Developing an Accessible, Low-Cost Air Cleaner for Safer Spaces During Wildfires

2021 REU Symposium

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Healthy Buildings Research Lab

Portland State UNIVERSITY

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Introduction

- Exposure to wildfire smoke can cause detrimental health effects and increase overall mortality in humans[1]
  - Fine particulate matter ($PM_{2.5}$) can penetrate lungs and cause respiratory issues
- Access to air cleaners may be limited during a wildfire event
  - DIY designs rely on high MERV-rated and HEPA filters, which will likely be in short supply
  - The Western U.S. wildfires of late Summer 2020 are an example of such a shortage
- We set out to develop a prototype air cleaner with such cost and resource restraints in mind
  - Box fans used to push large flowrates (>750 cfm) through filter
  - Common household fabrics deployed as particle filters, affixed to box fan—design is akin to a windsock

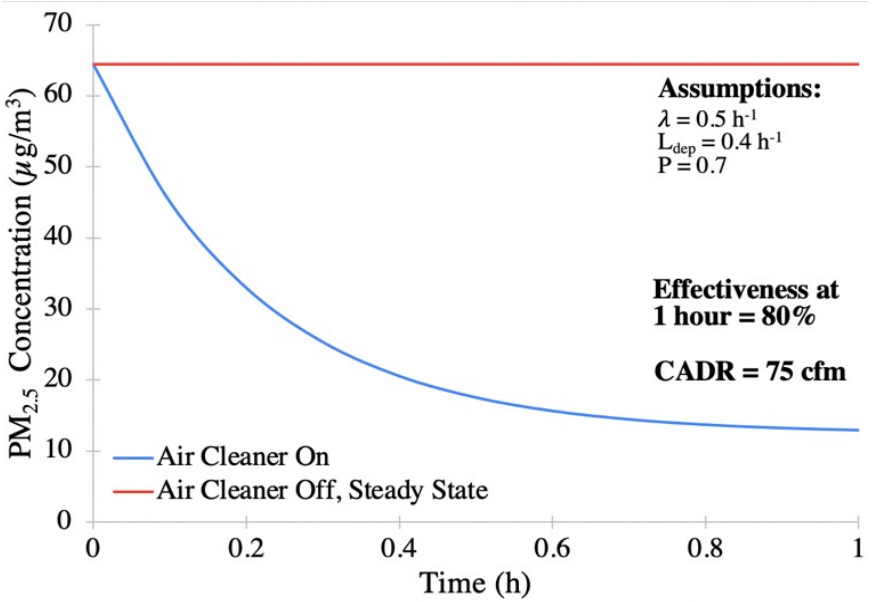
Images: Western U.S. wildfires; September 2020 (www.prevention.com, www.enr.com, www.crosscut.com)
References: [1]Residential air exchange rates in the United States: Empirical and estimated parametric distributions by season and climatic region: Murray D.M., Burmaster D.E., Risk Analysis, Vol. 15, Number. 4, 1995, pp. 459–465. *Insurance: Mathematics and Economics* **18**, 133 (1996).

Rationale

- U.S. Environmental Protection Agency's (EPA) *Cleaner Indoor Air During Wildfires Challenge* criteria used as a benchmark for adequate air cleaning

- Air cleaner needed to achieve an 80% reduction of $PM_{2.5}$ in 1 hour
  - 150 ft^2 room
  - 8 ft ceilings

- Assumptions:
  - Outdoor $PM_{2.5}$ concentration of 165 $\mu g/m^3$
  - Air exchange rate (λ) of 0.5 h^{-1}
  - Deposition loss rate (L_{dep}) of 0.4 h^{-1}
  - Penetration factor (P) of 0.7



$$C_{i,t} = \left(P\frac{\lambda}{\alpha}C_o + \frac{S}{\alpha V}\right)(1 - e^{-\alpha t}) + C_{i,t=0}e^{-\alpha t} \qquad \alpha = \lambda + \frac{CADR}{V} + L_{dep}$$

- In theoretical room, $PM_{2.5}$ concentration stabilizes around 64 $\mu g/m^3$

- With 64 $\mu g/m^3$ inputted as an initial condition, a dynamic mass balance shows that **a clean air delivery rate (CADR) of 75 cfm results in an 80% reduction of $PM_{2.5}$ in 1 hour**

