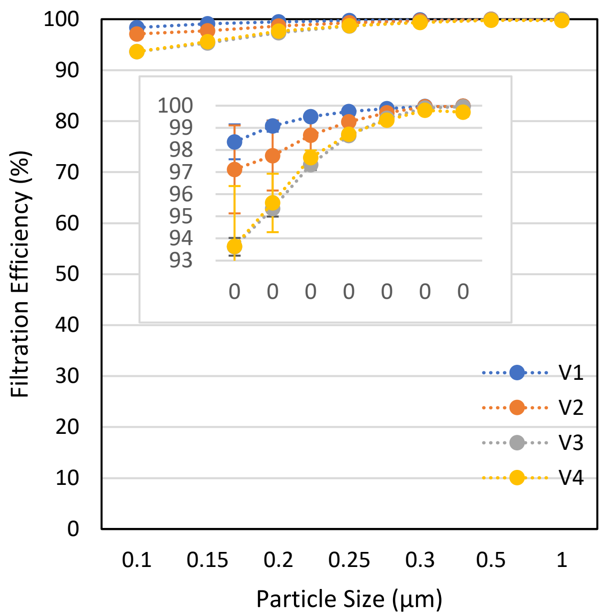
Tests were run at V2 and V4 for the Firm Grip (Design 1), Tilley, disposable (E), and Level 3 surgical masks. These masks represent commercially available masks that are used by the public. The Firm Grip and Tilley masks, while made from similar materials, represent two common mask designs – a basic 3-layer mask and a mask with a filter pouch built in, respectively. After data from the tests at V2 and V4 were completed, they were compiled into one graph along with the data for V1 and V3 for each mask. All tests for this section were done on two samples, and for each sample, the measurements were run in triplicate both upstream and downstream of the mask. These velocity comparison graphs are included in Figure 4-15. All graphs are done with a 0-100% degree scale in the y-direction for easy comparison. For the L3 masks since they have such high efficiencies a second, smaller scale graph is included so that more detail can be seen.



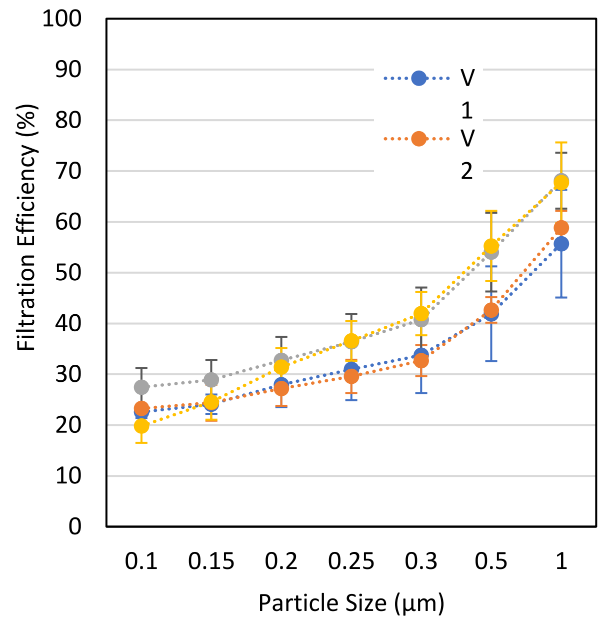

*a) Disposable mask*




*b) Tilley mask*




*c) Level 3 mask )*




*d) Firm Grip- D1*

***Figure 4-15*** *Velocity comparison graphs, a) Disposable mask, b) Tilley mask, c) Level 3 mask , d) Firm Grip (Design 1). Error bars represent standard deviation of 6 measurements (two samples).*

### 4.2.2. Discussion of Mask Performance at Different Face Velocities

In Table 4-2 it is illustrated that on average there was a reduction in filtration efficiency as the face velocity increased. On average for all the masks and materials tested, the filtration efficiency at 10 cm/s was 4.42% and 1.76% higher than at 25 cm/s for the 0.15 µm and 0.3 µm particle size, respectively. When only the masks and materials that showed a loss of efficiency with the velocity increase, the average efficiency losses were 7.8% and 6.6 % for 0.15 µm and 0.3 µm respectively. This is expected considering the diffusion filtration mechanisms is inversely related to velocity while impaction efficiency increases with velocity increase [12]. Since smaller particles are more reliant on diffusion and interception filtration mechanisms, it is expected that the smaller the particle, the greater the loss in filtration efficiency as velocity increases. This is also supported in the literature [49], [44]. From Table 4-2 we can see that the only fabrics or masks that do not follow this expected trend are the Old Navy masks, at the 0.3 µm size only, and the Firm Grip masks, woven fabrics, and knitted fabrics at both sizes The Old Navy mask is made from 100% cotton poplin which is a medium thread density weave with fine horizontal ribs, this fine spacing could explain the reason that the Old Navy mask is more efficient at higher face velocities for the larger particle size of 0.3 µm instead of at both. The weave was not specified in the Firm Grip masks. Contrarily the fabrics that presented the greatest loss of efficiency with the velocity increase were all non-woven materials, specifically the disposable masks, the AF1500 and the Filti material. A similar trend was also noted in Hao et al., where for particles greater than 0.2 µm, fabric materials had an increase in FE with increased FV and fibrous materials had a decreased in FE with increased FV [49]. Non-woven materials are generally more permeable, thinner and with smaller fibers than the fabric woven/knitted materials [62]. The non-woven fabrics used (ACF, AF1500, AF2400, Filti) have fibers of diameters 5.66 - 23.4 µm while the woven and knitted fabrics used (BSH 180, BSH 300 and T-shirt) have yarn threads of 117 – 195 µm. The AF1500 and AF2200 were the most permeable of the materials tested while the BSH 300 and Filti were the least permeable materials tested. The AF1500 and AF 2200 also had the greatest reduction in efficiency with increased face velocity and the BSH 300 had the greatest increase in efficiency with increased face velocity and Filti had the lowest reduction in efficiency of the non-woven materials [62]. This means that non-woven materials with high air permeability have a shorter residence time for the fluid passing through and it also means that impaction and interception are more important for woven fabrics when compared to non-woven fabrics. Both of these factors can help explain why face velocity has different effects on these different types of materials. Hao [49] and Rengasamy [44] presented a similar analysis for similar observations.

Despite the velocities chosen being equally distant from each other, the filtration efficiency impact of face velocity does not seem linear. Figure 4-15 and Figure 4-16 illustrates that for three out of four masks that have been tested at all four face velocities, the greatest change in filtration efficiency occurs between the 17.5 and 25 cm/s velocities. This is interesting considering both of these velocities are within the acceptable testing range according to ASTM F2299 standards. For the Tilley mask, however, the greatest change in efficiency occurs between the 25 and 32.5 cm/s which is what would be expected since this velocity is left out of the testing range. Three out of four tested masks show a decrease in filtration efficiency as face velocity is increased, the only mask that shows the opposite trend is the Firm Grip mask. In Figure 4-15 it is evident that for both of the non-woven masks, L3 and disposable, as particle size increases, the face velocity has a decreased impact on filtration efficiency. This is expected; impaction as a filtration mechanism becomes more important with larger particles and impaction efficiency is increased with velocity. This trend also seems to be the case with the Tilley mask; however, it is less pronounced than with the non-woven masks. Filtration velocity seems to have the least impact on the L3 masks which can be a function both of the consistent quality of these masks and the generally superior performance and manufacturing of these masks compared to the others tested here.

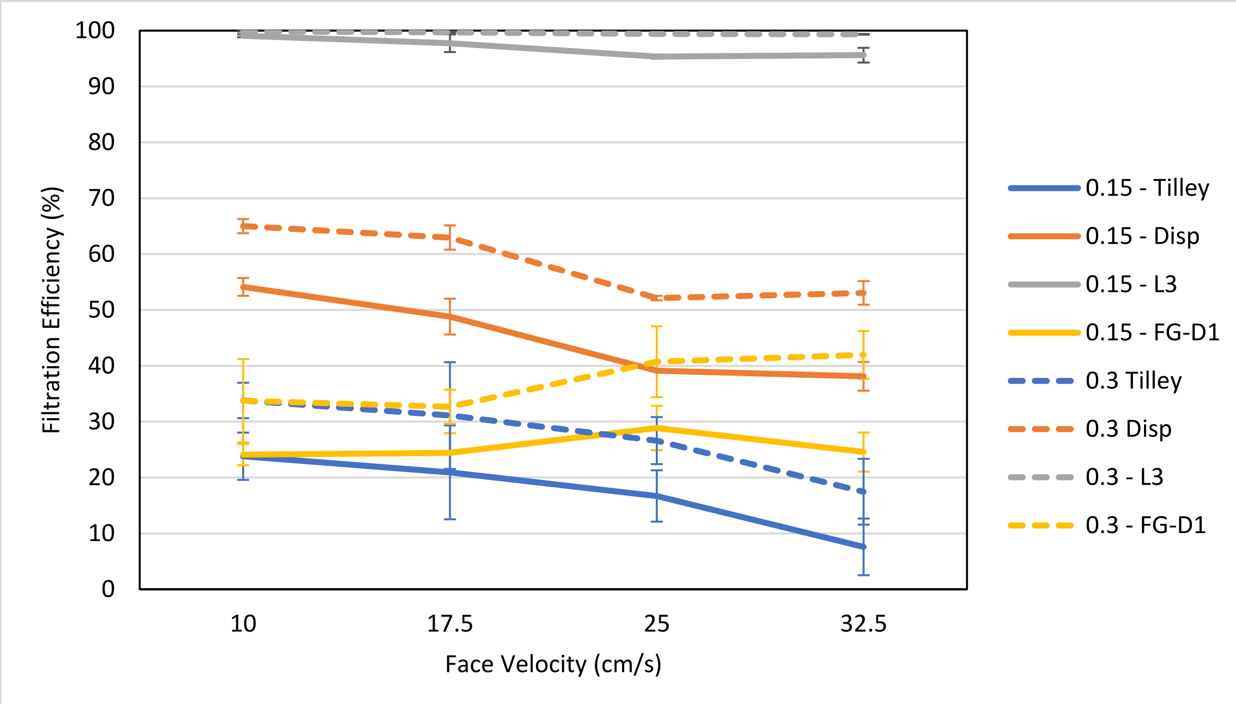



***Figure 4-16*** *Filtration efficiency as a function of face velocity. Error bars represent standard deviation of 6 measurements (two samples).*

## 4.3. Breath Condensate on Mask Performance and Wear Time

This section presents data and analysis for the third objective: investigation of the impact breath condensate can have on mask performance for COVID-19 transmission protection. For this section of testing, masks were attached to the outlet of a bubbler filled with simulated exhaled breath condensate (EBC) and were exposed to EBC for different lengths of time. Procedure for these tests is described in more detail in Chapter 3 and details on the contents and synthesis of the simulated EBC can be found in Appendix B. Masks with both hygroscopic and hydrophobic materials were tested. First, one cloth and one disposable mask type were tested after 1-hour, 4-hour, 8-hour, and 24-hour EBC exposure times. These preliminary tests were used to decide which exposure durations would be tested further with the other masks. Each scenario was tested on three separate mask samples. Masks were oven dried before EBC exposure and weighed before exposure and after, this EBC weight data is presented in the results. Filtration efficiency and pressure drop results from masks exposed to EBC are compared to results from Section 4.1. All FE and breathability tests were done at a face velocity of 25 cm/s with NaCl aerosols.

#### 4.3.1. Filtration Efficiency and Pressure Drop Results of Reusable Masks Exposed to EBC

Reusable masks tested for this section include the Tilley, Firm Grip Design 1, and Firm Grip Design 2. The Tilley masks were tested in triplicate with 1-hour, 4-hour, 8-hour, and 24-hour EBC accumulation. Based on the results from this testing, the two Firm Grip mask types were tested in triplicate with 4-hour and 8-hour EBC exposure. The reusable masks tested for this section represent three different reusable cloth masks: 100% cotton with a filter pouch, 100% cotton, and mixed fabric (polyester, polyester nano mesh, cotton). All three mask types are made of 3 layers, which means that each mask can be evaluated in terms or design and material response to EBC exposure. The Tilley masks were also tested with the AF2200 filter inserts.

4- and 8-hour exposure represent important practical applications as well as correspond to recommendations by a variety of organizations including governmental organizations [1], [42], [60], [63],. It is recommended that surgical masks and respirators be worn for a maximum of 4 hours and 8 hours respectively [63]. Also, considering a workday is 8 hours and members of the public are likely to wear their mask for one workday length it is important to understand how mask performance varies throughout this time period. One workday is recommended as the longest period someone can wear a mask without washing it [42] [60] [1]. 4-hour exposure is also important since individuals at work will remove their mask after about 4 hours for a meal break this would be an ideal time to change masks if a mask change is needed. Another common mask use scenario is short term events such as grocery shopping, the 1-hour EBC exposure was used to simulate this short-term mask use. While individuals will not likely wear a single mask for 24 hours straight, it is important to understand what happens at the boundaries of this case. Hence, 24-hour exposure was tested with the intent to compare the 4- and 8- hour exposure and as an extreme case, to help determine around when EBC saturation was reached, however, this data was not used for analysis. For the 24-hour test, it was observed that as the EBC levels in the bubbler decrease throughout the test, the aerosolized EBC decreases to a point where after the mask has reached saturation it can start to partially dry. This also means the EBC weight measured for the 24-hour case was less consistent than for the other EBC exposure times as can be seen by the large standard deviation in Table 4-3. For these reasons, time requirements and the lack of applicability, the 24-hour exposure tests were only done on one cloth and one disposable mask. Considering this data is not reliable it is not presented here in the results, the 24-hour data is presented in Appendix B.

The average weight difference between before and after EBC exposure including the standard deviation of these measurements are presented in Table 4-3  Pressure drop was measured for each sample, the average pressure drop for the EBC exposure tests as well as the corresponding no-EBC data are presented in Figure 4-17. It is important to note that the no-EBC breathability data, taken from earlier tests, is the average of five samples while the EBC exposure samples are the average of the three samples exposed to EBC.

