MAPPING OUTDOOR PARTICLE SIZE DISTRIBUTIONS TO HVAC FILTRATION EFFICIENCY FOR PM2.5 AND ULTRAFINE PARTICLES

BERGs Summer Meeting Presentation

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PARTICULATE MATTER

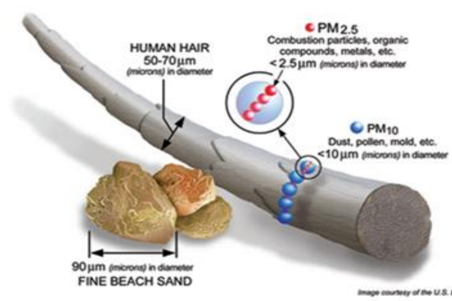
Tiny pieces of solid or liquid matter associated with the Earth's atmosphere.

Source: dust, motor vehicles, power plants

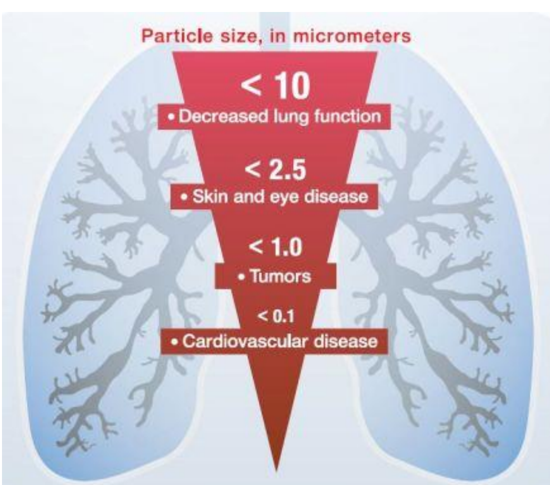
PM10: particles smaller than 10 µm

PM2.5: particles smaller than 2.5 µm

UFP: Ultrafine Particles, smaller than 100 nm



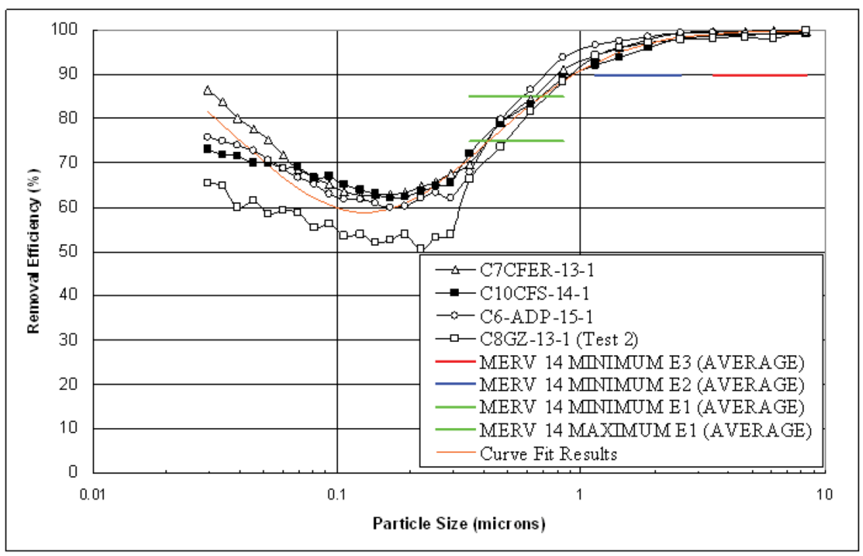
http://www.epa.gov/airquality/particulatematter/basic.html



http://www.tesa-clean-air.com/eng/fine_dust_particles

HVAC FILTERS

- ASHRAE classify the HVAC filters with standard 52.2 based on measured efficiency and pressure drop after subjecting filter to test aerosols. The results is MERV (Minimum efficiency reporting value)
- It is based on minimum values for three particle size ranges.
- E1: 0.3-1 μm
- E2: 1-3 μm
- E3: 3-10 μm



R. Hecker, K.C. Hofacre ; Development of Performance Data for Common Building Air Cleaning Devices, Final Report, U.S. EPA, Dec 2008.

TABLE 12-1 Minimum Efficiency Reporting Value (MERV) Parameters

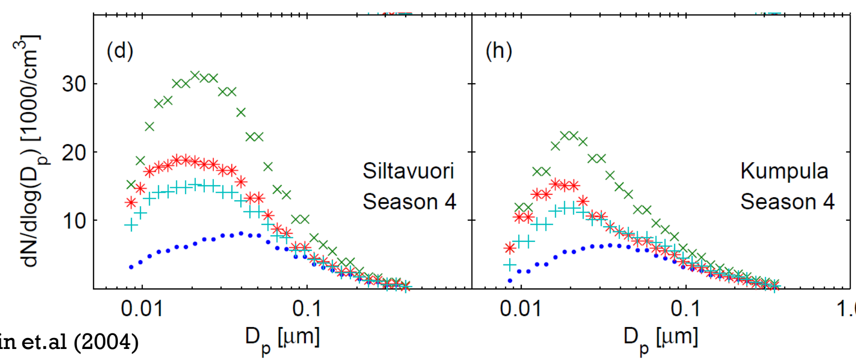
Standard 52.2 Minimum Efficiency Reporting Value (MERV)	Composite Average Particle Size Efficiency,% in Size Range, µm			Average Arrestance,%, by Standard 52.1 Method	Minimum Final Resistance	
	Range 1 0.30–1.0	Range 2 1.0–3.0	Range 3 3.0–10.0		Pa	in. of water
1	n/a	n/a	$E_3 < 20$	$A_{avg} < 65$	75	0.3
2	n/a	n/a	$E_3 < 20$	$65 \le A_{avg} < 70$	75	0.3
3	n/a	n/a	$E_3 < 20$	$70 \le A_{avg} < 75$	75	0.3
4	n/a	n/a	$E_3 < 20$	$75 \le A_{avg}$	75	0.3
5	n/a	n/a	$20 \le E_3 < 35$	n/a	150	0.6
6	n/a	n/a	$35 \le E_3 < 50$	n/a	150	0.6
7	n/a	n/a	$50 \le E_3 < 70$	n/a	150	0.6
8	n/a	n/a	$70 \le E_3$	n/a	150	0.6
9	n/a	$E_2 < 50$	$85 \le E_3$	n/a	250	1.0
10	n/a	$50 \le E_2 < 65$	$85 \le E_3$	n/a	250	1.0
11	n/a	$65 \le E_2 < 80$	$85 \le E_3$	n/a	250	1.0
12	n/a	$80 \le E_2$	$90 \le E_3$	n/a	250	1.0
13	$E_1 < 75$	$90 \le E_2$	$90 \le E_3$	n/a	350	1.4
14	$75 \le E_1 < 85$	$90 \le E_2$	$90 \le E_3$	n/a	350	1.4
15	$85 \le E_1 < 95$	$90 \le E_2$	$90 \le E_3$	n/a	350	1.4
16	$95 \le E_1$	$95 \le E_2$	$95 \le E_3$	n/a	350	1.4

HEPA → 99.9% or greater removal efficiency for most particle sizes

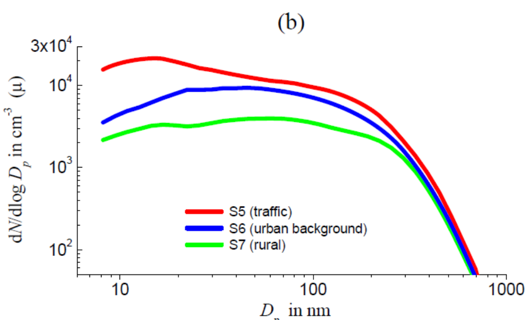
R. Hecker, K.C. Hofacre ; Development of Performance Data for Common Building Air Cleaning Devices, Final Report, U.S. EPA, Dec 2008.