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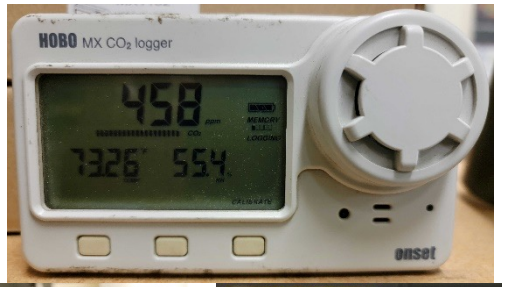
Materials: Field Study

Material	Cost
Box Fan	$17
Windsock Fabric	$18-$25
Ratchet Strap	$9
Total:	$44-$51



- Air cleaner constructed from:
  - Holmes 21” x 21.1” x 4.4”, three speed portable box fan
  - 52” long, 19” diameter cotton batting fabric
  - Ratchet strap

- CO_2 measured with Onset HOBO MX1102 battery-powered logger
- $PM_{2.5}$ levels measured with Dylos DC1700 laser particle counter
- Mainichi-Koh sandalwood incense used to simulate wildfire $PM_{2.5}$ concentrations

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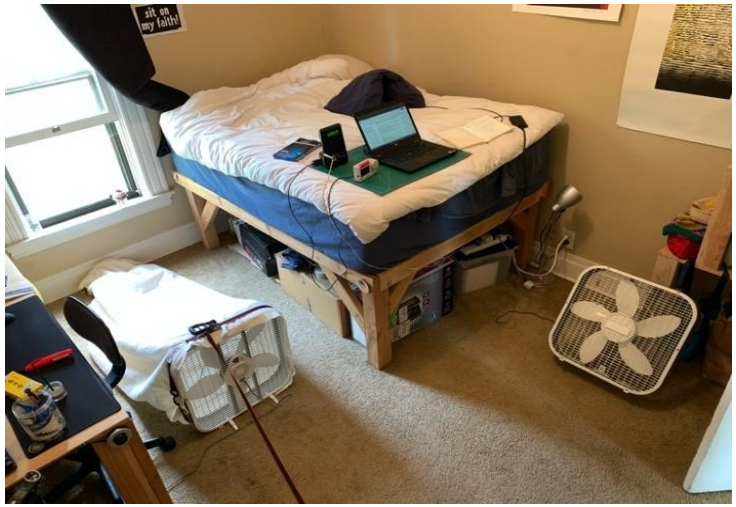
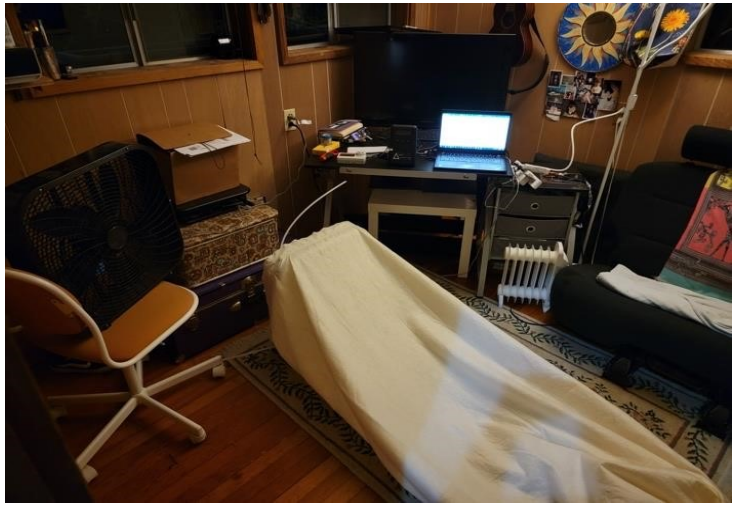
Experimental Design: Field Study





- Experiment carried out twice in two locations, both older homes in Oregon
- CO_2 elevated above 1000 ppm by excessively breathing and talking in the room.