***Table 4-3*** *Weight change in reusable masks from dry to after EBC exposure (Estimated EBC accumulation). Standard deviation based on 9 measurements (three samples).*

| **Mask Type** | **EBC Exposure** | **Average EBC Weight (mg)** | **Standard deviation (mg)** |
|---|---|---|---|
| Tilley | 1-hr | 335.67 | 11.060 |
| | 4-hr | 390.67 | 11.590 |
| | 8-hr | 393.67 | 11.846 |
| | 24-hr | 362.00 | 24.576 |
| FG-D1 | 4-hr | 508.33 | 4.163 |
| | 8-hr | 519.00 | 19.000 |
| FG-D2 | 4-hr | 91.00 | 13.528 |
| | 8-hr | 93.00 | 2.000 |
| Tilley w AF2200 | 4-hr | 327.00 | 17.088 |
| | 8-hr | 375.33 | 13.204 |

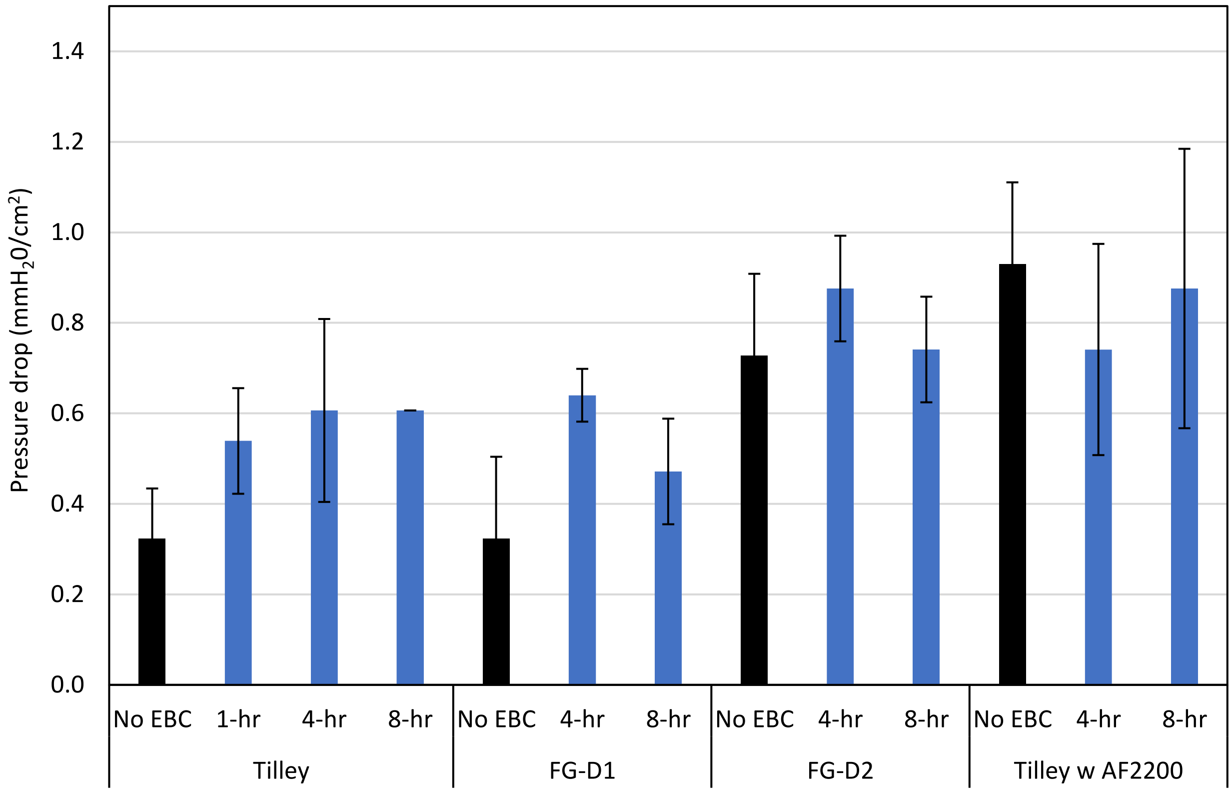



***Figure 4-17*** *Pressure drop results of reusable masks by EBC exposure scenario. Error bars represent standard deviation of 3 measurements (three samples) for the EBC cases, 5 for the no EBC case.*

Figure 4-18 presents the filtration efficiency results from testing the Tilley masks for different durations of EBC exposure. The standard deviation error bars are not included in the first Tilley figure for clarity; the second figure represents the same data as the first but in a different form for visualization and includes error bars. Figure 4-19 exhibits the filtration efficiency results from testing the other reusable cloth masks after EBC exposure. These masks were tested after 4- and 8-hour exposure only, as these exposure durations are both the most practically applicable scenarios as well as the worst-case scenario as determined from preliminary testing of the Tilley masks.

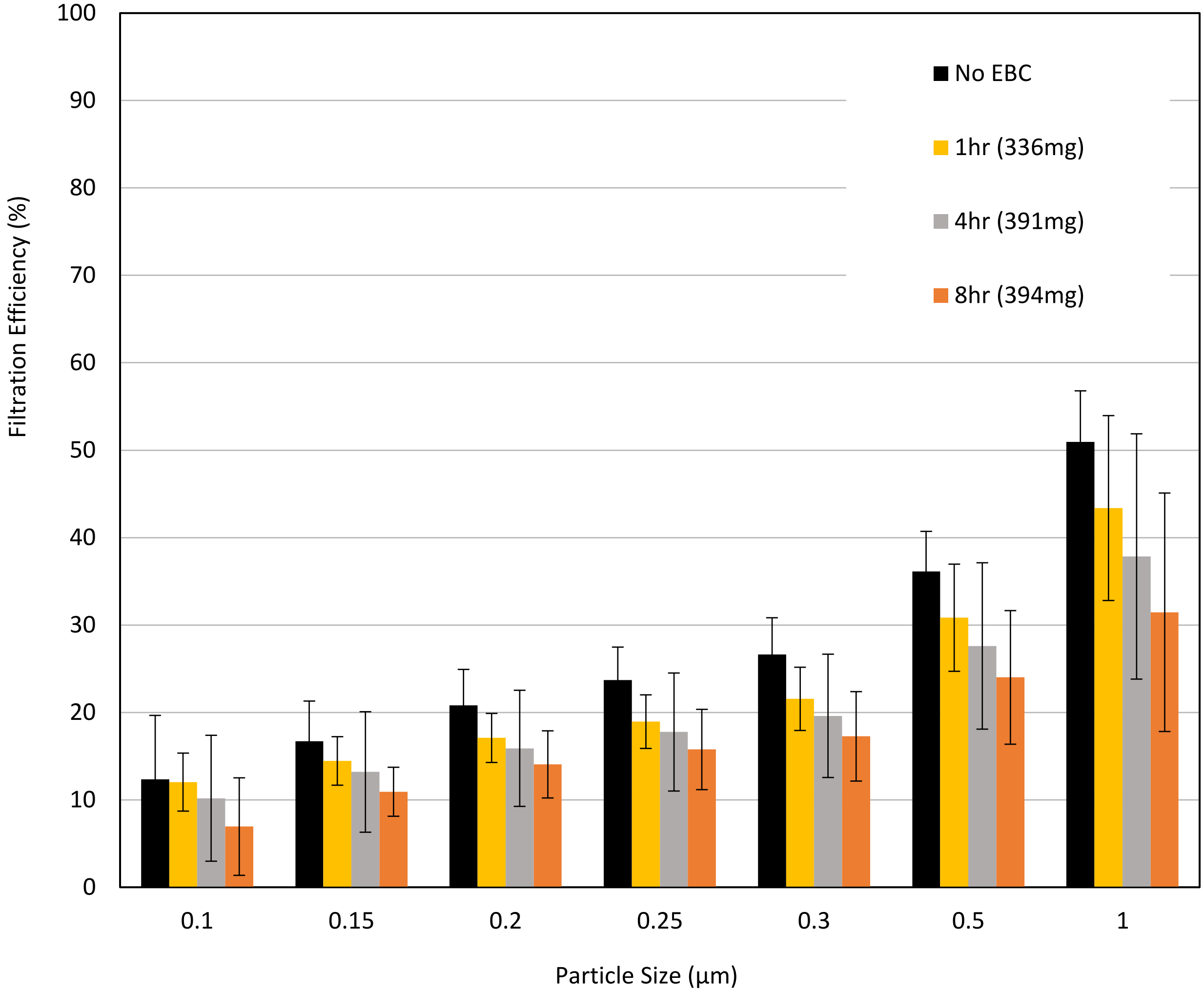
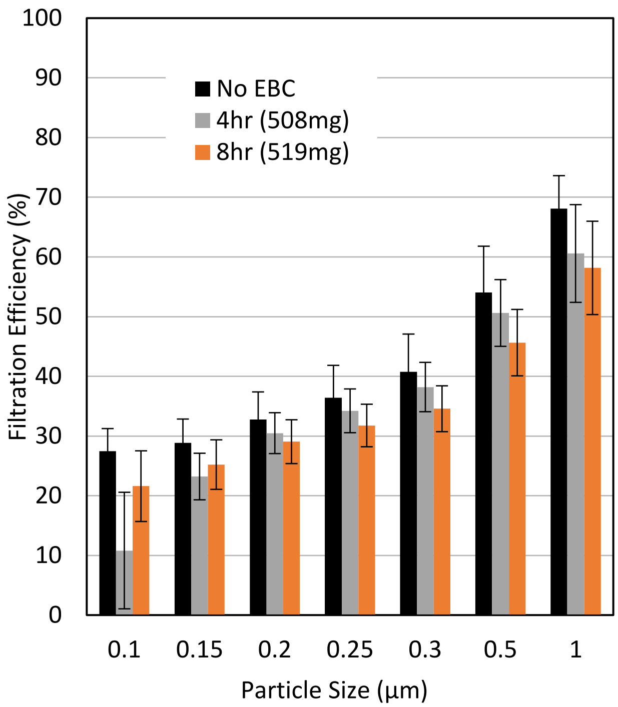
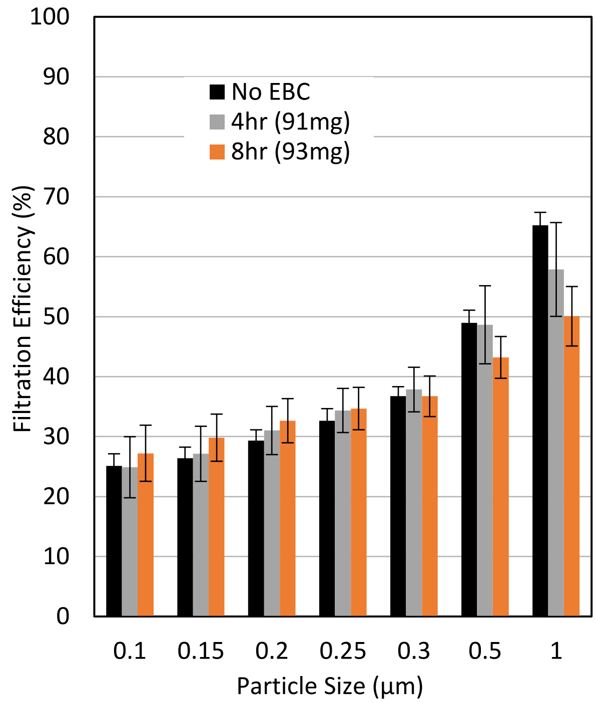


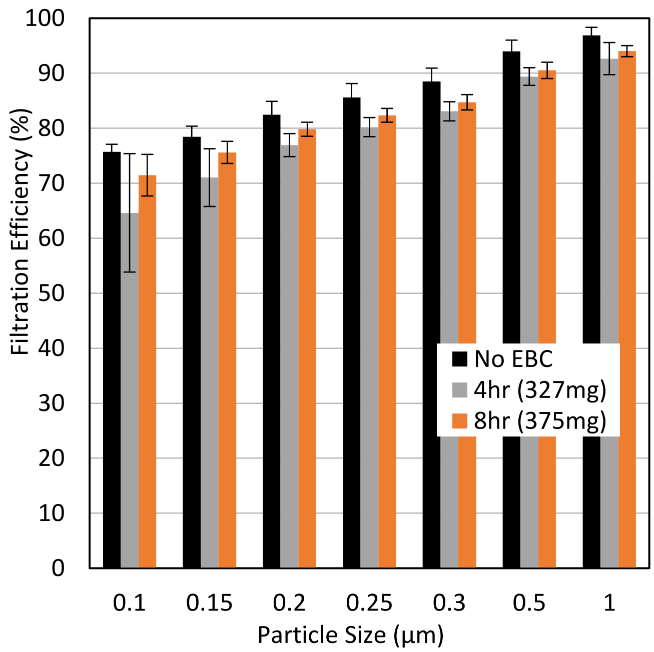

***Figure 4-18*** *Filtration efficiency results of Tilley masks in different EBC scenarios. Error bars represent standard deviation of 9 measurements (three samples) for the EBC cases, 6 measurements (two samples) for the no EBC case.*




*a) FG-D1*




*b) FG-D2*




*c) Tilley w AF2200*

***Figure 4-19*** *Filtration efficiency results of reusable masks tested at 4- and 8-hour EBC exposure, a) FG-D1, b) FG-D2, c) Tilley with insert. Error bars represent standard deviation of 9 measurements (three samples) for the EBC cases, 6 measurements (two samples) for the no EBC case.*

#### 4.3.2. Filtration Efficiency and Pressure Drop Results of Disposable Masks Exposed to EBC

Disposable masks tested for this section include the Ecoparksg brand non-medical, level 3, and N95 masks. The non-medical disposable masks were tested in triplicate with 1-hour, 4-hour, 8-hour, and 24-hour EBC accumulation. Based on the results from this testing, the medical mask types were tested in triplicate with 4-hour and 8-hour EBC exposure. The masks tested for this section represent the two different designs of common medical masks, the surgical mask style and the N95 as well as a non-medical option. Disposable masks, in particular the medical masks, are made with both hygroscopic and hydrophobic layers. Since the layer that acts as the primary filter, the middle layer, is protected from EBC by the absorbent inner layer, the mask is designed to resist interference from EBC [64]. The average weight difference between before and after EBC exposure including the standard deviation of these measurements are presented in Table 4-4. Pressure drop was measured for each sample and the average pressure drop for the EBC exposure tests as well as their corresponding no EBC data are presented in Figure 4-20. Like the previous section, the no-EBC breathability data is the average of five samples, other than the N95 masks, while the EBC exposure samples are the average of three samples.