PARTICLE-SIZE DISTRIBUTIONS

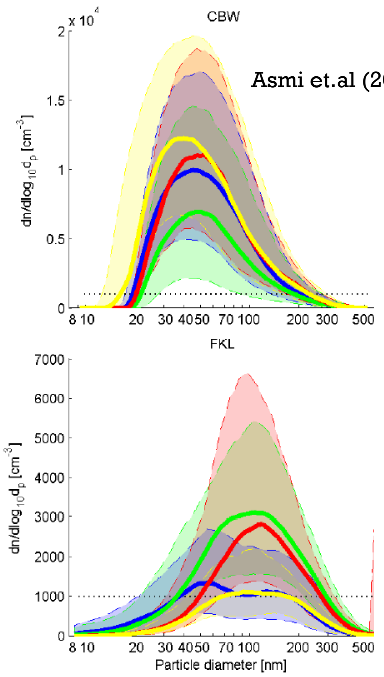
- Number and mass concentration of particles are varied for different particle sizes.
- Also it is changing during day or from one location to other one. Even the shape of distribution can be changed.



Hussein et.al (2004)



Costabile et.al (2009)



Asmi et.al (2011)

Costabile et.al Spatio-temporal variability and principal components of the particle number size distribution in an urban atmosphere, Atmos. Chem. Phys., 9, 3163–3195, 2009

T. Hussein et.al. Urban aerosol number size distributions Atmos. Chem. Phys., 4, 391–411, 2004.

A.Asmi et.al. Number size distributions and seasonality of submicron particles in Europe 2008–2009, Atmos. Chem. Phys., 11, 5505–5538, 2011

MAIN GOAL

- We want to find UFP and PM2.5 removal efficiency of different HVAC filters.
- It is a function of size-resolved removal efficiency of filters and size distribution of outdoor particles.

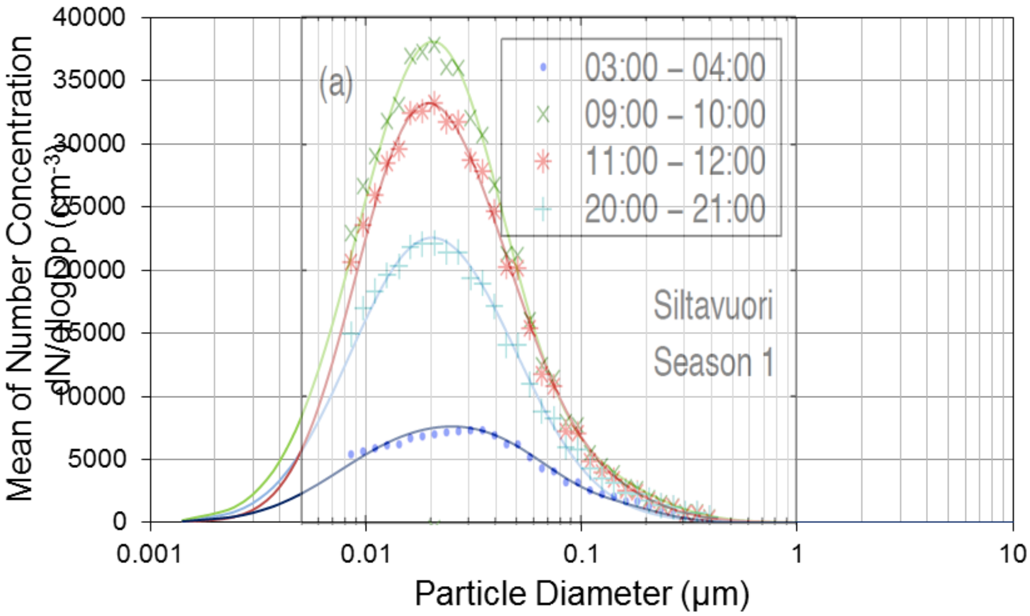
$$RE_{UFP} = 1 - \frac{\sum_{i=1}^{100} N_i \times (1 - R_i)}{\sum_{i=1}^{100} N_i}$$

$$RE_{PM2.5} = 1 - \frac{\sum_{i=1}^{2500} N_i \times \rho_i \times \frac{\pi d_i^3}{6} \times (1 - R_i)}{\sum_{i=1}^{2500} N_i \times \rho_i \times \frac{\pi d_i^3}{6}}$$

- RE_{UFP}: UFP Removal efficiency of a filter
- $RE_{PM2.5}$: UFP Removal efficiency of a filter
- d_i: diameter size of particles in size bin i (nm)
- N_i: Number of concentration of particles with diameter of d_i
- R_i: Removal efficiency of filter for particles with diameter of d_i
- ρ_i : Density of particles with diameter of d_i (gr/cm^3)

MODELING PARTICLE-SIZE DISTRIBUTION OF AEROSOLS

- The most common way to present particle size distribution data for aerosols is in term of three modes, the nuclei, accumulation, and coarse particle modes. Each mode is a log normal distribution which they are added together.