Each trial consisted of 3 periods:

- Baseline measurements
  - Determined ambient $PM_{2.5}$ concentrations needed for mass balance
  - Room flushed out until $PM_{2.5}$ levels decreased substantially
  - Windows and doors were then closed, steady-state concentrations averaged over 15-30 minutes
- Background measurements
  - Mixing fan turned on, 3 sticks of incense lit simultaneously
  - Incense extinguished when particle count sufficiently high
  - Mixing fan turned off, researcher leaves room, concentrations allowed to decay for 45-60 minutes
- Air-cleaner test measurements
  - Same procedure as background measurements, except air cleaner was turned on before leaving room
  - Satisfactory decay period achieved in around 30 minutes

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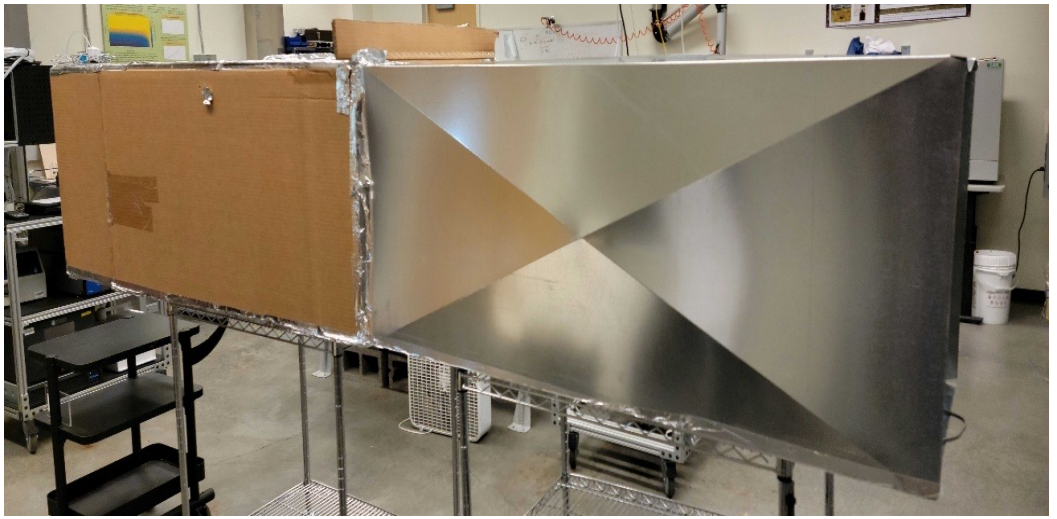
Materials: Laboratory Study

- Removal efficiency apparatus constructed from:
  - 12V pump
  - 47 mm diameter filter holder
  - Primary flow calibrator
  - Rotameter
  - TSI Optical Particle Sizer

- Flowrate measurement apparatus constructed from:
  - 24” x 24” x 10’ steel ducting
  - 24” x 24” x 10’ cardboard ducting
  - Ducting affixed with foil duct tape
  - Minneapolis Duct Blaster



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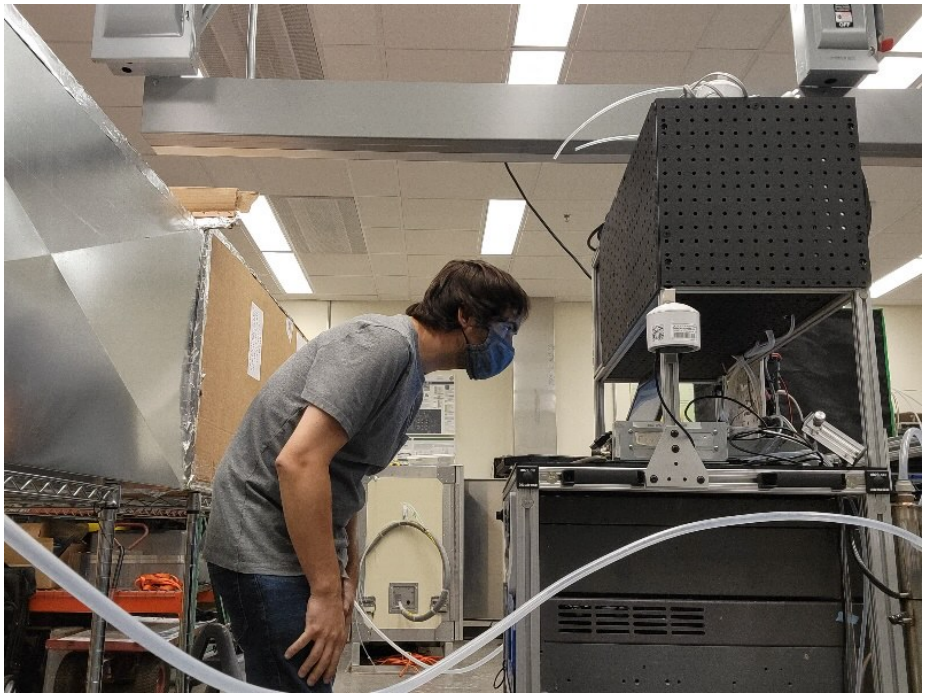
Experimental Design: Laboratory Study