***Table 4-4*** *Weight change in disposable masks from dry to after EBC exposure (Estimated EBC accumulation)*

| **Mask Type** | **EBC Exposure** | **Average EBC Weight (mg)** | **Standard deviation (mg)[1]** |
|---|---|---|---|
| Disposable (Ecoparksg) | 1-hr | 0.67 | 0.577 |
| | 4-hr | 0.67 | 0.577 |
| | 8-hr | 1.67 | 0.577 |
| | 24-hr | 2.33 | 2.082 |
| L3 | 4-hr | 1.33 | 1.155 |
| | 8-hr | 2.67 | 4.619 |
| N95 | 4-hr | 2.67 | 3.786 |

| | | | |
|---|---|---|---|
| | 8-hr | 5.67 | 3.055 |

Weight averaged over three replicates
[1]The disposable masks have very low EBC collection weight considering they are hydrophobic. The EBC collection weights found (0 mg - 8 mg) are near the uncertainty of the scale used (0.002 g) and therefore are not reliable and have a high standard deviation.

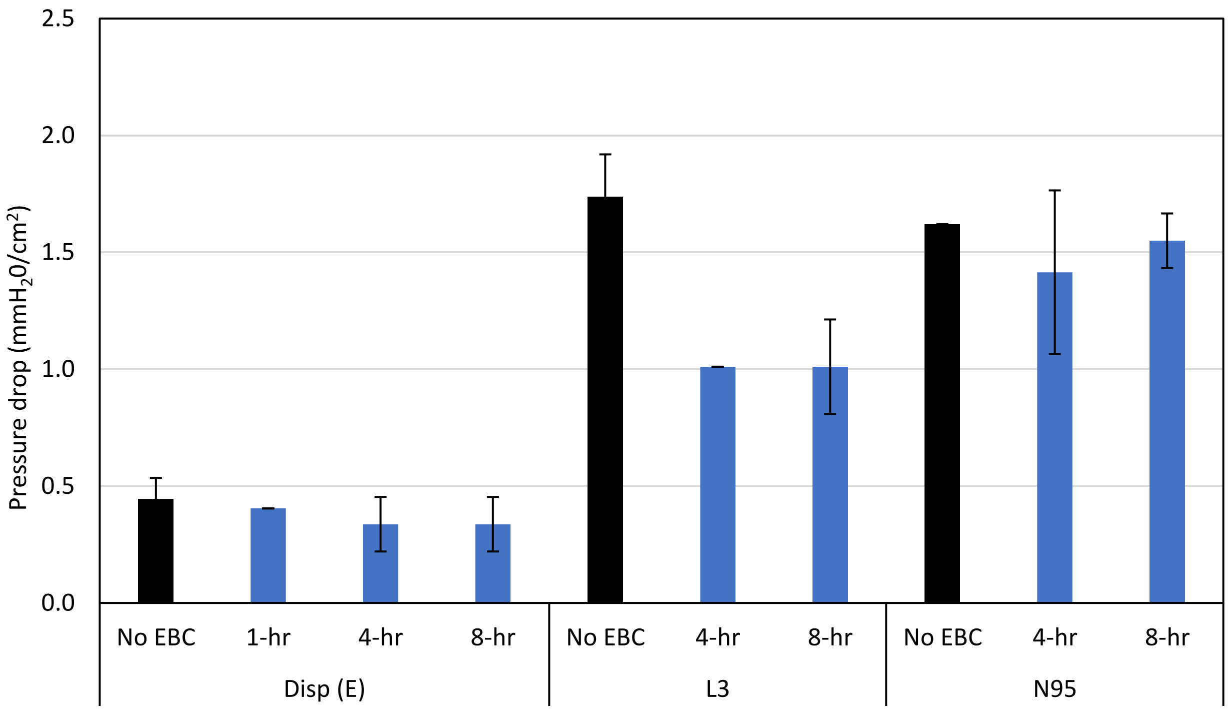



***Figure 4-20*** *Pressure drop results of disposable masks by EBC exposure scenario. Error bars represent standard deviation of 3 measurements (three samples) for the EBC cases, 5 for the no EBC case.*

Figure 4-21 presents the filtration efficiency results from testing the Ecoparksg non-medical disposable masks for different durations of EBC exposure. Figure 4-22 exhibits the filtration efficiency results from testing the other disposable masks after EBC exposure. These masks were tested after 4- and 8-hour exposure only as determined from preliminary testing of the disposable non-medical masks. Filtration efficiency testing was done immediately after EBC exposure with the same methodology as in the previous two results sections.

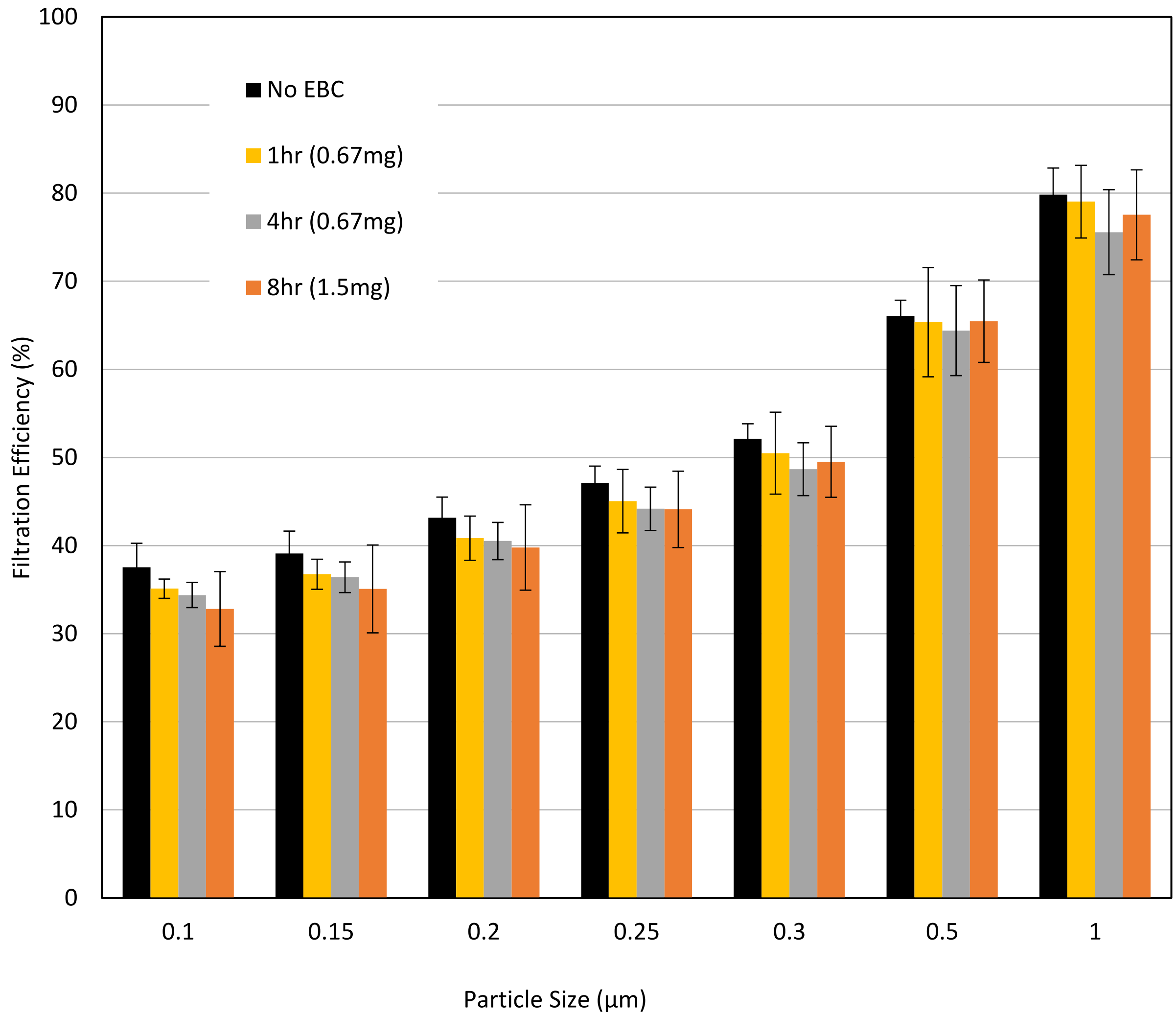
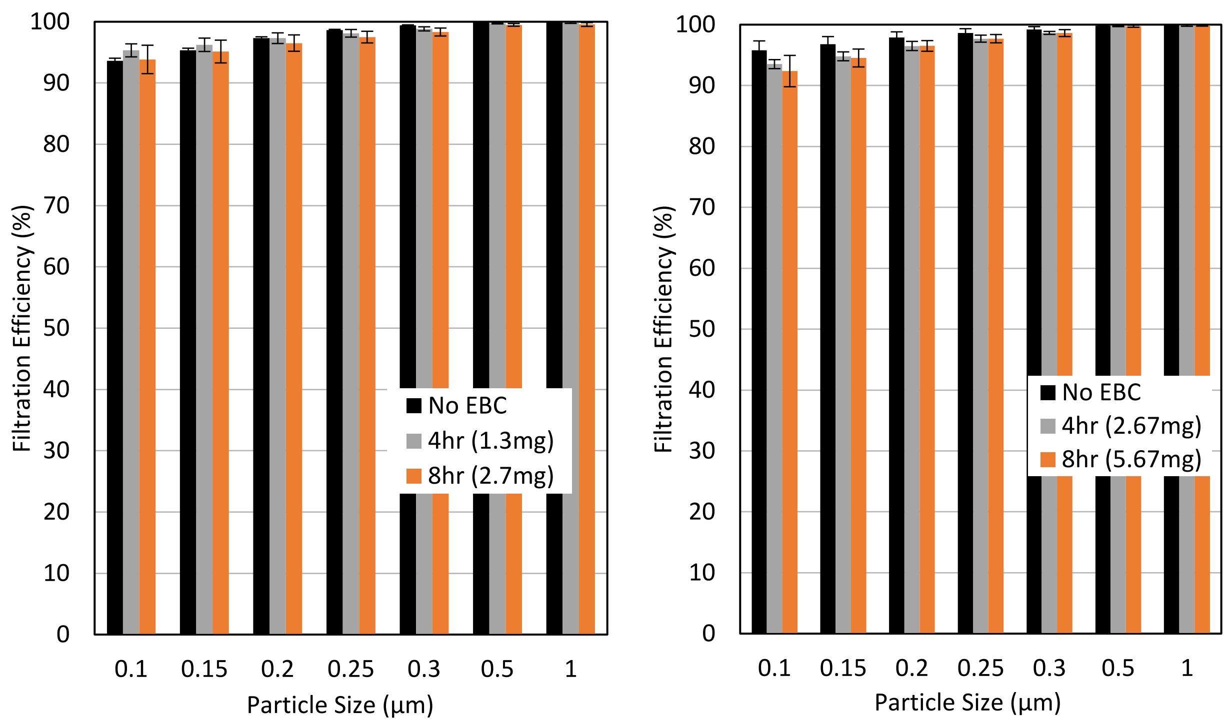



***Figure 4-21*** *Filtration efficiency results of Disposable (E) masks in different EBC scenarios. Error bars represent standard deviation of 9 measurements (three samples) for the EBC cases, 6 measurements (two samples) for the no EBC case.*

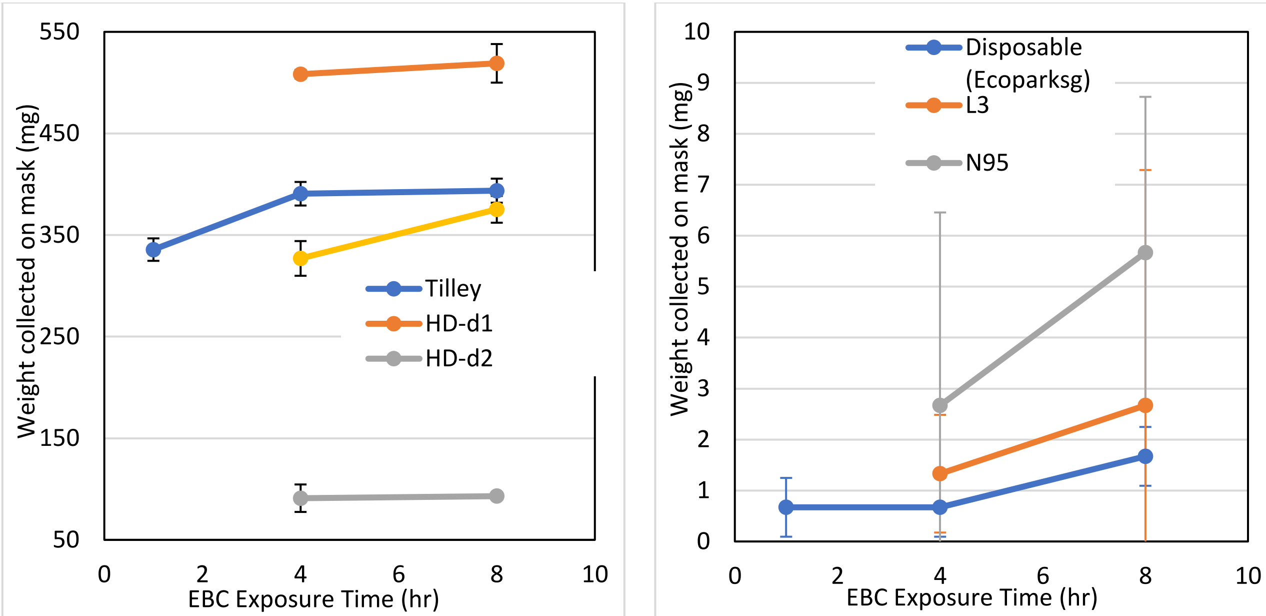



*a) L3* *b) N95*

***Figure 4-22*** *Filtration efficiency results of disposable masks tested at 4- and 8-hour EBC exposure, a) L3, b) N95. Error bars represent standard deviation of 9 measurements (three samples) for the EBC cases, 6 measurements (two samples) for the no EBC case.*

### 4.3.3. Discussion

The impact of EBC accumulation on mask performance is of vital importance for reusable mask use. Reusable masks are often made, wholly or in part, with hygroscopic cloth such as cotton and are used in non-health care scenarios. This means that the wearers may not be familiar with mask care and best practices and could be more likely to wear their mask for longer than appropriate, thus allowing more EBC accumulation. From the results presented in 4.1, 4.3.1, and 4.3.2 it is clear that generally filtration efficiency seems to decrease as the reusable masks are exposed to EBC. From Figure 4-18 we can see that with each increase in EBC exposure time, the filtration efficiency decreases further from the no EBC exposure scenario. In order to visualize the change of EBC weight over time for analysis, Figure 4-23 was included.




*a) Reusable masks* *b) Disposable masks*

***Figure 4-23*** *Graphical representation of EBC exposure weight change, a) Reusable masks, b) Disposable masks. . Error bars represent standard deviation of 3 measurements (three samples).*

The EBC weight for the 4-hour sample is much closer to the 8-hour sample, suggesting EBC accumulation is non-linear.