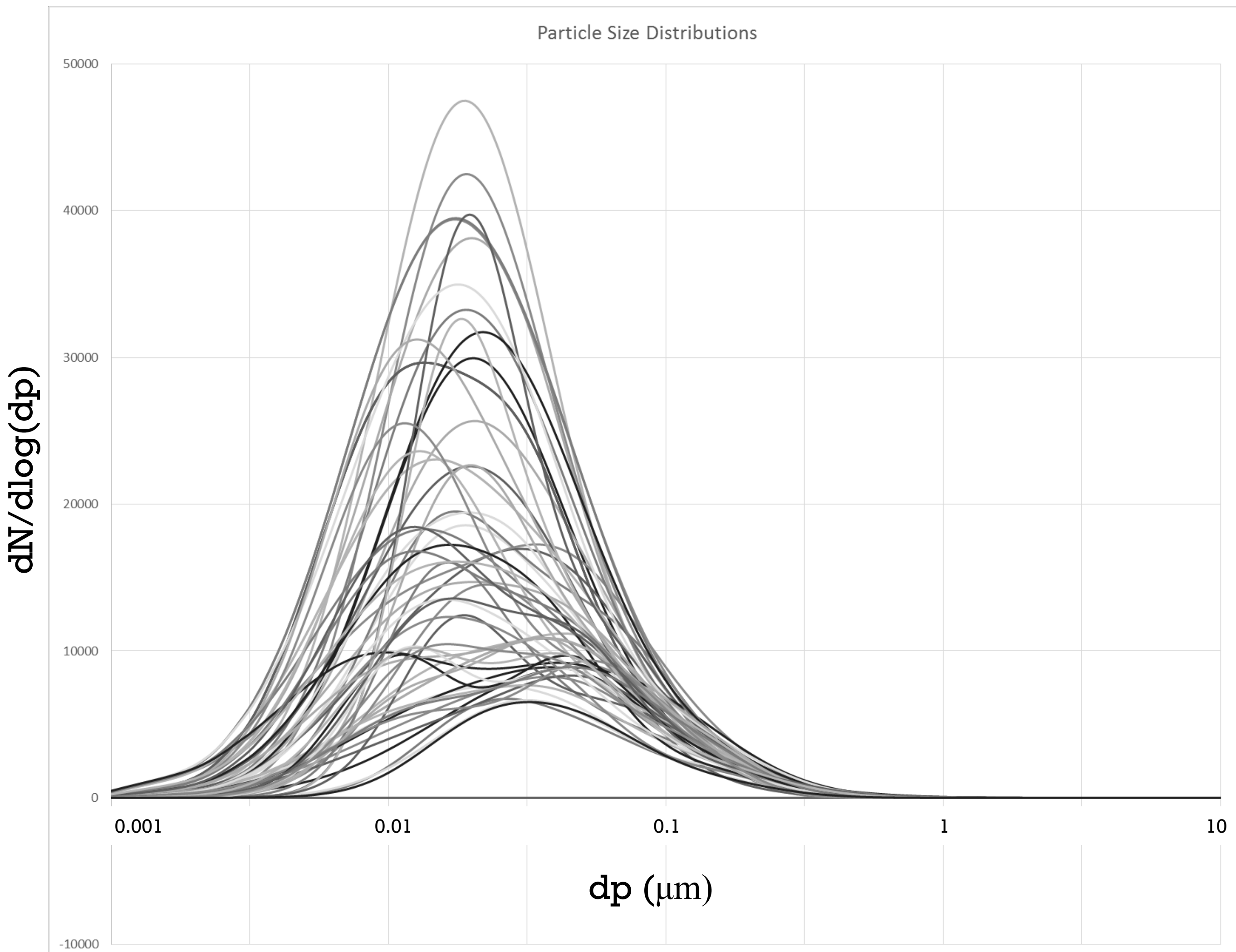


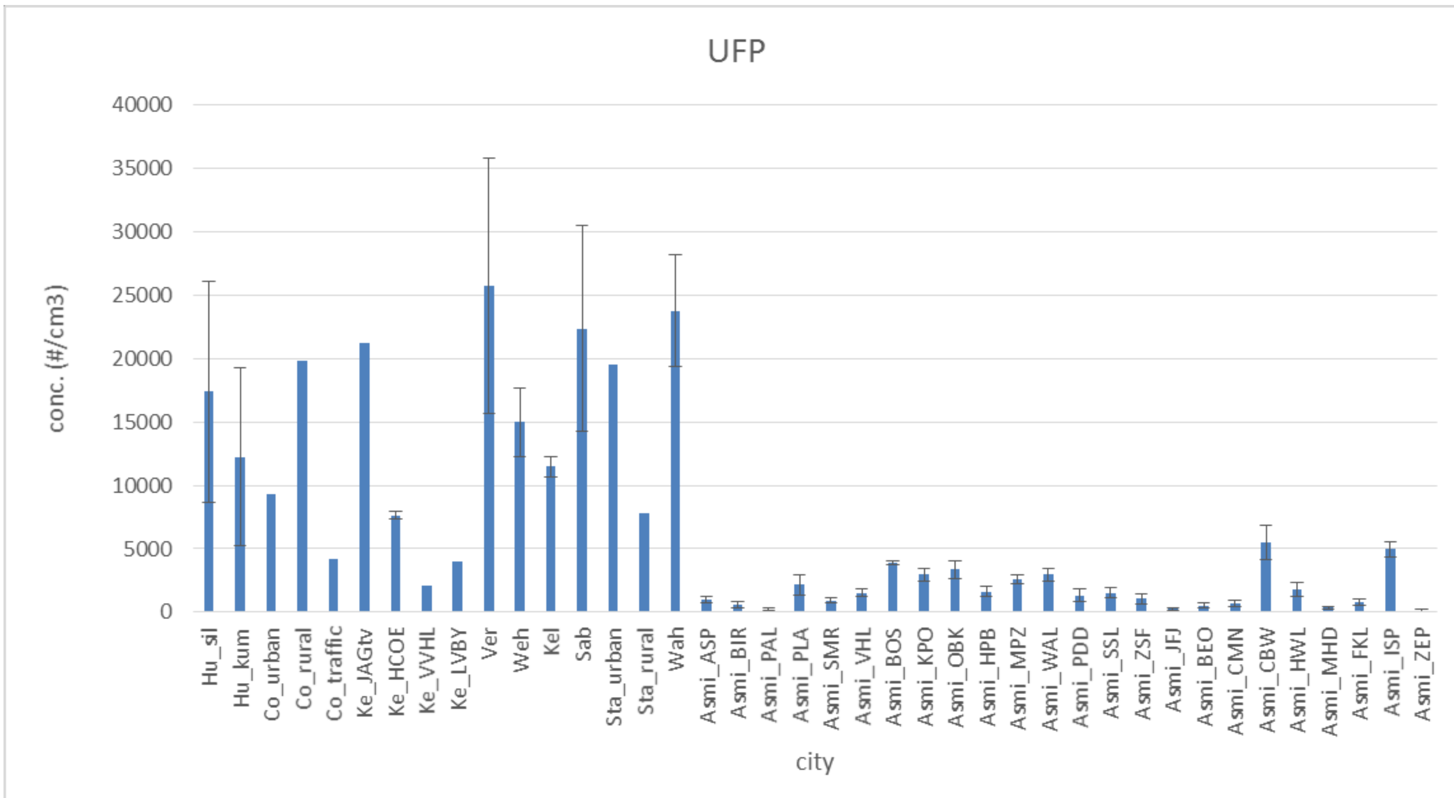
Mode 1	N, #/cm3	24300
	Dp, μm	0.017
	log SD	0.33
Mode 2	N, #/cm3	8000
	Dp, μm	0.03
	log SD	0.28
Mode 3	N, #/cm3	2000
	Dp, μm	0.12
	log SD	0.28
	N, #/cm3	15800
	Dp, μm	0.0145
Mode 1	log SD	0.27
	N, #/cm3	12000
	Dp, μm	0.033
Mode 2	log SD	0.28
	N, #/cm3	2000
	Dp, μm	0.1
Mode 3	log SD	0.3
	N, #/cm3	13000
	Dp, μm	0.015
Mode 1	log SD	0.32
	N, #/cm3	8000
	Dp, μm	0.035
Mode 2	log SD	0.31
	N, #/cm3	200
	Dp, μm	0.15
Mode 3	log SD	0.25
Mode 1	N, #/cm3	5000
	Dp, μm	0.015
	log SD	0.35
Mode 2	N, #/cm3	3200
	Dp, μm	0.045
	log SD	0.3
Mode 3	N, #/cm3	300
	Dp, μm	0.17
	log SD	0.18

SUMMARY OF PARTICLE SIZE DISTRIBUTIONS

- We have found the mass concentration of particles from number concentration assuming
  - The particles are spherical
  - Density of particles is constant and equal to 1 gr/cm3 or it is varied from 1.25 gr/cm3 to 1.75 gr/cm3 with average of 1.3 g/cm3 for dp < 140 nm; 1.4 g/cm3 for 140 nm ≤ dp < 420 nm; 1.5 g/cm3 for 420 nm ≤ dp < 1.2 μm; 1.6 g/cm3 for 1.2 μm ≤ dp < 3.5 μm; 1.7 g/cm3 for 3.5 μm ≤ dp < 10 μm.
- We totally found and modeled
  - 197 distribution
  - From 40 locations all over the world (urban, rural and close to traffic)
  - From 12 different references and studies
  - which measured the long term size-resolved concentration of particles (more than 1 year)

NO	Ref	Location Type	Location Name	Exp. duration	Season	UFP (#/cm3)	PM2.5 case 1 (μg/cm3)	PM2.5 case 2 (μg/cm3)	daytime	other charac.	MODE 1			MODE 2			MODE 3		
											N, #/cm3	Dp, μm	log SD	N, #/cm3	Dp, μm	log SD	N, #/cm3	Dp, μm	log SD
1	[1]	UR	Siltavori, EU	6 yr	WI	7785	3.1	4.4	3:00 - 4:00	Workday	16000	0.0189	0.19	8000	0.04	0.28	1800	0.11	0.25
65	[2]	UR	Schleussig, EU	2 yr	ALL	9340	15.1	21.6	N/A	Workday	800	0.06	0.28	550	0.075	0.15	400	0.18	0.2
66	[3]	RU	Melpitz, EU	2 yr	ALL	19780	17.5	24.9	N/A	Workday	3500	0.023	0.24	2000	0.06	0.24	500	0.17	0.18
180	[4]	TR	Pittsburg, US	1 yr	1	20416	3.6	5.1	morning	Workday	5100	0.022	0.27	3400	0.061	0.25	700	0.16	0.24