- Five fabrics were tested:
  - Cotton batting
  - Polyester
  - Flannel
  - Felt
  - Chiffon

- Using the removal efficiency apparatus:
  - Five air flowrate readings were averaged
  - Particle counts measured upstream: through the filter and system
  - Particle counts measured downstream: ambient laboratory conditions

- Using the airflow measurement apparatus:
  - *Have not completed this research yet*
  - A pressure matching technique will be employed through the ducting, with a Minneapolis Duct Blaster
  - Airflows will be recorded for each fabric at each fan setting

- Fabric surface area and airflow through the removal efficiency apparatus will be iterated upon to match the face velocity of the ducting system

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Calculations

Field Study Equations

$$-\ln\frac{C_{CO_2,t}-C_{CO_2,bg}}{C_{CO_2,t=0}-C_{CO_2,bg}}=\lambda t \qquad \text{(Eq. 1)}$$

$C_{CO_2,t}$ = CO_2 concentration at time t (ppm)
$C_{CO_2,t=0}$ = CO_2 concentration at time t=0 (ppm)
$C_{CO_2,bg}$ = average background CO_2 concentration as measured during steady-state conditions (ppm)
λ = air exchange rate of the room (h^{-1}).

$$-\ln\frac{C_{i,t}-C_{bg}}{C_{i,t=0}-C_{bg}}=(\lambda+\beta)t \qquad \text{(Eq. 2)}$$

$C_{i,t}$ = $PM_{2.5}$ particle concentration at time t ($\mu g/m^3$)
$C_{i,t=0}$ = $PM_{2.5}$ particle concentration at time t=0 ($\mu g/m^3$)
C_{bg} = average background $PM_{2.5}$ particle concentration as measured during steady-state conditions ($\mu g/m^3$)
$(\lambda+\beta)$ = the total particle loss rate loss rate (h^{-1}).

Laboratory Study Equations

$$\eta=\frac{C_{upstream}-C_{downstream}}{C_{upstream}} \qquad \text{(Eq. 3)}$$

η = removal efficiency of the fabric
$C_{upstream}$ = ambient particle concentration present in the laboratory ($\#/cm^3$)
$C_{downstream}$ = particle concentration of air after having been pulled through the fabric and system ($\#/cm^3$).

$$V_{face}=\frac{Q}{A_{fab}} \qquad \text{(Eq. 4)}$$

V_{face} = face velocity of air moving across the filter (ft/min)
Q = air flowrate (ft^3/min)
A_{fab} = surface area of the fabric, approximated as a circle for the removal efficiency apparatus and a cone for the ducting apparatus.