To better visualize the difference in filtration efficiency with and without EBC exposure, the filtration efficiency differential was plotted in Figure 4-24 and Figure 4-25. Three particle sizes are highlighted for this analysis. As previously mentioned, 0.15 µm and 0.3 µm are the particle sizes most relevant to COVID-19 research and testing and are therefore important particle sizes. The 1 µm particle size is also highlighted in this section because the impact that EBC exposure has on filtration efficiency appears to be more notable for large particle sizes from the initial results. This indicates that EBC exposure may interfere with only some filtration mechanisms, this is discussed more later.

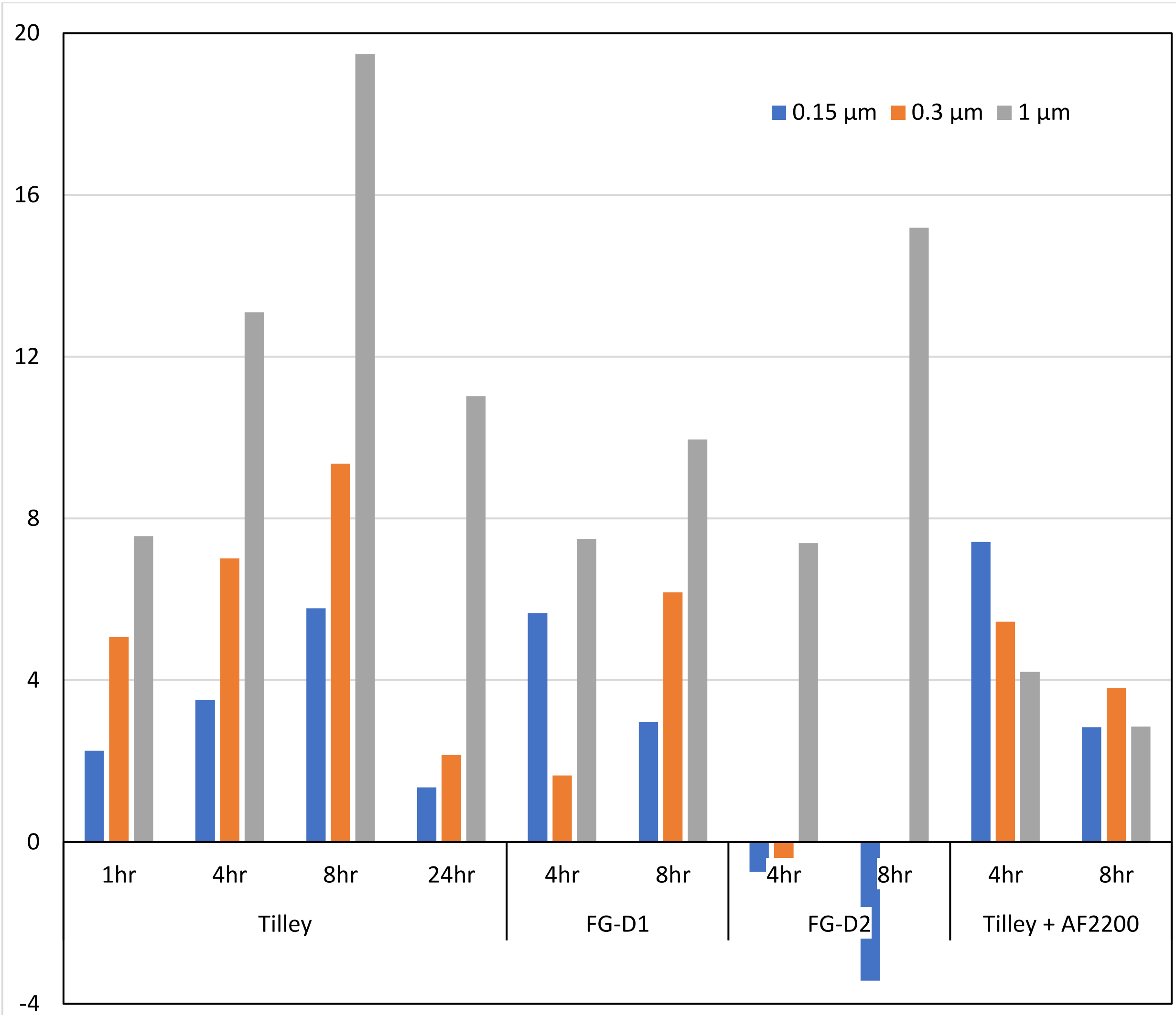



***Figure 4-24*** *Filtration efficiency differential results for reusable masks between no EBC scenario and the different exposure scenarios at 3 particle sizes*

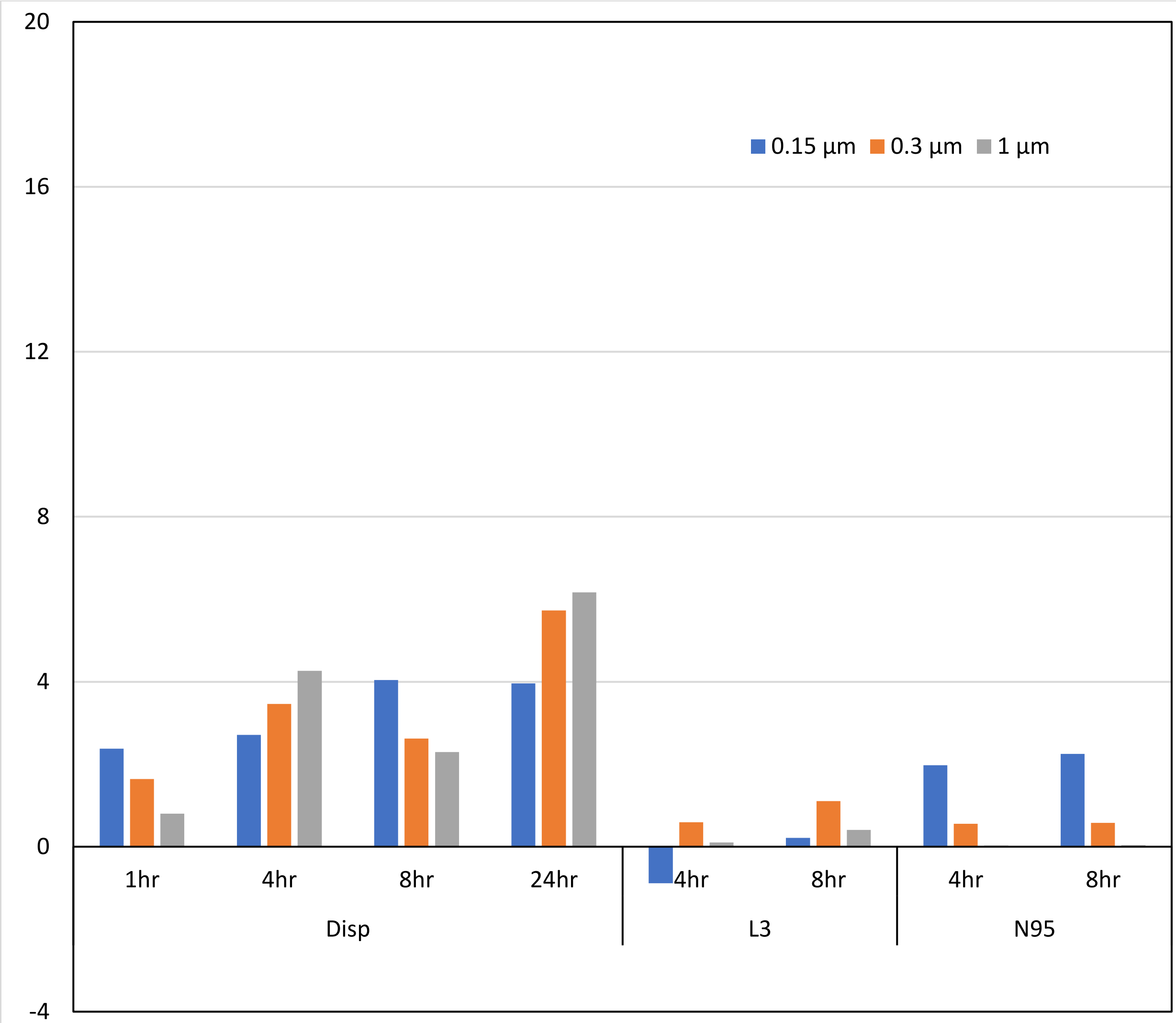


***Figure 4-25*** *Filtration efficiency differential results for disposable masks between no EBC scenario and the different exposure scenarios at 3 particle sizes*

Figure 4-24 and Figure 4-25 show that for the majority of the masks tested filtration efficiency in the no-EBC case is greater than the filtration efficiency in the EBC exposure cases. The Firm Grip design 2 and the level 3 mask are the only masks that do not exhibit this trend for all particle sizes shown. The disposable non-medical and N95 masks have a filtration efficiency difference relative to the no EBC case of less than 6%. Therefore, even if there is a correlation between EBC exposure and filtration efficiency decrease, it is small and likely negligible in terms of a reduction in mask performance. For the cloth masks, this loss in efficiency is up to 20%. From Figure 4-24, the largest reduction in efficiency is for an EBC exposure length of 8-hour period for particle sizes 0.3 µm and 1.0 µm. Though the 8-hour scenario seems to have a greater impact overall, the 4-hour scenario also had large decreases in filtration efficiency (up to 12%) and had a larger FE reduction than the 1- and 24- hour scenarios for the Tilley mask. Also, the 4-hour scenario had similar amounts of EBC present on the masks after exposure as the 8-hour scenario (4-hour EBC weight was 98-99.2% of the 8-hour EBC weight). This potentially suggests that mask use after 4-hours is essentially similar in terms of EBC accumulation and filtration efficiency decrease to 8-hour wear.

To better quantify the trends seen in the results, statistical analysis was performed. Table 4-5 shows the results of linear regression analysis with filtration efficiency as the dependent variable and number of hours spent exposed to EBC as the independent variable. For the analysis of this data, the measured weight of EBC collected could also theoretically be used as the independent variable however, considering the low weight of EBC collected on the disposable masks this is not a consistent way to analyze this data. Furthermore, the EBC weight was determined as the weight difference between after drying the mask and after EBC exposure, since EBC exposure was collected in open air in the lab some of this weight could be due to relative humidity. A Tilley mask was dried, weighed and then left in the lab without EBC exposure and then weighed after 4 and 8 hours, respectively. After 4 hours in ambient conditions the mask weight increased by 207 mg and in the second 4-hour period (hour 4 to 8) the mask gained another 2 mg for a total of 209 mg. This indicates that potentially up to half of the weight recorded during the EBC exposure tests could be due to ambient conditions.

Considering this, since the masks tested without EBC were not oven dried this is not an accurate way to compare the samples with and without EBC exposure. As mentioned previously, the 24-hour results were inconsistent and thus not used in the regression analysis.

***Table 4-5*** *Linear Regression analysis of EBC impact on filtration efficiency*

| Type of Mask | Mask | Particle Size | Multiple R | Slope | P-Value of slope |
|---|---|---|---|---|---|
| Reusable Cloth | Tilley (Cotton) | 0.15 µm | 0.522 | -0.619 | 0.099 |
| | | 0.3 µm | 0.559 | -0.916 | 0.074 |
| | | 1.0 µm | 0.613 | -2.106 | 0.045 |
| | FG-D1 (Cotton) | 0.15 µm | 0.347 | -0.384 | 0.399 |
| | | 0.3 µm | 0.583 | -0.782 | 0.129 |
| | | 1.0 µm | 0.618 | -1.190 | 0.103 |
| | FG-D2 (Nano mesh, cotton, polyester) | 0.15 µm | 0.468 | 0.447 | 0.242 |
| | | 0.3 µm | 0.037 | -0.022 | 0.931 |
| | | 1.0 µm | 0.899 | -1.90 | 0.002 |
| | Tilley + AF 2200 | 0.15 µm | 0.171 | -0.240 | 0.685 |
| | | 0.3 µm | 0.494 | -0.407 | 0.214 |
| | | 1.0 µm | 0.454 | -0.304 | 0.258 |
| Disposable | Disposable (E) | 0.15 µm | 0.522 | -0.378 | 0.100 |
| | | 0.3 µm | 0.288 | -0.260 | 0.390 |
| | | 1.0 µm | 0.313 | -0.290 | 0.348 |
| | Level 3 | 0.15 µm | 0.107 | -0.046 | 0.802 |
| | | 0.3 µm | 0.747 | -0.137 | 0.033 |
| | | 1.0 µm | 0.865 | -0.052 | 0.005 |
| | N95 | 0.15 µm | 0.210 | -0.213 | 0.618 |
| | | 0.3 µm | 0.275 | -0.058 | 0.510 |
| | | 1.0 µm | 0.444 | -0.005 | 0.270 |
| Note: Statistically significant correlations (p-value <0.05) are highlighted in grey. | | | | | |

The results presented in this section and the linear regression presented in Table 4-5 show that for the Tilley masks, smaller particle sizes, ≤ 0.3 µm, tend towards a correlation between mask filtration performance and EBC exposure but the relationship between EBC and filtration efficiency is not statistically significant. Similarly, the Firm Grip design 1 masks also show this tendency for the larger particle sizes, ≥ 0.3 μm, but this trend is not statistically significant (P-value < 0.05). However, the Tilley masks, Firm Grip design 2 masks and level 3 masks all show a statistically significant reduction in filtration efficiency at the 1 μm particle size. The slope for the Firm Grip and Tilley masks at the 1 μm particle size from the regression analysis are larger than the slope for the Level 3 masks. This indicates that while all have a statistically significant reduction in filtration efficiency with increasing EBC, the reusable masks have a more notable reduction than the Level 3 mask. The other reusable masks, N95 and disposable non-medical masks, do not show any correlation with EBC exposure and any trends noted are likely due to experimental variance. The Tilley mask with the non-woven center shows trends from both the cloth and disposable masks. While the mask did seem to absorb notable amounts of EBC, similar to the Tilley mask alone, there is not statistical correlation between EBC and FE, similar to the non-woven disposable masks. Considering the high filtration efficiency of the Tilley mask with an insert primarily comes from the insert, this result is expected. Another general conclusion from this data is that all of the cloth masks with a potential or statistical correlation with EBC amounts have a larger slope and therefore larger magnitude of impact from the EBC exposure than for the disposable masks. The Firm Grip design 2 EBC exposure results are the most unique. These masks showed a positive slope at the 0.15 μm particle size, meaning that filtration efficiencies tend to increase with EBC exposure; however, these results were not statistically significant. Furthermore, these masks had the largest p-value at the 0.3 μm, indicating a strong independence of the two variables. The Firm Grip design 2 mask had a unique material and design when compared to the reusable and disposable masks.