Particle Size Distributions
50000
40000
30000
20000
10000
0
-10000
0.001
0.01
0.1
1
10
dN/dlog(dp)
dp (μm)



UFP
conc. (#/cm3)
40000
35000
30000
25000
20000
15000
10000
5000
0
Hu_sil
Hu_kum
Co_urban
Co_rural
Co_traffic
Ke_JAGtv
Ke_HCOE
Ke_VVHL
Ke_LVBY
Ver
Weh
Kel
Sab
Sta_urban
Sta_rural
Wah
Asmi_ASP
Asmi_BIR
Asmi_PAL
Asmi_PLA
Asmi_SMR
Asmi_VHL
Asmi_BOS
Asmi_KPO
Asmi_OBK
Asmi_HPB
Asmi_MPZ
Asmi_WAL
Asmi_PDD
Asmi_SSL
Asmi_ZSF
Asmi_JFJ
Asmi_BEO
Asmi_CMN
Asmi_CBW
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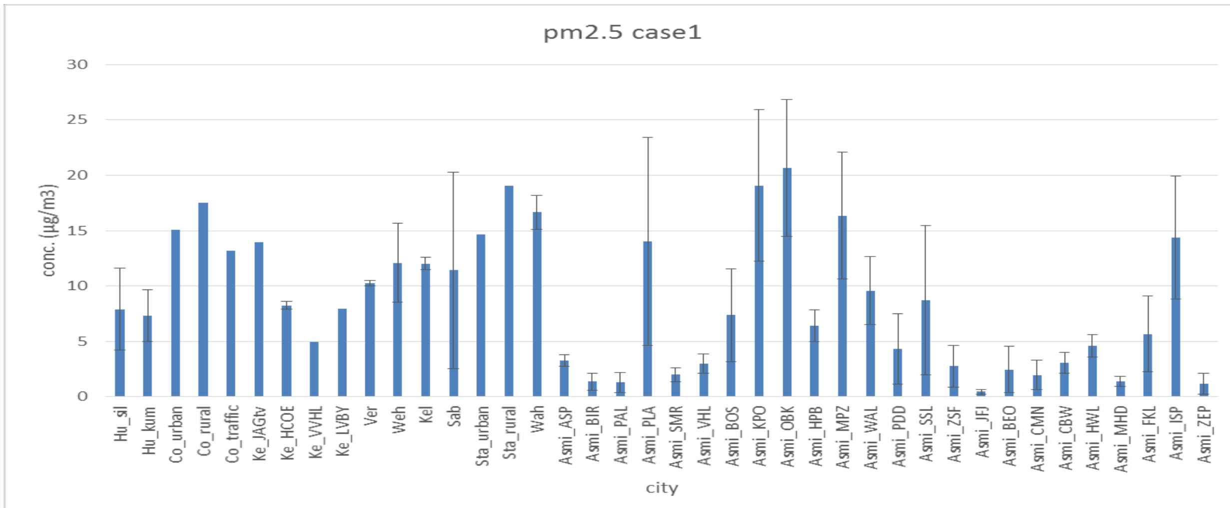
Asmi_FKL
Asmi_ISP
Asmi_ZEP
city


pm2.5 case1
conc. (µg/m3)
30
25
20
15
10
5
0
Hu_sil
Hu_kum
Co_urban
Co_rural
Co_traffic
Ke_JAGtv
Ke_HCOE
Ke_VVHL
Ke_LVBY
Ver
Weh
Kel
Sab
Sta_urban
Sta_rural
Wah
Asmi_ASP
Asmi_BIR
Asmi_PAL
Asmi_PLA
Asmi_SMR
Asmi_VHL
Asmi_BOS
Asmi_KPO
Asmi_OBK
Asmi_HPB
Asmi_MPZ
Asmi_WAL
Asmi_PDD
Asmi_SSL
Asmi_ZSF
Asmi_JFJ
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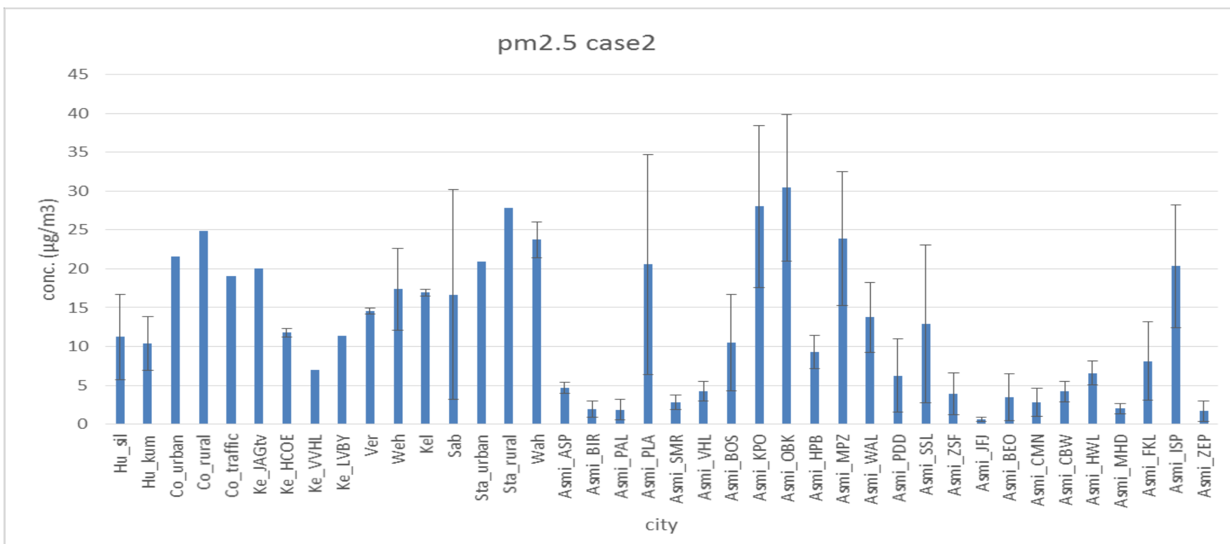
Asmi_CMN
Asmi_CBW
Asmi_HWL
Asmi_MHD
Asmi_FKL
Asmi_ISP
Asmi_ZEP
city


pm2.5 case2
conc. (µg/m3)
45
40
35
30
25
20
15
10
5
0
Hu_sil
Hu_kum
Co_urban
Co_rural
Co_traffic
Ke_JAGtv
Ke_HCOE
Ke_VVHL
Ke_LVBY
Ver
Weh
Kel
Sab
Sta_urban
Sta_rural
Wah
Asmi_ASP
Asmi_BIR
Asmi_PAL
Asmi_PLA
Asmi_SMR
Asmi_VHL
Asmi_BOS
Asmi_KPO
Asmi_OBK
Asmi_HPB
Asmi_MPZ
Asmi_WAL
Asmi_PDD
Asmi_SSL
Asmi_ZSF
Asmi_JFJ
Asmi_BEO
Asmi_CMN
Asmi_CBW
Asmi_HWL
Asmi_MHD
Asmi_FKL
Asmi_ISP
Asmi_ZEP
city

SIZE-RESOLVE REMOVAL EFFICIENCY OF HVAC FILTERS

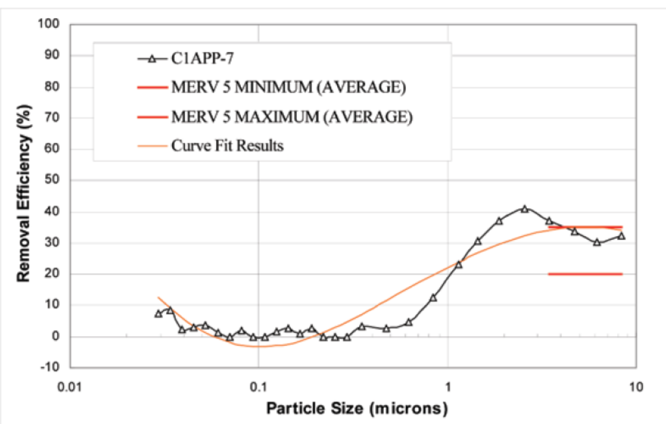
- We mostly used a report from EPA to find out the removal efficiency of the filters.