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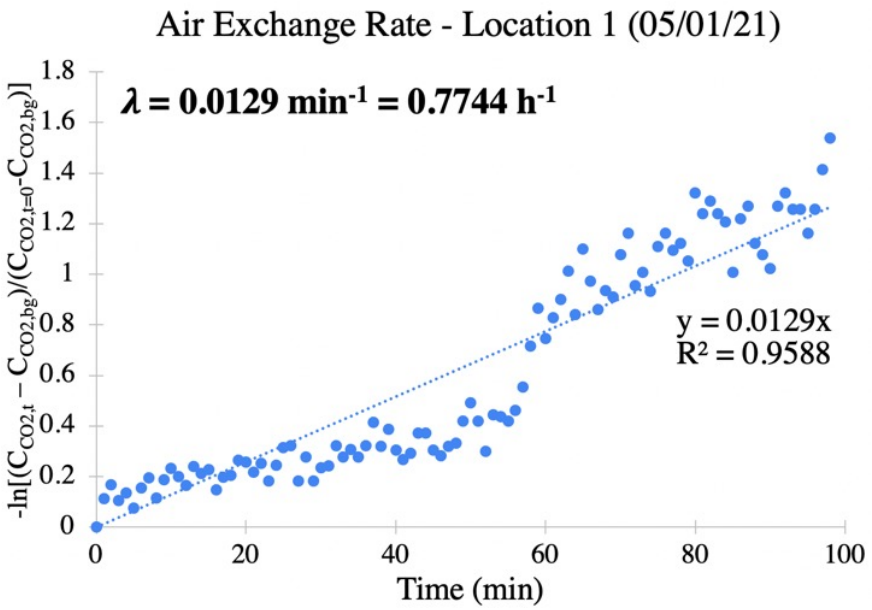
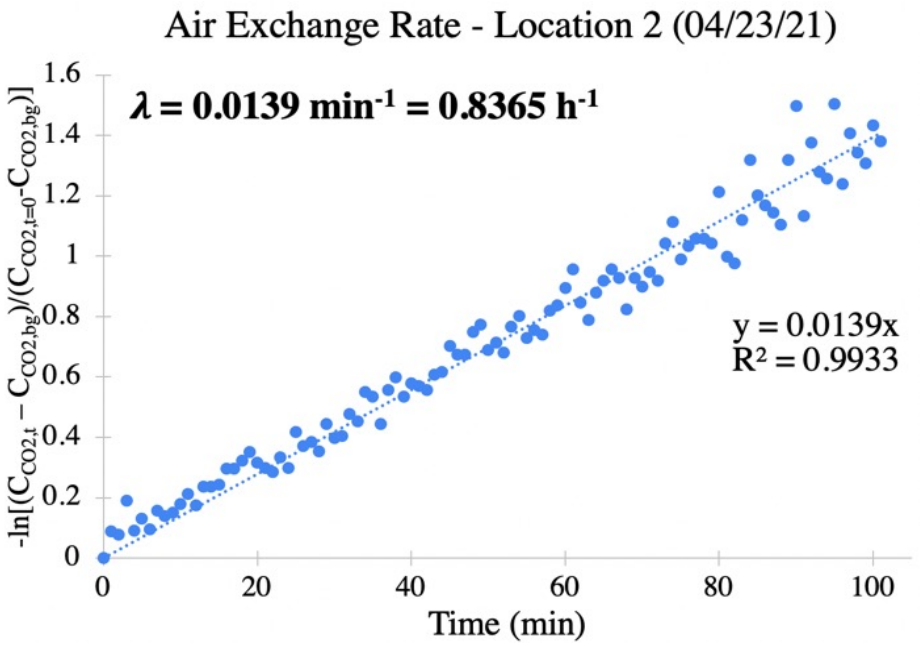
Results: Air Exchange Rates





- CO_2 concentrations deliberately elevated above 1000 ppm by way of human activity
- CO_2 allowed to decay over 100 minutes
- Linear regression performed to determine air exchange rates