According to Mao et al. [65], as moisture ratio increases for a cotton fabric, the average inter-fiber pore radius and total pore volume increase. Simultaneously however, the internal surface area of the fibers is also increasing [65] [66]. These two tendencies could have opposite effects on filtration efficiency. Larger pore radiuses and pore volume allows more particles of all sizes to pass through, the swelling of the fibers and their increased surface area, however, increases the particle capture ability of each fiber. Furthermore, the liquid in the mask can create surface tension, thus adding another particle capture mechanism [66]. These competing effects create a complex situation, especially considering that EBC was used, not just water. EBC also contains ions and protein which could impact the electrostatic filtration mechanisms. In the results found for this research, the only particle sizes that show a statistical correlation to EBC exposure are particles ≥ 0.3 µm. This is logical considering in single fiber particle efficiency capture equations for the different filtration mechanisms, fiber diameter is inversely proportional to filtration efficiency [12]. For impaction and interception however, the fiber diameter term in the denominator is to a greater power than in the diffusion term [12]. These equations are provided in Table 4-6 for reference. This indicates that an increase in fiber diameter has a larger negative impact on interception and impaction, which govern the filtration of larger particles. Conceptually it fits with the changes that occur to fiber and pore sizes as well.

***Table 4-6*** *Single fiber efficiency equations*

| **Filtration Mechanism** | **Equation** |
|---|---|
| Diffusion | $E_D = 2(\frac{d_f U_0}{D})^{-2/3}$ [12] |
| Impaction | $E_l = \frac{p_\rho {d_p}^2 C_c U_0 J}{36 \eta d_f K u^2}$ [12] |

| | |
|---|---|
| Interception | $E_R = \frac{(1-\alpha)(\frac{d_p}{d_f})^2}{Ku(1+\frac{d_p}{d_f})}$ [12] |
| Where $E_R$= single fiber efficiency; $d_p$=pore diameter; $d_f$=fiber diameter; α= 1-porosity; Ku is a function of α; D=particle diffusion coefficient | |

Zangmeister et al. [66] investigated a similar research question and found opposing results to this research, a positive effect on FE from humidity. Though the objective of this work was similar, the methodology was quite different and can account for the differences in results. While this research used simulated EBC, kept in the refrigerator between experiments due to the albumin, exposed to a mask over realistic time periods, Zangmeister et. al used a high relative humidity environment at 25°C over a time period of 12-16 hours. Furthermore, the masks used were different, the cotton mask used by Zangmeister et. al had 2 layers while the Tilley and Firm Grip masks used in this research had 3 layers which will impact both EBC absorption capabilities and filtration properties. Likely the greatest source of discord among findings is that [66] investigated particle sizes up to 0.8 µm, and this research found the most statistically significant trends at 1 µm.

Figure 4-17 and Figure 4-20 from the results portion of this section show there may be a potential correlation between EBC exposure and pressure drop. In Figure 4-17 all 3 cloth masks (with no inserts) show higher pressure drops for the EBC exposure scenarios when compared to the average pressure drop found with no EBC exposure, especially the cotton masks (Tilley and FG-D1). Figure 4-20 and the Tilley mask with the non-woven insert show the opposite trend; the pressure drops measured with no EBC are higher than the pressure drops recorded with EBC exposure. To further investigate this observation a linear regression analysis was done with pressure drop in the same method as described for the filtration efficiency analysis. Table 4-7 presents the results from this linear regression.

***Table 4-7*** *Linear Regression analysis of EBC impact on pressure drop*

| Type of Mask | Mask | Multiple R | Slope | P-Value of slope |
|---|---|---|---|---|
| Reusable Cloth | Tilley | 0.645 | 0.030 | 0.013 |
| | FG-D1 | 0.424 | 0.023 | 0.193 |
| | FG-D2 | 0.097 | 0.004 | 0.777 |
| | Tilley + AF 2200 | 0.151 | -0.010 | 0.659 |
| Disposable | Disposable (E) | 0.464 | -0.014 | 0.094 |
| | Level 3 | 0.837 | -0.097 | 0.001 |
| | N95 | 0.085 | 0.006 | 0.841 |
| Note: Statistically significant correlations (p-value <0.05) are highlighted in grey. | | | | |

**Table 4-7** shows that there is a statistically significant correlation between the Tilley brand reusable cloth masks pressure drop and EBC exposure. The x-value is positive indicating that as EBC exposure increases so does the pressure drop of the Tilley masks. Despite the earlier identified trends for the other two reusable masks there is no statistical evidence for this. This is likely due to the high variance between the pressure drop measurements for the cloth masks. Among the disposable masks, the level 3 masks show statistically significant correlation between a decrease in pressure drop and EBC exposure time. The slope for this relationship is over three times larger for the level 3 masks than the Tilley masks. This indicates that EBC exposure may increases air permeability for non-reusable masks while decreasing air permeability for cloth masks.

# 5. Conclusion and Recommendations

## 7.1. Conclusions

The goal of this research was to investigate the suitability in terms of filtration efficiency and breathability of various fabrics and commercially available face masks in different use scenarios for the prevention of SARS-CoV-2 airborne transmission. From this investigation the aim was to provide practical recommendations to improve public mask use for reduction in transmission of COVID-19. Three different objectives were determined. The first was to determine basic suitability of different fabrics that could be used in homemade masks, combinations of these fabrics as homemade masks, commercially available cloth masks, layering options with cloth masks and medical masks for comparisons. These individual masks and fabrics were tested for filtration efficiency and pressure drop at face velocities of 10 cm/s and 25 cm/s with NaCl aerosols. These initial tests were used to inform fabric combination testing at 25 cm/s with NaCl aerosols. The second objective included investigating the impact of face velocity on mask performance. Four face velocities were chosen at equal intervals from each other, including three velocities that were within the range specified for mask testing in the ASTM medical mask testing standards. The final objective included wetting the masks with a simulated exhaled breath condensate to investigate the impact that wetting has on mask efficiency and breathability.

The following are some of the main conclusions from this work, organized by objective.

Objective one:

- Using appropriate layers and high-quality inserts, homemade masks can achieve suitability of a facemask, in terms of both FE and breathability, as required by ASTM standards for level 2 and level 3 surgical masks.
- Generally medical masks are far superior to any basic 3 layer homemade, cloth or disposable option in terms of FE.
- Some disposable masks are very suitable for transmission protection in terms of FE and quality factor; however, there is large variability in quality.
- Commercial cloth masks can be effective when paired with a filter or disposable mask.
- Commercial cloth masks have large variability in quality, even within the same brand due to a lack of regulation

Objective two:

- Cloth masks may be more suited to higher face velocities such as running or working out.
- The range of face velocities allowed in current ASTM is unacceptable as there is large variance.
- Generally, FE decreases with increasing face velocity and therefore mask use scenarios with heavy breathing, such as while doing physical activity, may present more of a transmission hazard, even when wearing masks.

Objective three:

- The change in pressure drop from EBC exposure is negligible. For non-woven fabrics, the pressure drop generally decreases with EBC exposure while for woven fabrics there is no strong correlation.
- The effect that EBC exposure has on masks made of non-woven material is negligible to none.
- Filtration efficiency of cloth masks tend to decrease with increased EBC exposure. This decrease in filtration efficiency tends to increase with particle size, with a statistically significant negative relationship between filtration efficiency and EBC exposure time occurring at the 1.0 µm particle size for two types of cloth masks.
- Cloth masks absorb >98% of the EBC weight found after 8-hour exposure in 4 hours, meaning the majority of EBC absorption occurs in the first 4 hours.
- EBC exposure had less of a negative impact on the performance of the cloth masks made with a mixture of nano mesh, polyester and cotton when compared to the masks with 100% cotton.
- Insertion of a non-woven filter layer into the cloth mask with a filter pouch reduced the impact of EBC on FE by up to 6 times for some particle sizes.

## 7.2. Recommendations

Overall, in this research it was determined that all fabrics and masks tested do provide some level of filtration at the particle sizes relevant to COVID-19 transmission. Some materials and masks are evidently much more efficient and provide a notably higher level of protection than others.

Sustainability is one motivator for this research and is considered in the following recommendations. The public use of disposable masks is creating significant amounts of waste related to the fabrication, transport, and disposal of these single use masks. This will may have a long-lasting effect on the environment and needs to be mitigated where possible. While sustainability needs to be considered, public health cannot be compromised. Optimization of filtration efficiency and breathability with as little waste as possible is ideal.

- While all cloth masks alone had lower filtration efficiency than the disposable masks (non-medical and medical included), the masks that had a blend of nano mesh, polyester and cotton are arguably more suitable for protection against SARS-CoV-2 or other similarly transmitted viruses in realistic scenarios compared to other reusable masks.
- For a basic 100% cotton masks to perform near medical mask quality, a high-quality filter, such as a high MPR furnace filter, is necessary. Cotton cloth masks should be made with a filter pocket to allow the insertion of a filter.
- With proper layering, household materials can achieve high FE similar to medical masks. Considering this, suggestions for layering should be provided for the public so that homemade masks can be made to higher standards. Using household materials can eliminate waste, be more cost effective and promote reuse; however, this should not be done in a way to compromise the mask quality. Homemade masks should have a layer or two of high quality non-woven filter material such as a high MPR furnace filter. While the use of the furnace filter will create some waste, the cloth exterior is reusable and there is less waste than a fully disposable mask.

- More regulation is needed for disposable non-medical, and reusable commercially sold masks. Performance and quality are inconsistent, even among disposable non-medical masks which have similar designs and materials to medical masks. More regulation and some testing requirements for masks being sold for the purpose of COVID-19 protection would greatly increase consistency and quality. Also, with more regulation or testing requirements, the public can make more informed decisions when purchasing commercial non-medical masks.
- The velocity range allowed for medical mask testing as per ASTM F2299 is too large and should be revised. Filtration efficiency varies too much within this range which means masks that are all certified under this standard can be inconsistent and potentially less efficient then needed or than advertised.
- Cloth masks should be removed and cleaned after an 8-hour workday. If possible, removal after 4-hours would be preferred. Medical and non-medical disposable masks are not largely impacted by breath condensate and therefore should be worn according to manufacturer's specifications. Since filter inserts reduce the impact of breath condensate on the performance of a cloth mask, this is another preferred option. The filter can be changed regularly depending on type of wear.
- Further research should be conducted on the subject of how filtration mechanisms are impacted by breath condensate considering conflicting research currently available and about mask maintenance, lifespan and fit which were not included in this scope.

# References


[1] World Health Organization (WHO), "Mask use in the context of COVID-19," WHO, 2020.

[2] World Health Organization (WHO) , "Shortage of personal protective equipment endangering health workers worldwide.," 2020. [Online]. Available: https://www.who.int/news-room/detail/03-03-2020-shortage-of-personal-protective-equipment-endangering-health-workers-worldwide. [Accessed 3 March 2021].

[3] A. Konda, A. Prakash, G. Moss, M. Schmoldt, G. Grant and S. Guha, "Erratum: Aerosol filtration efficiency of common fabrics used in respiratory cloth masks," *ACS Nano,* vol. 14, no. 5, pp. 6339-6347, 2020.

[4] L. Morawska and J. Cao, "Airborne transmission of SARS-CoV-2: The world should face the reality," *Environment International,* vol. 139, 2020.

[5] J. Lu, J. Gu, K. Li, C. Xu, W. Su, Z. Lai, D. Zhou, C. Yu, B. Xu and Z. Yang, "COVID-19 outbreak associated with air conditioning in restaurant, Guangzhou, China, 2020.," *Emerg. Infec. Dis.,* vol. 26, p. 1628–1631., 2020.

[6] S. Asadi, A. S. Wexler, C. D. Cappa, S. Barreda, N. M. Bouvier and W. D. Ristenpart, "Aerosol emission and superemission during human speech increase with voice loudness," *Scientific Reports ,* vol. 9, no. 2348, 2019.

[7] L. Bourouiba, "Turbulent Gas Clouds and Respiratory Pathogen Emissions: Potential Implications for Reducing Transmission of COVID-19," *JAMA Insights,* vol. 323, no. 18, pp. 1837-1838, 2020.

[8] P. Bahl, C. Doolan, C. d. Silva, A. A. Chughtai, L. Bourouiba and C. R. MacIntyre, "Airborne or droplet precautions for health workers treating COVID-19?," *The Journal of Infectious Diseases,* vol. jiaa189, 2020.

[9] E. Movert, Y. Wu, G. Lambeau, F. Kahn, L. Touqui and T. Areschoug, "Airborne or droplet precautions for health workers treating coronavirus disease 2019?," *Journal of Infectious Diseases,* vol. jiaa189, 2020.

[10] Z. Baboli, N. Neisi, A. A. Babaei, M. Ahmadi, A. Sorooshian, Y. T. Birgani and G. Goudarzi, "On the airborne transmission of SARS-CoV-2 and relationship with indoor conditions at a hospital," *Atmospheric Environment,* vol. 261, no. 118563, 2021.

[11] Z.-D. Guo, Z.-Y. Wang, S.-F. Zhang, X. Li, L. Li, C. Li, Y. Cui, R.-B. Fu, Y.-Z. Dong, X.-Y. Chi, M.-Y. Zhang, K. Liu, C. Cao, B. Liu, K. Zhang, Y.-W. Gao, B. Lu and W. Chen, "Aerosol and Surface Distribution of Severe Acute Respiratory Syndrome Coronavirus 2 in Hospital Wards, Wuhan, China, 2020," *Emerg Infect Dis.,* vol. 26, no. 7, pp. 1583-1591, 2020.

[12] W. Hinds, "Chapter 9 Filtration," in *Aerosol technology: properties, behavior, and measurement of airborne particles.*, Hoboken, NJ, John Wiley & Sons, 1999, pp. 182-205.

[13] A. Fehr and S. Perlman, "Coronaviruses: an overview of their replication and pathogenesis," *Methods Mol Biol,* vol. 1282, pp. 1-23, 2015.

[14] M. Cascella, M. Rajnik, A. Aleem, S. C. Dulebohn and R. D. Napoli, Features, Evaluation, and Treatment of Coronavirus (COVID-19) [, StatPearls Publishing LLC., 2021.