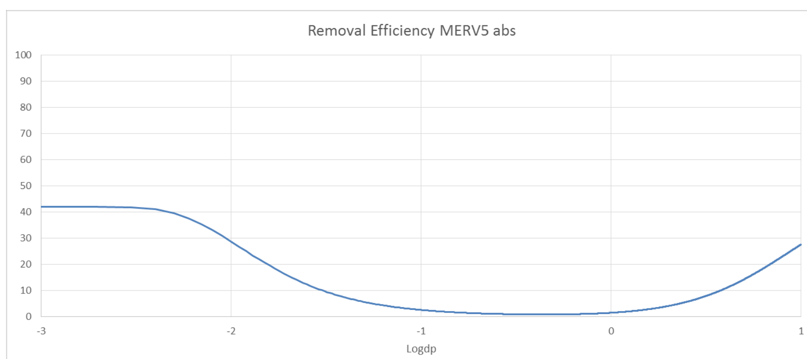
- They measured removal efficiency filters with 9 MERV ratings for particle sizes from 0.03 μm to 10 μm.

MERV Rating	Equation	Parameters	Correlation Coefficient (r^2)
5	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 1.8906 b = -0.1722 c = 0.0307 d = 0.0793	0.8935
6	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 1.9311 b = -0.1441 c = -0.1243 d = -0.0234	0.8332
7	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 1.7467 b = -0.3314 c = -0.0036 d = 0.1381	0.9064
8	$(1/Y) = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 0.5839 b = 0.1675 c = 0.1289 d = 0.0188	0.9658
10	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 1.7083 b = -0.5759 c = -0.6721 d = -0.1775	0.9852
12	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 1.3943 b = -0.9080 c = -0.6240 d = -0.0404	0.9902
14	$Y = a + bx + cx^2 + dx^3$ where Y = log of percent penetration x = log of particle diameter	a = 0.9531 b = -1.4941 c = -0.8443 d = -0.0013	0.9668
16	$\ln Y = a + bx + cx^2 + dx^3$ where Y = percent penetration x = log of particle diameter	a = 0.3855 b = -2.0698 c = 0.5326 d = 1.3895	0.9728
16+ (HEPA)	$Y = a + bx + cx^2 + dx^3 + ex^4$ where Y = percent penetration x = log of particle diameter	a = 0.0361 b = -0.3506 c = 0.5119 d = 0.0481 e = -0.1816	0.8917

R. Hecker, K.C. Hofacre ; Development of Performance Data for Common Building Air Cleaning Devices, Final Report, U.S. EPA, Dec 2008.

SIZE-RESOLVE REMOVAL EFFICIENCY OF HVAC FILTERS





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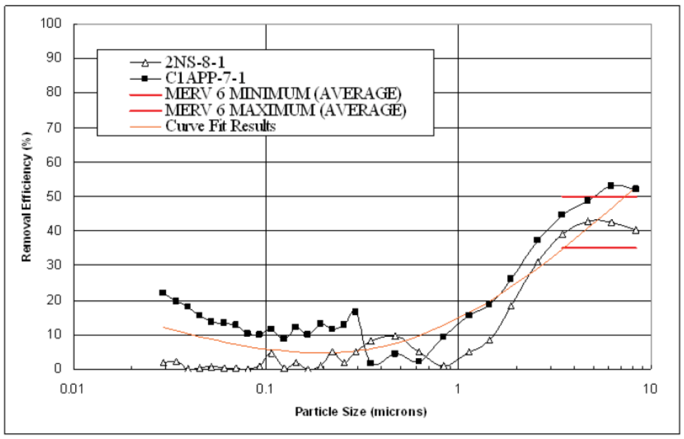

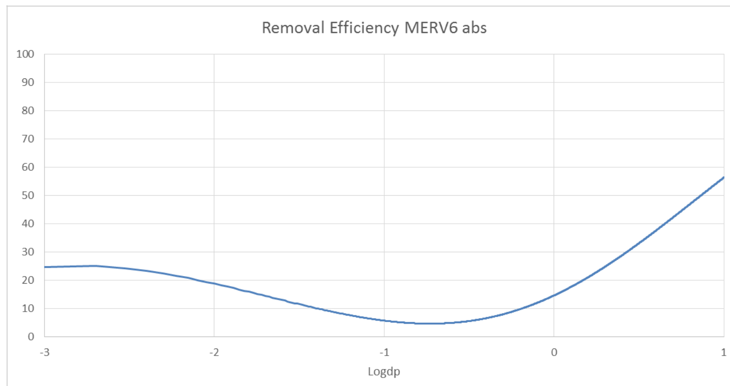

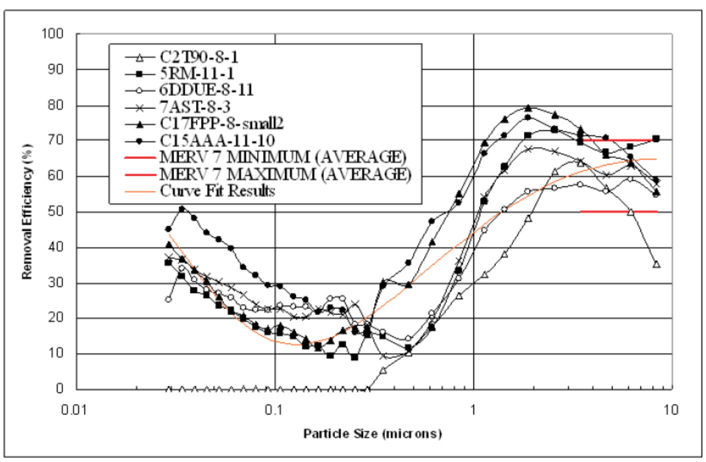

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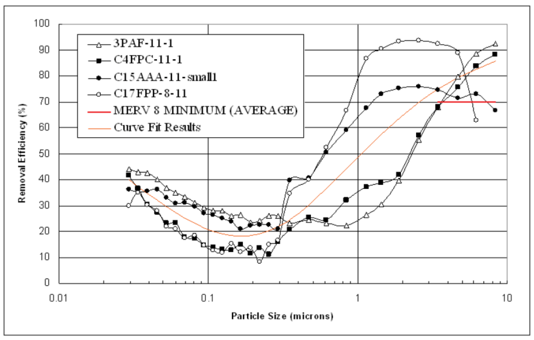