Location 1: $\lambda = 0.77\ h^{-1}$
Location 2: $\lambda = 0.84\ h^{-1}$

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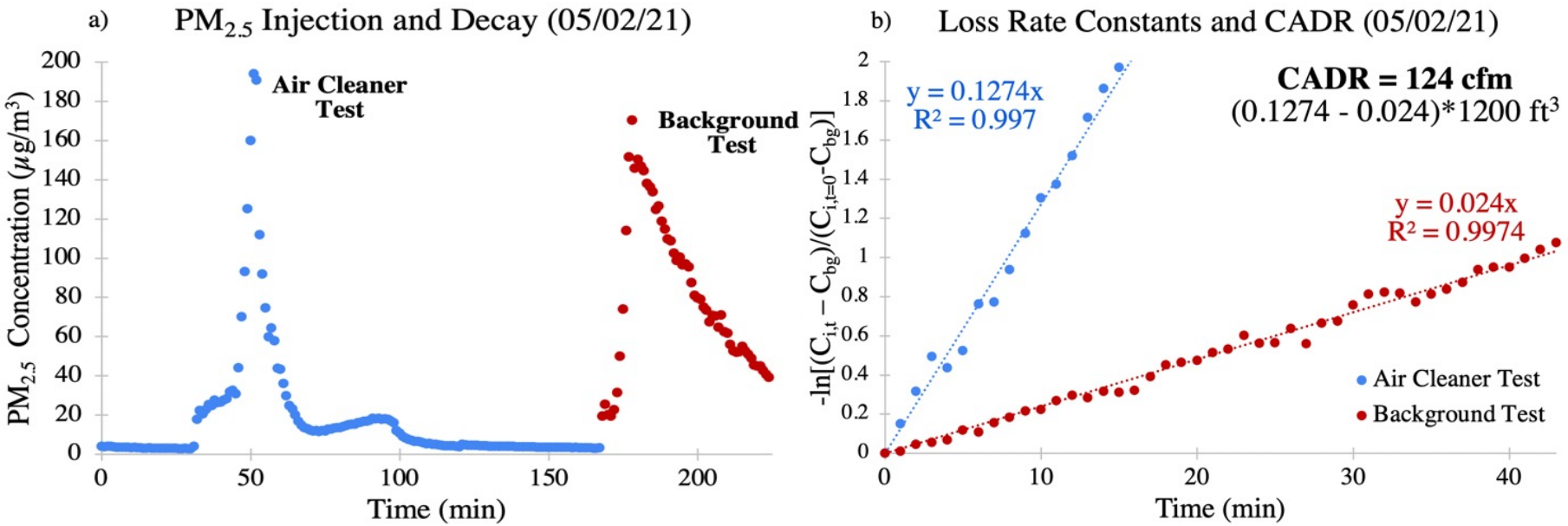
Results: Loss Rates and CADRs



- Figure a)
  - Sample plot of $PM_{2.5}$ concentration vs. time for the air cleaner and background tests at location 1
- Figure b)
  - Linear regression for both tests and corresponding slopes (particle loss rate constants)
  - Resulting CADR calculation during the same experiment
- Across four trials, air cleaner yielded average CADR of 103 cfm, well above EPA challenge requirement
- Air cleaner yielded an average net $PM_{2.5}$ reduction of 83% after just 30 minutes of operation following peak concentrations

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Results: Field Study Complete

	Location 1		Location 2	
	Trial 1	*Trial 2*	*Trial 1*	*Trial 2*
Date	05/01/21	05/02/21	04/22/21–04/23/21	04/23/21
Time	14:20–18:36	11:02–14:35	21:29–0:37	8:58–11:07
Room Volume (ft^3)	1200	1200	582.06	582.06
Sound Level (dB)	45	45	59	59
Temperature (°F)	67.04	68.38	64.87	56.25
Relative Humidity (%)	51.28	48.35	42.44	47.98
Air Exchange Rate (h^{-1})	0.77	0.77	0.84	0.84
PM2.5 Loss Rate (Background Test) (h^{-1})	0.51	1.44	2.30	2.63
PM2.5 Loss Rate (Air Cleaner Test) (h^{-1})	5.37	7.64	11.803	13.18
CADR (cfm)	97.04	123.98	92.15	102.37
Net $PM_{2.5}$ Reduction After 30 Min. (%)	84.67	77.14	84.48	87.53

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Results: Removal Efficiencies

Material	*Air Flowrate (L/min)*	*Average Concentration Upstream (#/cm³)*	*Average Concentration Downstream (#/cm³)*	*Average Removal Efficiency (%)*
Cotton	4.03	65.41	43.78	33.15
Polyester	4.14	93.73	65.82	29.68
Flannel	4.07	93.56	68.82	26.46
Felt	4.04	75.40	56.57	24.96
Chiffon	4.19	61.12	46.34	24.16

- Removal efficiencies relatively low in comparison to high-MERV rated and HEPA filters found in retail portable air cleaners
- Our prototype was designed to offset the low removal efficiency of the household fabric with large fabric surface areas and increased flowrates