[15] Y. Wang, Z. Deng and D. Shi, "Donglu," *Medical Devices and Sensors,* vol. 4, no. 1, 2021.

[16] D. Vallero, "30.4.1.4 Electrostatic Mechanisms.," in *Fundamentals of Air Pollution* , 5th ed., Elseiver, 2014, pp. 847-848.

[17] NIOSH, "Current Strategies for Engineering Controls in Nanomaterial Production and Downstream Handling Processes," U.S. Department of Health and Human, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH), Cincinnati, OH, 2013.

[18] NIOSH, "Title 42: Public Health PART 84—APPROVAL OF RESPIRATORY PROTECTIVE DEVICES," 2021.

[19] ASTM International, "ASTM F2100–19: Standard specification for performance of materials used in medical face masks," ASTM International, West Conshohocken, PA, 2019.

[20] Z. Zhao, Z. Zhang, M. Lanzarini-Lopes, S. Sinha, H. Rho, P. Herckes and P. Westerhoff, "Germicidal Ultraviolet Light Does Not Damage or Impede Performance of N95 Masks upon Multiple Uses," *Environmental Science and Technology Letters,* vol. 7, no. 8, pp. 600-605, 2020.

[21] E. Hossain, S. Bhadra, H. Jain, S. Das, A. Bhattacharya, S. Ghosh and D. Levine, "Recharging and rejuvenation of decontaminated N95 masks," *Physics of Fluids,* vol. 32, no. 9, 202.

[22] J. C. Rubio-Romero, M. d. C. Pardo-Ferreira, J. A. Torrecilla-Garcia and S. Calero-Castro, "Disposable masks: Disinfection and sterilization for reuse, and non-certified manufacturing, in the face of shortages during the COVID-19 pandemic," *Safety Science,* vol. 129, 2020.

[23] D. Wang, B.-C. Sun, J.-X. Wang, Y.-Y. Zhou, Z.-W. Chen, Y. Fang, W.-H. Yue, S.-M. Liu, K.-Y. Liu, X.-F. Zeng, G.-W. Chu and J.-F. Chen, "Can Masks Be Reused After Hot Water Decontamination During the COVID-19 Pandemic?," *Engineering,* vol. 6, no. 10, pp. 1115-1121, 2020.

[24] U.S. Food and Drug Administration, "Face Masks, Including Surgical Masks, and Respirators for COVID-19," [Online]. Available: https://www.fda.gov/medical-devices/coronavirus-covid-19-and-medical-devices/face-masks-including-surgical-masks-and-respirators-covid-19. [Accessed 22 06 2021].

[25] Levitt Safety, "All Masks/Respiratory Protection," 2021. [Online]. Available: https://www.levitt-safety.com/products-category/masks-respiratory-protection-2/. [Accessed 22 06 2021].

[26] Government of Canada, "Regulatory considerations on the classification of non-medical masks or face coverings: Notice to industry," 21 04 2021. [Online]. Available: https://www.canada.ca/en/health-canada/services/drugs-health-products/covid19-

industry/medical-devices/personal-protective-equipment/medical-masks-respirators/face-covering-classifications-notice.html#shr-pg0. [Accessed 06 07 2021].

[27] L. Russell, L. Campani, J. Jones and B. Healy, "Fluid-repellent surgical mask (FRSM) fit – one size does not fit all," *Clinical Medicine (Lond),* vol. 21, no. 3, pp. e283-e286, 2021.

[28] T. Oberg and L. M. Brosseau, "Surgical mask filter and fit performance," *American Journal of Infection Control,* vol. 36, no. 4, pp. 276-282, 2008.

[29] P. Forouzandeh, K. O'Dowd and S. C. Pillai, "Face masks and respirators in the fight against the COVID-19 pandemic: An," *Safety Science ,* vol. 133, no. 104995, 2021.

[30] ASTM International, "Standard test method for determining the initial efficiency of materials used in medical face masks to penetration by particulates using latex spheres," ASTM international, West Conshohocken, PA, 2017.

[31] ASTM International, *Standard Test Method for Evaluating the Bacterial Filtration Efficiency (BFE) of Medical Face Mask Materials, Using a Biological Aerosol of Staphylococcus aureus,* West Conshohocken, PA: AASTM International, 2019.

[32] European Committee for Standardization Technical Committee, *Medical face masks - Requirements and test methods,* Brussels, 2019.

[33] P. Z. Chen, A. Ngan, N. Manson, J. T. Maynes, G. H. Borschel, O. D. Rotstein and F. X. Gu, "Transmission of aerosols through pristine and reprocessed N95 respirators," 2020.

[34] G. Nallathambi, B. Robert, S. Esmeralda, J. Kumaravel and V. Parthiban, "Development of SPI/AC/PVA nano-composite for air-filtration and purification," *Research Journal of Textile and Apparel,* vol. 24, no. 1, pp. 72-83, 2020.

[35] S. Anand and Y. Mayya, "Size distribution of virus laden droplets from expiratory ejecta of infected subjects," *Scientific Reports,* vol. 10, no. 21174, 2020.

[36] CDC - The National Institute for Occupational Safety and Health (NIOSH), "42 CFR Part 84 Respiratory Protective Devices," 2020.

[37] NIOSH, "Determination of particulate filter efficiency level for N95 series filters against solid particulates for non-powered, air purifying respirators standard testing procedure," National Personal Protective Technology Laboratory, Pitsburgh, Pa, 2019.

[38] R. M. Effros, K. W. Hoagland, M. Bosbous, D. Castillo, B. Foss, M. Dunning, M. Gare, W. Lin and F. Sun, "Dilution of Respiratory Solutes in Exhaled Condensates," *American Journal of Respiratory and Critical Care Medicine,* vol. 165, 2002.

[39] L. Scheideler, H.-G. Manke, U. Schwulera, O. Inacker and H. Hämmerle, "Detection of Nonvolatile Macromolecules in Breath: A Possible Diagnostic Tool?," *American Review of Respiratory Disease,* vol. 148, no. 3, 1992.

[40] J. B. McCafferty, T. A. Bradshaw, S. Tate, A. P. Greening and J. A. Innes, "Effects of breathing pattern and inspired air conditions on breath condensate volume, pH, nitrite, and protein concentrations," *Thorax,* vol. 59, pp. 694-698, 2004.

[41] B. R. Winters, J. D. Pleil, M. M. Angrish, M. A. Stiegel, T. H. Risby and M. C. Madden, "Standardization of the collection of exhaled breath condensate and exhaled breath aerosol using a feedback regulated sampling device," *J. Breath Res.* , vol. 11 , no. 047107, 2017.

[42] Association Française de Normalisation (AFNOR), *Masques barrieres: Guide d'exigences minimales, de methodes d'essais, de confection et d'usage,* 2020.

[43] K. M. Shakya, A. Noyes, R. Kallin and R. E. Peltier, "Evaluating the efficacy of cloth facemasks in reducing particulate matter exposure," *Journal of Exposure Science & Environmental Epidemiology,* vol. 27, pp. 352-357, 2017.

[44] S. Rengasamy, B. Eimer and R. E. Shaffer, "Simple Respiratory Protection—Evaluation of the Filtration Performance of Cloth Masks and Common Fabric Materials Against 20–1000 nm Size Particles," *The Annals of Occupational Hygiene,* vol. 54, no. 7, pp. 789-798, 2010.

[45] A. Davies, K. Thompson, K. Giri, G. Kafatos, J. Walker and A. Bennett, "Testing the Efficacy of Homemade Masks: Would They Protect in an Influenza Pandemic?," *Disaster Medicine and Public Health Preparedness,* vol. 7, no. 4, pp. 413-418, 2013.

[46] M. v. d. Sande, P. Teunis and R. Sabel, "Professional and Home-Made Face Masks Reduce Exposure to Respiratory Infections among the General Population," *PLOS ONE,* vol. 3, no. 7, p. e2618, 2008.

[47] K. Ardon-Dryer, J. Warzywoda, R. Tekin, J. Biros, S. Almodovar, B. Weeks, L. Hope-Weeks and A. J. Sacco, "Mask Material Filtration Efficiency and Mask Fitting at the Crossroads: Implications during Pandemic Times," *Aerosol Air Qual. Res.,* vol. 21, no. 200571, 2021.

[48] L. Li, M. Niu and Y. Zhu, "Assessing the effectiveness of using various face coverings to mitigate the transport of airborne particles produced by coughing indoors," *Aerosol Science and Technology,* vol. 55, no. 3, pp. 332-339, 2020.

[49] W. Hao, A. Parasch, S. Williams, J. Li, H. Ma, J. Burken and Y. Wang, "Filtration performances of non-medical materials as candidates for manufacturing facemasks and respirators," *International Journal of Hygiene and Environmental Health,* vol. 229, no. 113582, 2020.

[50] C. D. Zangmeister, J. G. Radney, E. P. Vicenzi and J. L. Weaver, "Filtration Efficiencies of Nanoscale Aerosol by Cloth Mask Materials Used to Slow the Spread of SARS-CoV-2," *ACS Nano,* vol. 14, p. 9188−9200, 2020.

[51] S. R. Lustig, J. J. H. Biswakarma, D. Rana, S. H. Tilford, W. Hu, M. Su and M. S. Rosenblatt, "Effectiveness of Common Fabrics to Block Aqueous Aerosols of Virus-like Nanoparticles," *ACS Nano,* vol. 14, no. 7651−7658, 2020.

[52] M. Zhao, L. Liao, W. Xiao, X. Yu, H. Wang, Q. Wang, Y. L. Lin, F. S. Kilinc-Balci, A. Price, L. Chu, M. C. Chu, S. Chu and Y. Cui, "Household Materials Selection for Homemade Cloth Face Coverings and Their Filtration Efficiency Enhancement with Triboelectric Charging," *Nano Lett.,* vol. 20, p. 5544−5552, 2020.

[53] R. Pemmada, X. Zhu, M. Dash, Y. Zhou, S. Ramakrishna, X. Peng, V. Thomas, S. Jain and H. S. Nanda, "Science-based strategies of antiviral coatings with viricidal properties for the COVID-19 like pandemics," *Materials,* vol. 13, no. 18, 2020.

[54] L. B. Bezek, J. Pan, C. Harb, C. E. Zawaski, B. Molla, J. R. Kubalak, L. C. Marr and C. B. Williams, "Additively manufactured respirators: quantifying particle transmission and identifying system-level challenges for improving filtration efficiency," *Journal of Manufacturing Systems,* 2021.

[55] Q. Ou, C. Pei, S. C. Kim, E. Abell and D. Y. H. Pui, "Evaluation of decontamination methods for commercial and alternative respirator and mask materials - view from filtration aspect," *J Aerosol Sci.,* vol. 150, no. 15609, 2020.

[56] H. Lu, D. Yao, J. Yip, C.-W. Kan and H. Guo, "Addressing COVID-19 spread: Development of reliable testing system for mask reuse," *Aerosol and Air Quality Research,* vol. 20, no. 11, pp. 2309-2317, 2020.

[57] J. M. Carnino, S. Ryu, K. Ni and Y. Jin, "Pretreated household materials carry similar filtration protection against pathogens when compared with surgical masks," *American Journal of Infection Control,* vol. 48, p. 883−889, 2020.

[58] A. Kumar, D. N. Sangeetha, R. Yuvaraj, M. Menaka, V. Subramanian and B. Venkatraman, "Quantitative performance analysis of respiratory facemasks using atmospheric and

laboratory generated aerosols following with gamma sterilization," *Aerosol and Air Quality Research,* vol. 21, no. 1, pp. 1-17, 2021.

[59] ASTM International, "F2299/F2299M-03(2017) Standard Test Method for Determining the Initial Efficiency of Materials Used in Medical Face Masks to Penetration by Particulates Using Latex Spheres," ASTM International, West Conshohocken, PA, 2017.

[60] Centers for Disease Control and Prevention, "Improve How Your Mask Protects You," 6 April 2021. [Online]. Available: https://www.cdc.gov/coronavirus/2019-ncov/your-health/effective-masks.html. [Accessed 3 August 2021].

[61] J. K. Gupta, C.-H. Lin and Q. Chen, "Characterizing exhaled airflow from breathing and talking," *Indoor Air,* vol. 20, pp. 31-39, 2010.

[62] E. Kosareva, "Textile material analysis for potential facemasks application," University of Alberta, Textiles & Apparel Science Department of Human Ecology, Edmonton Alberta, 2021.

[63] C. E. Commission, "Clinical Excellence Commission COVID-19 Infection Prevention and Control Manual for acute and non-acute healthcare settings Version 1.7," 2021. [Online]. Available: https://www.cec.health.nsw.gov.au/__data/assets/pdf_file/0018/644004/COVID-19-IPAC-manual.pdf. [Accessed 2 November 2021].

[64] S. S. Salvi, "In this pandemic and panic of COVID-19 what should doctors know about masks and respirators?," [Online]. Available: http://apiindia.org/wp-content/uploads/pdf/corona-virus/review-article-on-mask.pdf. [Accessed 2 November 2021].

[65] Z. Mao, H. Yu, Y. Wang, L. Zhang, Y. Zhong and H. Xu, "States of Water and Pore Size Distribution of Cotton Fibers with Different Moisture Ratios," *Industrial and Engineering Chemistry Research,* vol. 53, p. 8927−8934, 2014.

[66] C. D. Zangmeister, J. G. Radney, M. E. Staymates, E. P. Vicenzi and J. L. Weaver, "Hydration of Hydrophilic Cloth Face Masks Enhances the Filtration of Nanoparticles," *ACS Applied Nano Materials ,* vol. 4, no. 3, pp. 2694-2701, 2021.

[67] S. R. Lustig, J. J. H. Biswakarma, D. Rana, S. H. Tilford, W. Hu, M. Su and M. S. Rosenblatt, "Effectiveness of Common Fabrics to Block Aqueous Aerosols of Virus-like Nanoparticles," *ACS Nano,* vol. 14, no. 6, pp. 7651-7658, 2020.

[68] ASTM International, "Standard specification for performance of materials used in medical face masks," ASTM International, West Conshohocken, PA, 2019.

[69] L. Brosseau and R. B. Ann, "N95 Respirators and Surgical Masks," Centers for Disease Control and Prevention, 2009.