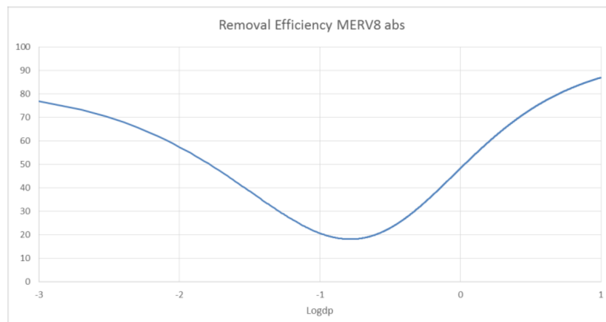

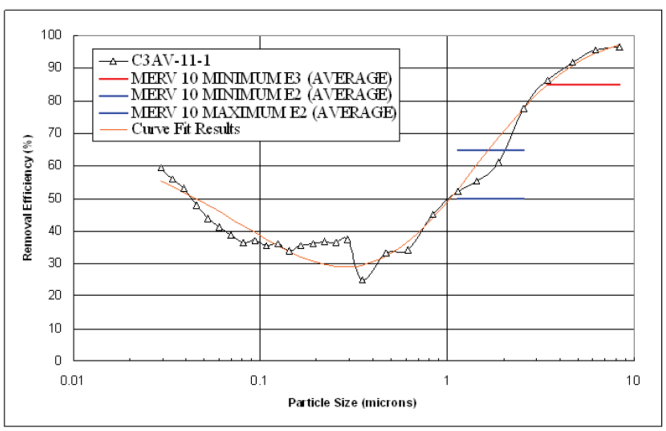

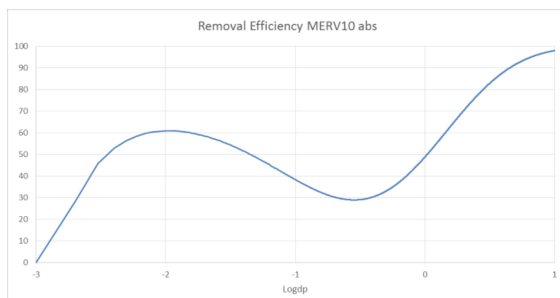

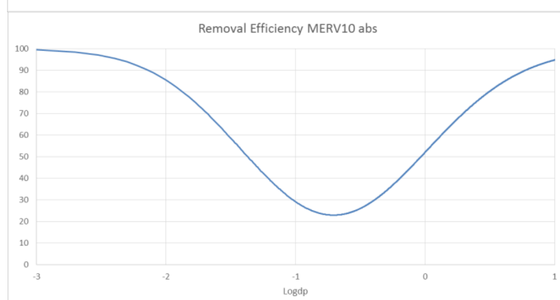

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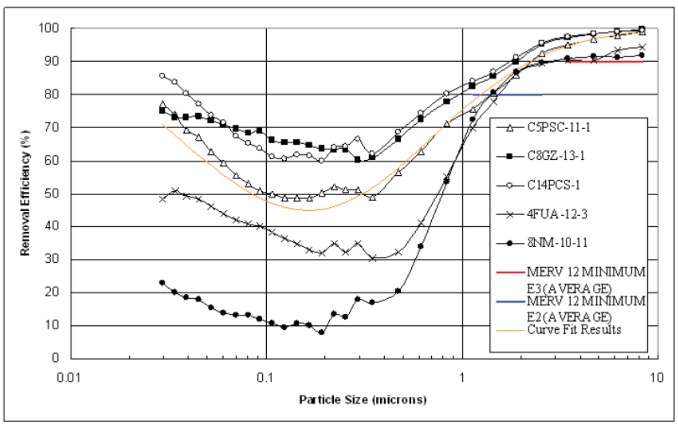