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Results: Air Flowrates and CADRs

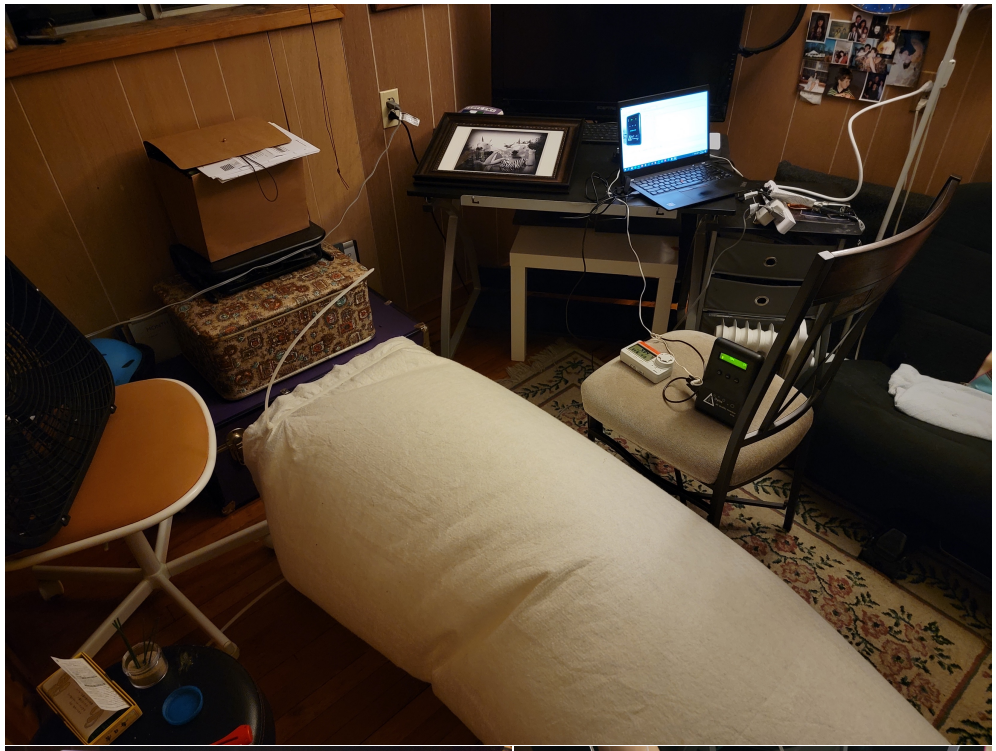
Air Flowrate (cfm)

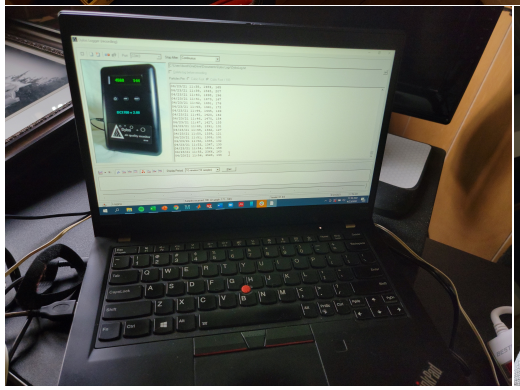
Material	*Low Speed*	*Medium Speed*	*High Speed*
Cotton			
Polyester			
Flannel			
Felt			
Chiffon			

CADR (cfm)

Material	*Low Speed*	*Medium Speed*	*High Speed*
Cotton			
Polyester			
Flannel			
Felt			
Chiffon			

Conclusion





- The air cleaner prototype is constructed from low-cost materials, accessible to most in the event of a wildfire
- Field study:
  - An average CADR of 103 cfm was realized, well above the 75 cfm target required to meet the EPA challenge criteria
  - A net reduction of $PM_{2.5}$ >80% in thirty minutes during injection and decay tests was realized
- Laboratory study:
  - Five fabrics were tested, yielding removal efficiencies between 25 and 35%
  - More work to be done, but large surface areas combined with high fan flowrates should offset low removal efficiencies

Acknowledgements

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Summer REU Symposium

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