## *Appendix A*

Filtration Efficiency and Pressure Drop Testing Procedure:

1. Turn on vacuum line and corresponding MFC to clear line for 15 minutes
2. Check silica gel to see if it needs to be replaced before the tests
3. Prepare filters (cut to size slightly larger than O-ring of filter holder, label, and store in clean Ziplock bag)
4. Fill the aerosolizer to indicated level (above nozzle) with appropriate aerosol solution (10g of salt with 200mL of deionized (DI) water, made in advance)
5. Plug in dilution, valve switcher, and OPC. Turn on OPC while line set to purge
6. Check filter holder is empty and sealed tightly
7. Start OPC and let run until upstream channel is reading <5000 particles in all channels, leave on purge after this threshold is reached
8. Set MFC controlling aerosol line to desired flow rate
9. Turn on airline and let system run for at least 3 minutes or until inlet concentration is consistent
10. Unplug both MFCs together, while unplugged place the filter into the filter holder and secure in place; turn on the manometer
11. Plug back in the MFCs together, after flow has settled to specified rate, take manometer reading of pressure drop
12. Plug in USB into the OPC and check USB has been recognized and is being used

13. Turn on OPC and perform experiment: change valve to upstream, let run for 3 minutes, purge for 2 measurement cycles (5 seconds each), change valve to downstream, let run for 3 minutes, purge for 2 cycles, this process is repeated 3 times
14. After the experiment is done, the USB is removed from the OPC and the data is stored on the computer and the test set up can be prepared for a new filter media
15. Once all experiments are done for the day, all MFCs, the OPC, the dilution machine and the valve switcher are all unplugged, and the vacuum and air lines are turned off

EBC Exposure Procedure

1. Dry mask to be tested in oven for 45 minutes at 50°C
2. Weigh dried mask and seal in Ziplock bag
3. Prepare EBC solution (29 mg of salt, 6 mg of albumin with 1 L DI water- albumin and extra solution kept in fridge)
4. Fill porous stone bubbler with EBC solution
5. Secure mask to funnel attached to outlet of bubbler with an elastic, mark the placement of the funnel on the mask
6. Plug in MFC attached to bubbler inlet, set bubbler flow to 15 lpm
7. Leave mask on exposure apparatus for desired exposure length
8. Prepare filtration efficiency and pressure drop set up for testing as per procedure in
9. Remove mask from funnel and weigh immediately
10. Place the mask into filter holder so that EBC exposed area is in line with filter holder opening and proceed with filtration efficiency and pressure drop testing procedure

# *Appendix B*

*Table A-1 Simulated EBC*

| | | |
|---|---|---|
| Ionic Concentration | 497 | µM |
| Protein concentration | 6 | µg/mL |
| Values from literature [38] [40] [41] | | |

$$C_{NaCl} = C_{Ionic} * MW$$

Molecular weight NaCl: 58.44 g/ mol

$$C_{NaCl} = 497\ \mu M * 10^{-6}\frac{M}{\mu M} * 58.44\ g/Mol =\ 0.029\ g/L\ =\ 29\ mg/L$$

$$C_{Protein} =\ 6\ \mu g/mL\ * Volume\ of\ EBC\ being\ prepared$$

Therefore, 1 L batch of simulated EBC contains 29 mg of NaCl and 6 mg of protein

*Table A-2 EBC testing raw weight data in order of completion*

| Mask Type | Exposure Time | Sample number | IW (Weight after drying) (g) | FW (Weight after EBC exposure) (g) | EBC Weight (g) |
|---|---|---|---|---|---|
| **Tilley** | 24 | 1 | 10.124 | 10.476 | 0.352 |
| **Tilley** | 24 | 2 | 10.453 | 10.843 | 0.390 |
| **Tilley** | 1 | 1 | 10.486 | 10.823 | 0.337 |
| **Tilley** | 1 | 2 | 9.935 | 10.259 | 0.324 |
| **Tilley** | 4 | 1 | 10.446 | 10.835 | 0.389 |
| **Disp (E)** | 1 | 1 | 3.008 | 3.009 | 0.001 |
| **Tilley** | 8 | 1 | 9.900 | 10.215 | 0.315 |
| **Tilley** | 4 | 2 | 10.322 | 10.702 | 0.380 |
| **Tilley** | 8 | 2 | 10.328 | 10.708 | 0.380 |
| **Disp (E)** | 1 | 2 | 3.025 | 3.025 | 0.000 |
| **Disp (E)** | 8 | 1 | 3.025 | 3.026 | 0.001 |
| **Disp (E)** | 4 | 1 | 3.076 | 3.076 | 0.000 |
| **Disp (E)** | 4 | 2 | 3.056 | 3.057 | 0.001 |
| **Disp (E)** | 8 | 2 | 3.033 | 3.035 | 0.002 |
| **Tilley** | 8 | 3 | 9.893 | 10.294 | 0.401 |
| **Disp (E)** | 24 | 1 | 3.066 | 3.069 | 0.003 |
| **Tilley** | 1 | 3 | 10.390 | 10.736 | 0.346 |

| | | | | | |
|---|---|---|---|---|---|
| **Disp (E)** | 24 | 2 | 3.073 | 3.077 | 0.004 |
| **Tilley** | 24 | 3 | 9.777 | 10.121 | 0.344 |
| **Tilley** | 8 | 4 | 10.526 | 10.926 | 0.400 |
| **Disp (E)** | 4 | 3 | 3.023 | 3.024 | 0.001 |
| **Tilley** | 4 | 3 | 10.393 | 10.796 | 0.403 |
| **L3** | 8 | 1 | 3.868 | 3.868 | 0.000 |
| **FG1** | 8 | 1 | 12.818 | 13.356 | 0.538 |
| **FG1** | 8 | 2 | 12.819 | 13.338 | 0.519 |
| **FG1** | 4 | 1 | 13.183 | 13.696 | 0.513 |
| **FG1** | 4 | 2 | 13.044 | 13.551 | 0.507 |
| **FG2** | 4 | 1 | 12.515 | 12.620 | 0.105 |
| **FG1** | 8 | 3 | 12.698 | 13.198 | 0.500 |
| **L3** | 8 | 2 | 3.865 | 3.865 | 0.000 |
| **L3** | 8 | 3 | 3.932 | 3.940 | 0.008 |
| **FG2** | 8 | 1 | 12.923 | 13.018 | 0.095 |
| **FG2** | 4 | 2 | 12.819 | 12.897 | 0.078 |
| **FG2** | 8 | 2 | 12.659 | 12.750 | 0.091 |
| **FG1** | 4 | 3 | 12.835 | 13.340 | 0.505 |
| **L3** | 4 | 1 | 3.930 | 3.932 | 0.002 |
| **L3** | 4 | 2 | 3.901 | 3.901 | 0.000 |
| **FG2** | 8 | 3 | 12.766 | 12.859 | 0.093 |
| **N95** | 4 | 1 | 6.412 | 6.413 | 0.001 |
| **FG2** | 4 | 3 | 12.587 | 12.677 | 0.090 |
| **Disp (E)** | 1 | 3 | 3.024 | 3.025 | 0.001 |
| **N95** | 4 | 2 | 6.224 | 6.231 | 0.007 |
| **Disp (E)** | 8 | 3 | 2.974 | 2.976 | 0.002 |
| **L3** | 4 | 3 | 3.895 | 3.897 | 0.002 |
| **N95** | 4 | 3 | 6.392 | 6.392 | 0.000 |
| **N95** | 8 | 1 | 6.353 | 6.358 | 0.005 |
| **Disp (E)** | 24 | 3 | 3.024 | 3.024 | 0.000 |
| **N95** | 8 | 2 | 6.429 | 6.432 | 0.003 |
| **Tilley+AF** | 4 | 1 | 10.665 | 10.974 | 0.309 |
| **N95** | 8 | 3 | 6.369 | 6.378 | 0.009 |
| **Tilley+AF** | 8 | 1 | 11.081 | 11.442 | 0.361 |
| **Tilley+AF** | 8 | 2 | 11.407 | 11.785 | 0.378 |
| **Tilley+AF** | 8 | 3 | 11.356 | 11.743 | 0.387 |
| **Tilley+AF** | 4 | 2 | 10.814 | 11.157 | 0.343 |
| **Tilley+AF** | 4 | 3 | 11.050 | 11.379 | 0.329 |

*Table A-3 24-hour EBC exposure data*

| | **Chanel size (µm)** | **0.1** | **0.15** | **0.2** | **0.25** | **0.3** | **0.5** | **1** |
|---|---|---|---|---|---|---|---|---|
| **Disposable (E)** | Average | 32.9 | 35.2 | 39.2 | 42.5 | 46.4 | 60.1 | 73.7 |
| | Standard deviation | 3.0 | 2.7 | 2.7 | 2.8 | 3.5 | 5.4 | 5.2 |
| **Tilley** | Average | 8.5 | 15.4 | 20.0 | 22.4 | 24.5 | 31.2 | 39.9 |
| | Standard deviation | 14.4 | 5.5 | 2.3 | 1.9 | 2.1 | 4.0 | 7.5 |

## *Appendix C*

*Table A-4 Summary of Results of Pressure Drop Data for Non-EBC Tests*

| **Fabric** | **Pressure drop @ 25cm/s ($mmH_2O/cm^2$)** | | | | | |
|---|---|---|---|---|---|---|
| | **Sample 1** | **Sample 2** | **Sample 3** | **Sample 4** | **Sample 5** | **avg** |
| **T-shirt** | 0.202 | 0.202 | 0.202 | 0.202 | 0.202 | 0.202 |
| **BSH180** | 0.404 | 0.202 | 0.202 | 0.202 | 0.202 | 0.243 |
| **BSH300** | 0.606 | 0.202 | 0.404 | 0.606 | 1.011 | 0.566 |
| **ACF** | 0.202 | 0.202 | 0.202 | 0.202 | 0.202 | 0.202 |
| **AF1500** | 0.101 | 0.000 | 0.202 | 0.000 | 0.202 | 0.101 |
| **AF2200** | 0.202 | 0.202 | 0.202 | 0.202 | 0.202 | 0.202 |
| **Filti** | 0.606 | 0.606 | 0.606 | 0.606 | 0.404 | 0.566 |
| **Combo 1** | 2.430 | 1.617 | 1.415 | 2.021 | 2.628 | 2.022 |
| **Combo 2** | 2.430 | 2.830 | 2.021 | 2.628 | 2.426 | 2.467 |
| **Combo 3** | 1.620 | 1.617 | 1.415 | 1.819 | 1.617 | 1.618 |
| **Combo 4** | 1.620 | 1.617 | 1.617 | 1.819 | 2.021 | 1.739 |
| **Combo 5** | 2.223 | 2.021 | 2.021 | 2.021 | 1.617 | 1.981 |
| **Combo 6** | 2.020 | 2.021 | 2.223 | 2.021 | 2.426 | 2.142 |
| **Combo 7** | 4.850 | 4.851 | 5.053 | 5.053 | 5.457 | 5.053 |
| **Firm Grip -D1** | 0.404 | 0.202 | 0.202 | 0.202 | 0.606 | 0.323 |
| **Old Navy** | 0.606 | 0.404 | 0.606 | 0.202 | 0.404 | 0.445 |
| **Tilley** | 0.404 | 0.202 | 0.404 | 0.404 | 0.202 | 0.323 |
| **Disposable (HL)** | 0.404 | 0.404 | 0.606 | 0.404 | 0.606 | 0.485 |
| **Level 2 SM** | 0.809 | 0.606 | 1.011 | 0.606 | 1.011 | 0.809 |
| **Level 3 SM** | 1.010 | 2.021 | 1.617 | 1.617 | 1.819 | 1.617 |
| **N95** | 1.620 | 1.620 | N/A | N/A | N/A | 1.620 |
| **Disposable (E)** | 0.404 | 0.606 | 0.404 | 0.404 | 0.404 | 0.445 |
| **Firm Grip - D 2** | 0.606 | 0.809 | 0.606 | 1.011 | 0.606 | 0.728 |
| **Tilley with AF2200** | 0.808 | 1.011 | 1.213 | 0.809 | 0.809 | 0.930 |
| **Tilley with Filti** | 1.213 | 0.606 | 0.809 | 0.606 | 1.011 | 0.849 |
| **Tilley with level 3** | 2.830 | 2.628 | 2.426 | 2.830 | 2.830 | 2.708 |
| **Tilley with Disp (HL)** | 1.617 | 1.213 | 1.213 | 1.011 | 1.617 | 1.334 |
| **FG with level 3** | 2.628 | 3.234 | 2.021 | 2.830 | 3.234 | 2.789 |

*Table A-5 Summary of Results of Pressure Drop Data Tests with EBC Exposure*

| Fabric | Pressure drop @ 25cm/s ($mmH_2O/cm^2$) | | | | | |
|---|---|---|---|---|---|---|
| | **Sample 1** | **Sample 2** | **Sample 3** | **Sample 4** | **Sample 5** | **avg** |
| **Tilley-24hour** | 0.404 | 0.606 | 0.404 | N/A | N/A | 0.472 |
| **Tilley-8hour** | 0.606 | 0.606 | 0.606 | N/A | N/A | 0.606 |
| **Tilley-4hour** | 0.606 | 0.404 | 0.809 | N/A | N/A | 0.606 |
| **Tilley-1hour** | 0.606 | 0.404 | 0.606 | N/A | N/A | 0.539 |
| **Disp(E)-24hour** | 0.202 | 0.202 | 0.404 | N/A | N/A | 0.270 |
| **Disp(E)-8hour** | 0.404 | 0.202 | 0.404 | N/A | N/A | 0.337 |
| **Disp(E)-4hour** | 0.202 | 0.404 | 0.404 | N/A | N/A | 0.337 |
| **Disp(E)-1hour** | 0.404 | 0.404 | 0.404 | N/A | N/A | 0.404 |
| **L3-8hour** | 1.213 | 1.011 | 0.809 | N/A | N/A | 1.011 |
| **L3-4hour** | 1.011 | 1.011 | 1.011 | N/A | N/A | 1.011 |
| **N95-8hour** | 1.415 | 1.617 | 1.617 | N/A | N/A | 1.550 |
| **N95-4hour** | 1.011 | 1.617 | 1.617 | N/A | N/A | 1.415 |
| **FG-D1-8hour** | 0.404 | 0.606 | 0.404 | N/A | N/A | 0.472 |
| **FG-D1-4hour** | 0.606 | 0.707 | 0.606 | N/A | N/A | 0.640 |
| **FG-D2-8hour** | 0.809 | 0.809 | 0.606 | N/A | N/A | 0.741 |
| **FG-D2-4hour** | 0.809 | 1.011 | 0.809 | N/A | N/A | 0.876 |
| **Tilley+AF-8hour** | 0.606 | 1.213 | 0.809 | N/A | N/A | 0.876 |
| **Tilley+AF-4hour** | 1.011 | 0.606 | 0.606 | N/A | N/A | 0.741 |