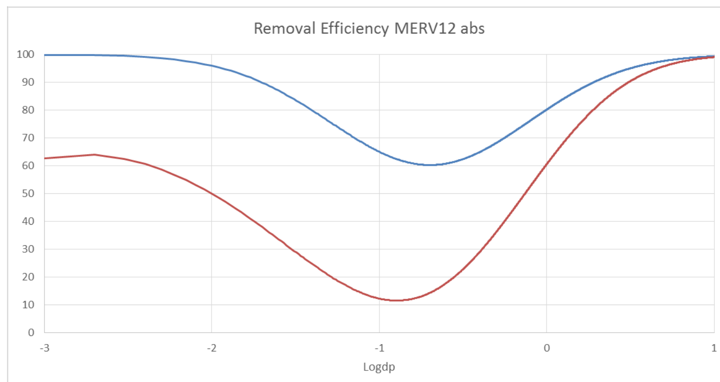

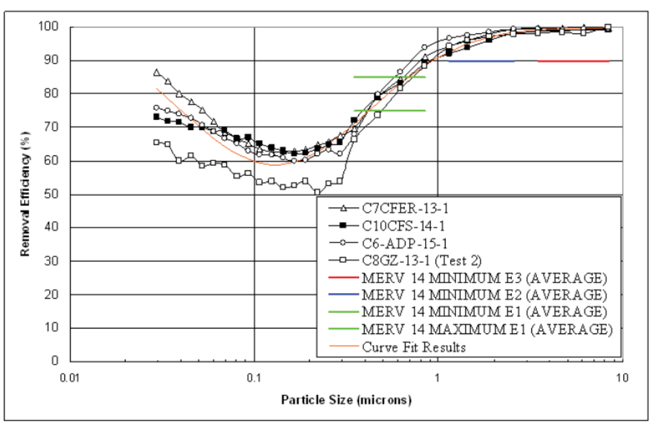

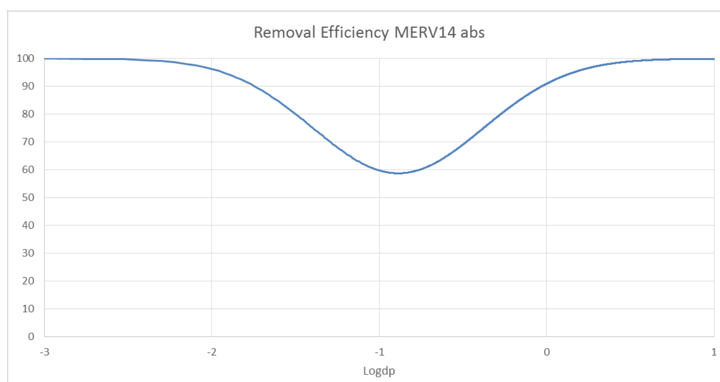

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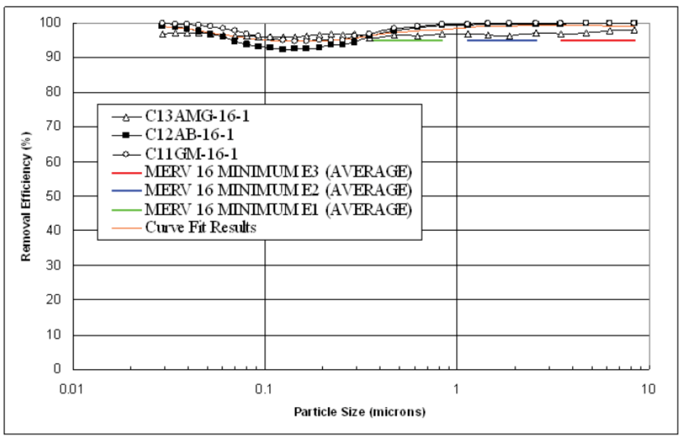
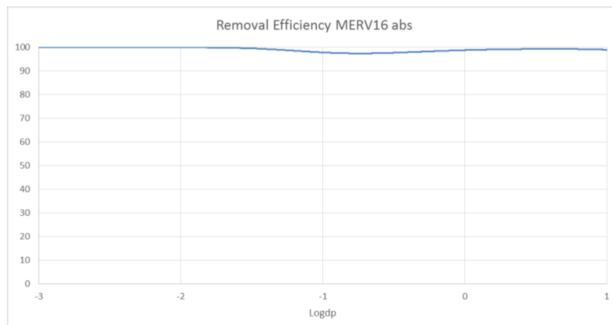
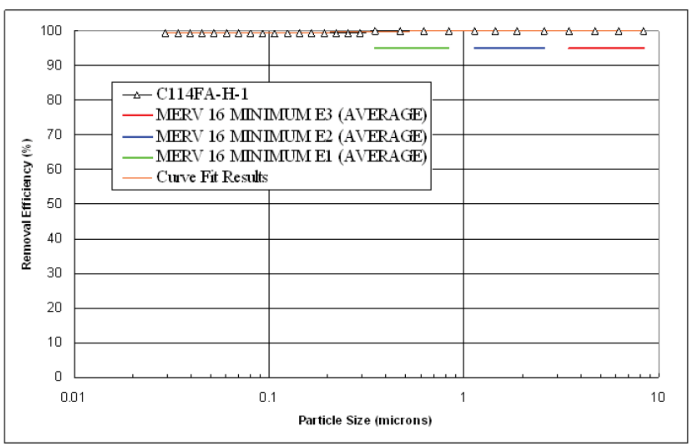
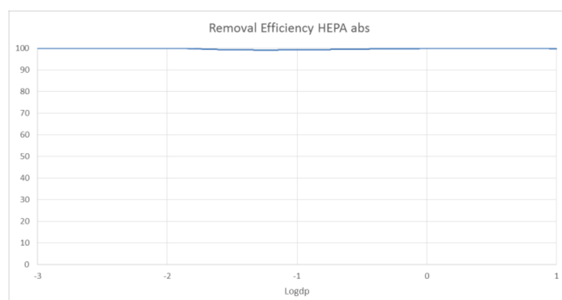
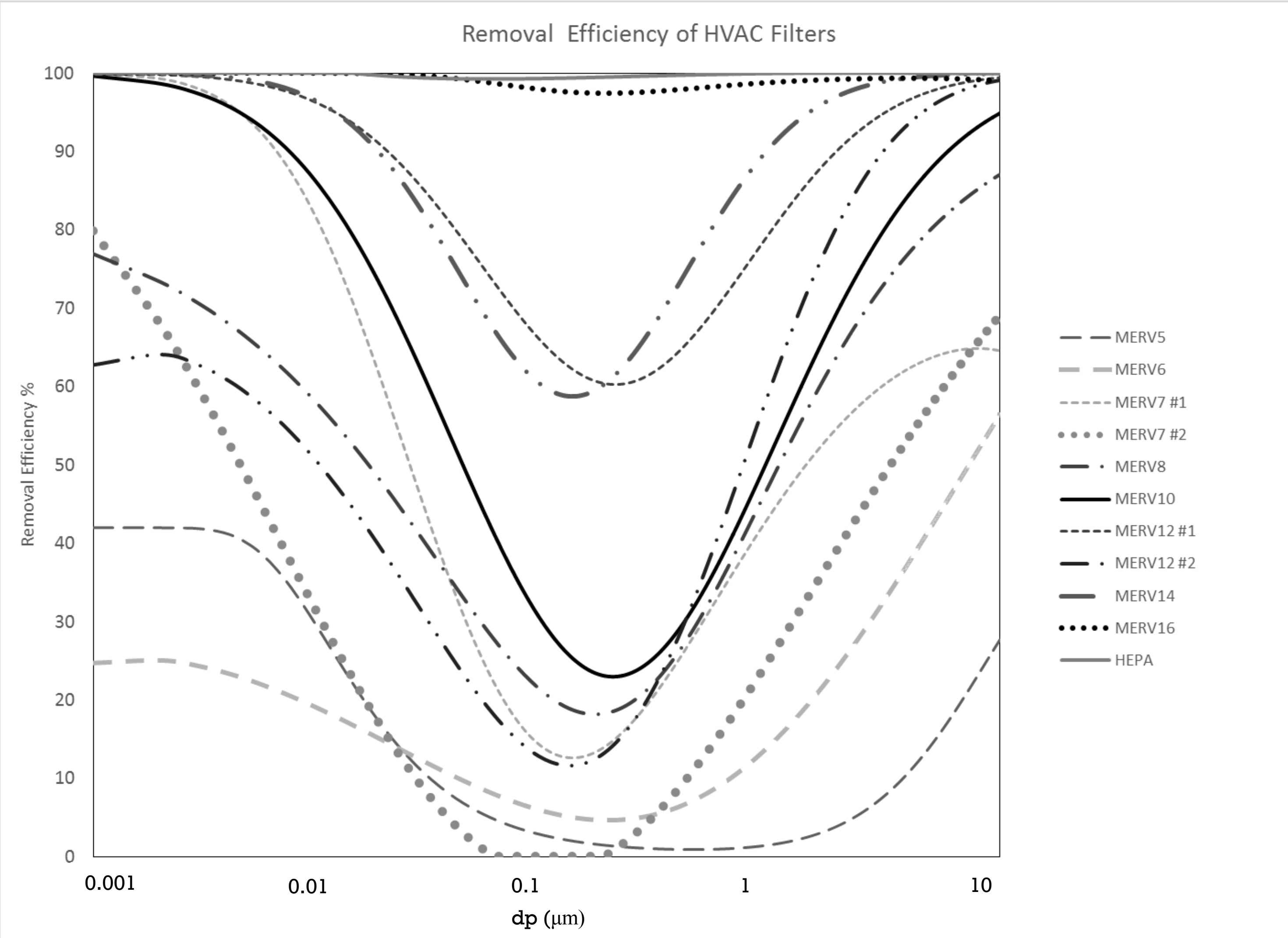










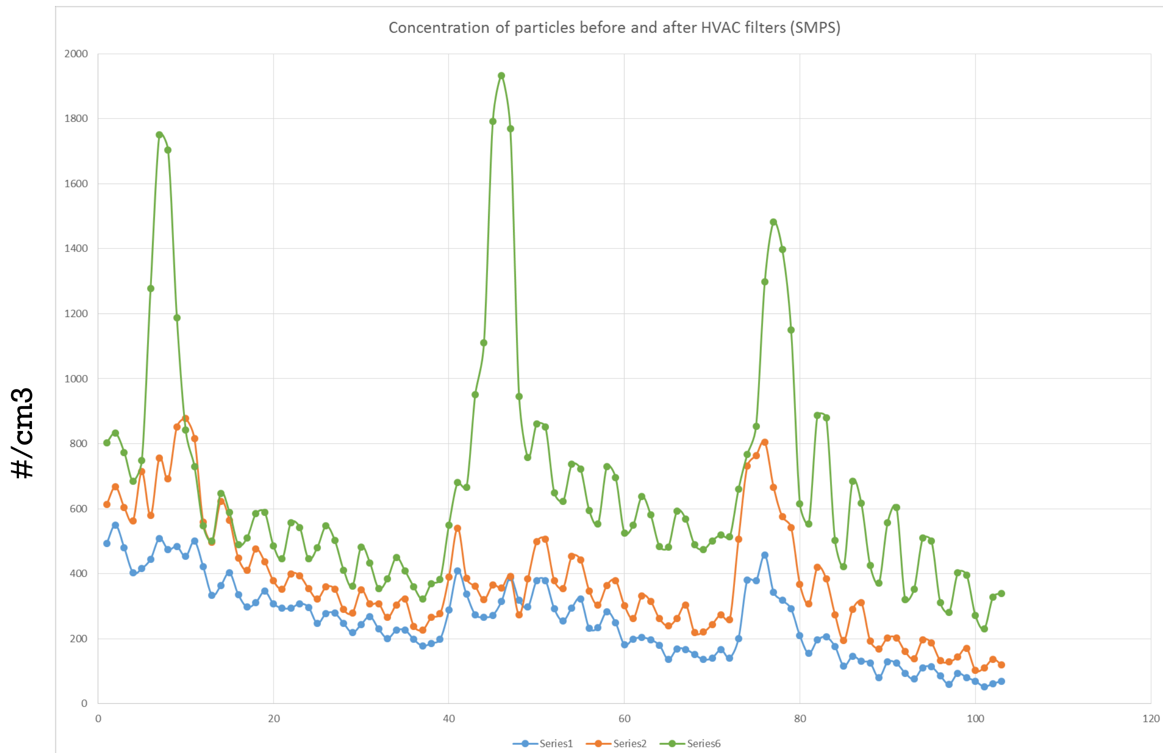
Removal Efficiency of HVAC Filters
Removal Efficiency %
100
90
80
70
60
50
40
30
20
10
0
0.001
0.01
0.1
1
10
dp (μm)
MERV5
MERV6
MERV7 #1
MERV7 #2
MERV8
MERV10
MERV12 #1
MERV12 #2
MERV14
MERV16
HEPA

PROBLEMS RELATED TO USING THESE REMOVAL EFFICIENCY DISTRIBUTIONS

- The removal efficiency of filters have been measured for particles sizes from 0.03 to 10 μm. We do not know what really would happen for smaller particles.
- The modeled removal efficiency curves are not fitted to the measured data points properly
- These removal efficiencies are not measured for outdoor origin particles.