Pressure drop conversion calculations:

Radius of filter holder opening is 2 cm.

$$\mathrm{P(mmH_2O/cm^2)} = \frac{\mathrm{P(inH_20)}}{\pi(2cm^2)} * \frac{25.4\ mmH_2 0}{1\ inH_2 0}$$

## *Appendix D*

*Table A-6 Summary of Tests Completed and Conditions*

| Objective | Test | Sample 1 | | Sample 2 | | Sample 3 | |
|---|---|---|---|---|---|---|---|
| | | Date | RH in lab | Date | RH in lab | Date | RH in lab |
| 1 | T-shirt @ 10 cm/s | Sept. 2 | 45% | N/A | | N/A | |
| | T-shirt @ 25 cm/s | Mar. 30 | ~30% | | | | |
| | BSH 180 @ 10 cm/s | Sept. 3 | 45.4% | | | | |
| | BSH 180 @ 25 cm/s | Mar. 30 | ~30% | | | | |
| | BSH 300 @ 10 cm/s | Sept. 2 | 46.5% | | | | |
| | BSH 300 @ 25 cm/s | Mar. 30 | ~30% | | | | |
| | Filti @ 10 cm/s | Sept. 3 | 43.6% | | | | |
| | Filti @ 25 cm/s | Mar. 30 | ~30% | | | | |
| | AF1500 @ 10cm/s | Sept. 2 | 45% | | | | |
| | AF1500 @ 25 cm/s | Mar. 30 | ~30% | | | | |
| | AF2200 @ 10cm/s | Sept. 3 | 45% | | | | |
| | AF2200 @ 25 cm/s | Mar. 30 | ~30% | | | | |
| | ACF @ 10 cm/s | Sept. 3 | 45% | | | | |
| | ACF @ 25 cm/s | Mar. 30 | ~30% | | | | |
| | N95 @ 10 cm/s | Apr. 29 | ~30% | N/A | | N/A | |
| | N95 @ 25 cm/s | Apr. 29 | ~30% | Oct. 13 | 25% | | |
| | Level 3 @ 10 cm/s | Apr. 29 | ~30% | Aug. 10 | 37.1% | | |
| | Level 3 @ 25 cm/s | Apr. 29 | ~30% | Aug. 10 | 35% | | |
| | Level 2 @ 10 cm/s | Sept. 16 | 31.7% | Sept. 16 | 31.4% | | |
| | Level 2 @ 25 cm/s | Sept. 17 | 30% | Sept. 17 | 30% | | |
| | Disp (HL) @ 10 cm/s | Apr. 29 | ~30% | Aug. 10 | 34.8% | | |
| | Disp (HL) @ 25 cm/s | Apr. 29 | ~30% | Aug. 10 | 35.6% | | |
| | Disp (E) @ 10 cm/s | Jul. 23 | 34.3% | Jul. 8 | 60% | | |
| | Disp (E) @ 25 cm/s | Jul. 23 | 37.5% | Jul. 8 | 62.2% | | |
| | ON @ 10 cm/s | May 25 | ~30% | Aug. 10 | 35.2% | N/A | |
| | ON @ 25 cm/s | May 25 | ~30% | Aug. 10 | 35.8% | | |
| | FG-D1 @ 10 cm/s | Jun. 8 | 43% | Aug. 10 | 36.9% | | |
| | FG-D1 @ 25 cm/s | May 31 | 38.3% | Aug. 11 | 41.1% | | |
| | FG-D2 @ 10 cm/s | Aug. 12 | 41% | Aug. 10 | 34.5% | | |
| | FG-D2 @ 25 cm/s | Aug. 12 | 34.5% | Aug. 12 | 42% | | |
| | Tilley @ 10 cm/s | Jun. 8 | 43% | Jul. 23 | 34.3% | | |
| | Tilley @ 25 cm/s | May 31 | 39.6% | Jul. 23 | 36 | | |
| | Tilley w AF2200 @ 25 cm/s | May 31 | 38.2% | Aug. 10 | 34.8% | N/A | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Tilley w Filti @ 25 cm/s | Jul. 27 | 35.2% | Aug. 10 | 45.4% | | |
| | FG w L3 @ 25 cm/s | June 22 | 46.9% | Aug. 11 | 38.6% | | |
| | Tilley w L3 @ 25 cm/s | June 22 | 45.5% | Aug. 10 | 35.8% | | |
| | Tilley w Disp (E) @ 25 cm/s | Sept. 2 | 45% | Sept. 2 | 43.5% | | |
| | Combo 1 @ 25cm/s | May 19 | ~30% | Aug. 10 | 35.2% | Aug. 10 | 35% |
| | Combo 2 @ 25cm/s | May 19 | ~30% | May 19 | ~30% | May 19 | ~30% |
| | Combo 3 @ 25cm/s | May 19 | ~30% | May 19 | ~30% | May 19 | ~30% |
| | Combo 4 @ 25cm/s | May 19 | ~30% | May 19 | ~30% | May 19 | ~30% |
| | Combo 5 @ 25cm/s | May 19 | ~30% | May 19 | ~30% | May 19 | ~30% |
| | Combo 6 @ 25cm/s | May 19 | ~30% | May 19 | ~30% | May 19 | ~30% |
| | Combo 7 @ 25cm/s | May 25 | ~30% | Aug. 16 | 32% | Aug. 16 | 32% |
| 2 | Tilley @ 17.5 cm/s | Aug. 10 | 33.2% | Jul. 23 | 33.8% | N/A | |
| | Tilley @ 32.5 cm/s | Jul. 23 | 36% | Aug. 12 | 43% | | |
| | Disp (E) @ 17.5 cm/s | Jul. 23 | 35.5% | Aug. 12 | 44.3% | | |
| | Disp (E) @ 32.5 cm/s | Jul. 23 | 37% | Aug. 12 | 37% | | |
| | L3 @ 17.5 cm/s | Aug. 10 | 34.5% | Aug. 10 | 34.2% | | |
| | L3 @ 32.5 cm/s | July 23 | 37% | Aug. 12 | 44.6% | | |
| | FG-D1 @ 17.5 cm/s | July 23 | 37% | Aug. 11 | 33.8% | | |
| | FG-D1 @ 32.5 cm/s | July 23 | 37% | Aug. 12 | 43% | | |
| 3 (all @ 25 cm/s) | Tilley-24hour | Sept. 19 | 36% | Sept. 20 | 33.6% | Sept. 26 | 37.7% |
| | Tilley-8hour | Sept. 21 | 30% | Sept. 22 | 37.6% | Sept. 28 | 31.2% |
| | Tilley-4hour | Sept. 20 | 33% | Sept. 21 | 36.4% | Sept. 27 | 42.2% |
| | Tilley-1hour | Sept. 20 | 32% | Sept. 20 | 32% | Sept. 24 | 31.7% |
| | Disp(E)-24hour | Sept. 24 | 30% | Sept. 25 | 38% | Oct. 7 | 27% |
| | Disp(E)-8hour | Sept. 22 | 37.6% | Sept. 24 | 38% | Oct. 6 | 30% |
| | Disp(E)-4hour | Sept. 29 | 41.1% | Sept. 22 | 40.6% | Sept. 22 | 32% |
| | Disp(E)-1hour | Sept. 20 | 31% | Sept. 21 | 36% | Oct. 5 | 30% |
| | L3-8hour | Sept. 29 | 30% | Oct. 1 | 30% | Oct. 2 | 30% |
| | L3-4hour | Oct. 4 | 28% | Oct. 4 | 28% | Oct. 6 | 28% |
| | N95-8hour | Oct. 6 | 35.6% | Oct. 8 | 27% | Oct. 8 | 25% |
| | N95-4hour | Oct. 5 | 27% | Oct. 5 | 30% | Oct. 6 | 30% |
| | FG-D1-8hour | Sept. 29 | 30% | Sept. 30 | 30% | Oct. 1 | 31% |
| | FG-D1-4hour | Sept. 30 | 31.6% | Sept. 30 | 35.7% | Oct. 4 | 30% |
| | FG-D2-8hour | Oct. 3 | 30% | Oct. 4 | 28% | Oct. 5 | 27% |
| | FG-D2-4hour | Sept. 30 | 39% | Oct. 3 | 30% | Oct. 5 | 30% |
| | Tilley+AF-8hour | Oct. 8 | 25% | Oct. 13 | 30% | Oct. 14 | 28% |
| | Tilley+AF-4hour | Oct. 8 | 25% | Oct. 14 | 25.2% | Oct. 14 | 24.5% |
| All tests done in 2021 | | | | | | | |

Sample of calculations from raw data:

Data from Level 3 August 10th, 10 cm/s test

Three-minute intervals of data for each size bin are averaged into raw inlet and outlet data.

$$Average\ Inlet\ Conc.\,(\mathrm{p/m3}) = \frac{(\ \mathrm{Inlet\ 1 + Inlet\ 2 + Inlet\ 3}) * 10}{3 * 0.002}$$

$$Average\ Outlet\ Conc.\,(\mathrm{p/m3}) = \frac{(\ \mathrm{Outlet\ 1 + Outlet\ 2 + Outlet\ 3}) * 10}{3 * 0.002}$$

$$Efficiency\ 1 = \frac{Inlet\ 1 - Outlet\ 1}{Inlet\ 1} * 100$$

$$Average\ Efficiency = \frac{Eff\ 1 +\ Eff2 + Eff3}{3}$$

Standard deviations found using standard deviation function in excel.

*Table A-7 Sample data from Level 3 August 10th, 10 cm/s test*

| **Chanel size (µm)** | **0.1** | **0.15** | **0.2** | **0.25** | **0.3** | **0.5** | **1** |
|---|---|---|---|---|---|---|---|
| **Raw Inlet data 1** | 1,390 | 988 | 799 | 695 | 593 | 305 | 65 |
| **Raw Inlet data 2** | 1,287 | 923 | 752 | 653 | 557 | 295 | 66 |
| **Raw Inlet data 3** | 1,375 | 983 | 797 | 686 | 582 | 307 | 71 |
| **Average Inlet Conc. (p/m$^3$)** | 6,752,843 | 4,824,172 | 3,913,765 | 3,390,294 | 2,886,556 | 1,511,303 | 337,126 |
| **Inlet StD** | 55.323 | 36.235 | 26.884 | 22.217 | 18.601 | 6.701 | 2.972 |
| **Raw outlet data 1** | 15.543 | 6.200 | 3.086 | 1.743 | 0.771 | 0.057 | 0.000 |
| **Raw outlet data 2** | 15.135 | 7.811 | 3.946 | 1.973 | 0.892 | 0.135 | 0.027 |
| **Raw outlet data 3** | 12.800 | 7.400 | 3.800 | 2.086 | 1.229 | 0.143 | 0.029 |
| **Average Outlet Conc. (p/m$^3$)** | 72,463 | 35,685 | 18,053 | 9,669 | 4,820 | 559 | 93 |
| **Inlet StD** | 1.480 | 0.837 | 0.460 | 0.175 | 0.237 | 0.047 | 0.016 |
| **EFF1** | 98.88 | 99.37 | 99.61 | 99.75 | 99.87 | 99.98 | 100.00 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **EFF2** | 98.82 | 99.15 | 99.48 | 99.70 | 99.84 | 99.95 | 99.96 |
| **EFF3** | 99.07 | 99.25 | 99.52 | 99.70 | 99.79 | 99.95 | 99.96 |
| **Eff STDV** | 0.13 | 0.11 | 0.07 | 0.03 | 0.04 | 0.02 | 0.02 |
| **Efficiency (%)** | 98.92 | 99.26 | 99.54 | 99.71 | 99.83 | 99.96 | 99.97 |

## *Appendix E*

*Table A-8 Summary of results from all quality factor data*

| Fabric | Eff (0.3µm) | ΔP (inh20) | ΔP (Kpa) | Q (0.3µm) | Eff (0.15µm) | Q (0.15µm) |
|---|---|---|---|---|---|---|
| **Combo 1** | 62.740 | 1.000 | 0.250 | 3.966 | 44.824 | 2.389 |
| **Combo 6** | 97.802 | 1.060 | 0.260 | 14.474 | 93.933 | 10.625 |
| **Combo 5** | 80.295 | 0.980 | 0.240 | 6.661 | 66.913 | 4.535 |
| **Combo 3** | 87.602 | 0.800 | 0.200 | 10.483 | 78.669 | 7.758 |
| **Combo 4** | 92.806 | 0.860 | 0.210 | 12.294 | 85.248 | 8.940 |
| **Combo 2** | 87.430 | 1.220 | 0.300 | 6.829 | 80.224 | 5.337 |
| **Combo 7** | 97.309 | 2.500 | 0.620 | 5.812 | 92.032 | 4.067 |
| **Disp (HL)** | 88.500 | 0.240 | 0.060 | 36.219 | 76.355 | 24.148 |
| **Level 2** | 96.015 | 0.40 | 0.100 | 32.377 | 91.325 | 24.561 |
| **Level 3** | 99.429 | 0.800 | 0.200 | 25.950 | 95.354 | 15.419 |
| **N95 mask** | 99.198 | 0.801 | 0.200 | 24.194 | 96.776 | 17.222 |
| **Tilley** | 26.628 | 0.160 | 0.040 | 7.778 | 16.707 | 4.592 |
| **Firm Grip** | 40.739 | 0.160 | 0.040 | 13.144 | 28.869 | 8.557 |
| **Old Navy** | 35.090 | 0.220 | 0.050 | 7.896 | 17.743 | 3.568 |
| **Tilley w AF2200** | 88.525 | 0.460 | 0.110 | 18.916 | 78.445 | 13.408 |
| **Tilley w Filti** | 72.255 | 0.420 | 0.100 | 12.267 | 60.874 | 8.979 |
| **Tilley w L3** | 99.565 | 1.340 | 0.330 | 16.307 | 95.584 | 9.357 |
| **Tilley w Disp (HL)** | 91.799 | 0.660 | 0.160 | 15.228 | 82.623 | 10.656 |
| **FG w L3** | 99.586 | 1.380 | 0.340 | 15.979 | 95.822 | 9.247 |
| **Disposable (E)** | 52.130 | 0.220 | 0.050 | 13.458 | 39.117 | 9.065 |
| **Firm Grip-D2** | 36.726 | 0.360 | 0.090 | 5.109 | 26.391 | 3.420 |
| **L2 and L3 ASTM requirements** | 98.000 | | 0.294 | 13.297 | | |