We tried to measured it for filters in StudioE but there were couple of problems:

- We measured concentration of particles before and after filters but in some cases results were not looking reasonable.
- The concentration of outdoor origin particles in some size bins was close to zero
- We could not reach to steady state conditions when the windows was open and when it was closed the concentration had been dropped down so fast, especially for high efficient filters

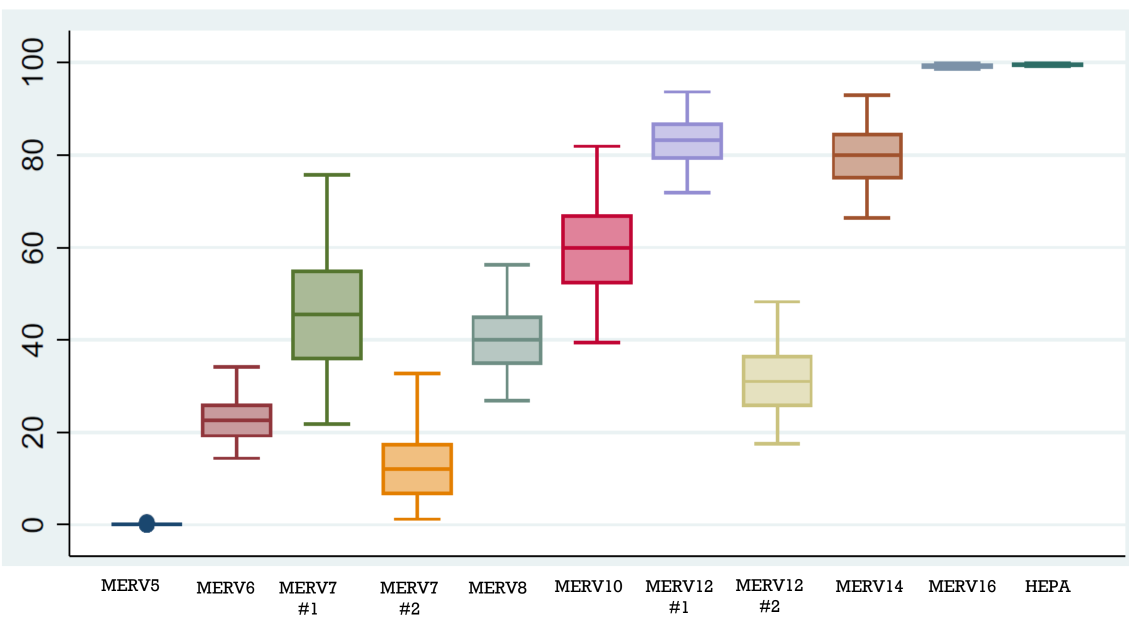


- We thought measuring the size-resolved removal efficiency of HVAC filters for outdoor origin particles would distract us from the main project, therefore we decided to leave it for now.
- We might measure removal efficiency based on the decay rate of particles. It has a capacity to become a master's thesis topic

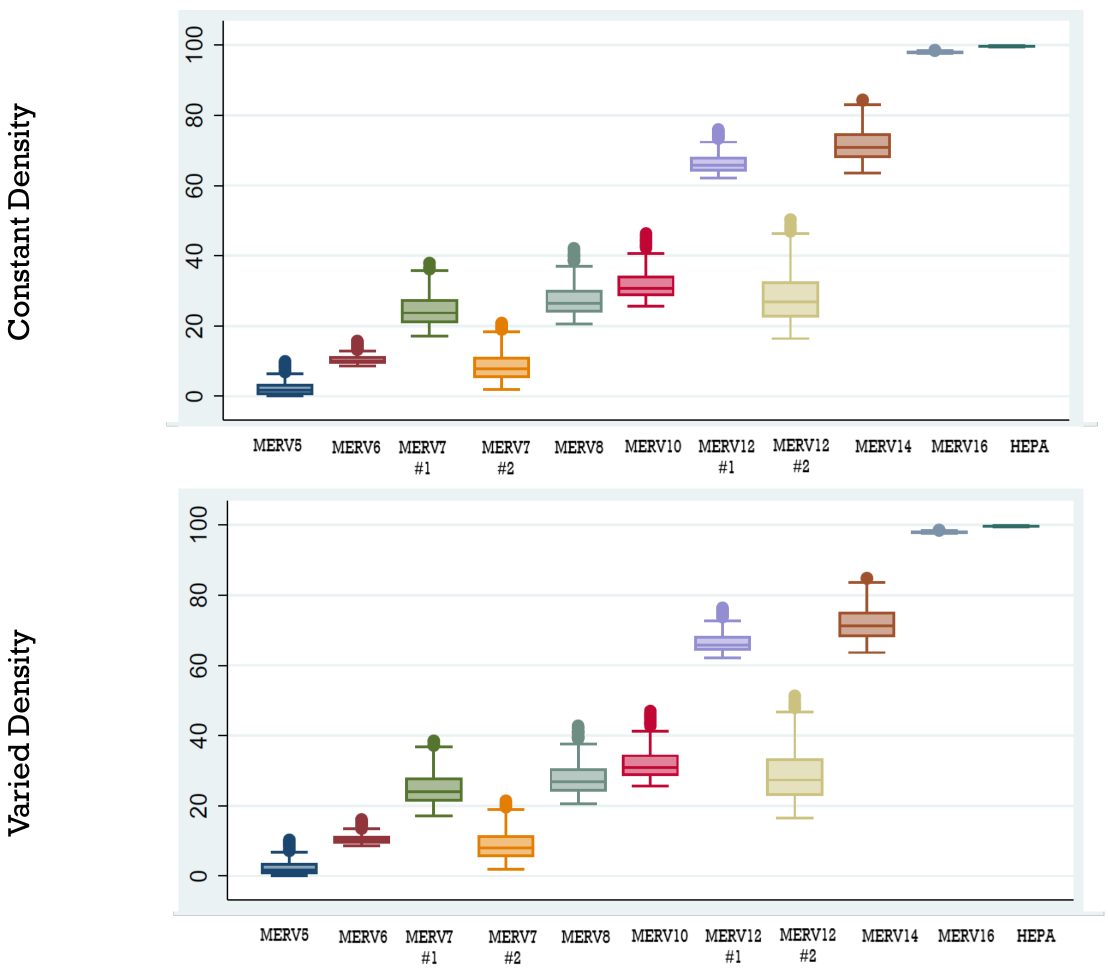
REMOVAL EFFICIENCY OF OUTDOOR ORIGIN UFP

$$RE_{UFP} = 1 - \frac{\sum_{i=1}^{100} N_i \times (1 - R_i)}{\sum_{i=1}^{100} N_i}$$

$$RE_{PM2.5} = 1 - \frac{\sum_{i=1}^{2500} N_i \times \rho_i \times \frac{\pi d_i^3}{6} \times (1 - R_i)}{\sum_{i=1}^{2500} N_i \times \rho_i \times \frac{\pi d_i^3}{6}}$$



REMOVAL EFFICIENCY OF OUTDOOR ORIGIN PM2.5



THANKS FOR YOUR ATTENTION

Questions

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