Electronic Supplementary Material (ESI) for Environmental Science: Nano.
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Supplemental Information for:

Particles in a box: Novel design and evaluation of an adaptable engineering control enclosure for a common split tube furnace to eliminate occupational exposure to refractory ceramic insulation fibers

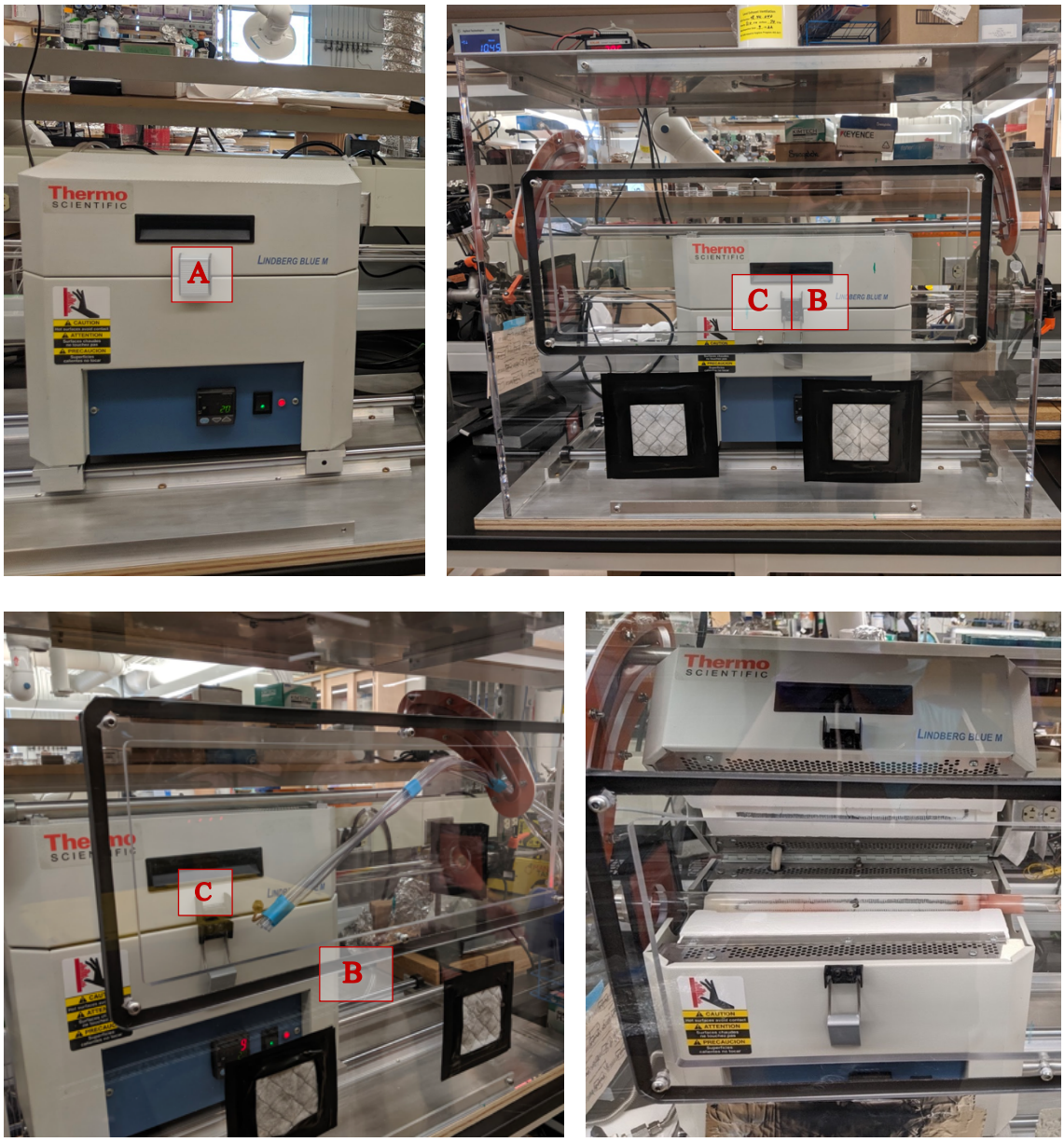
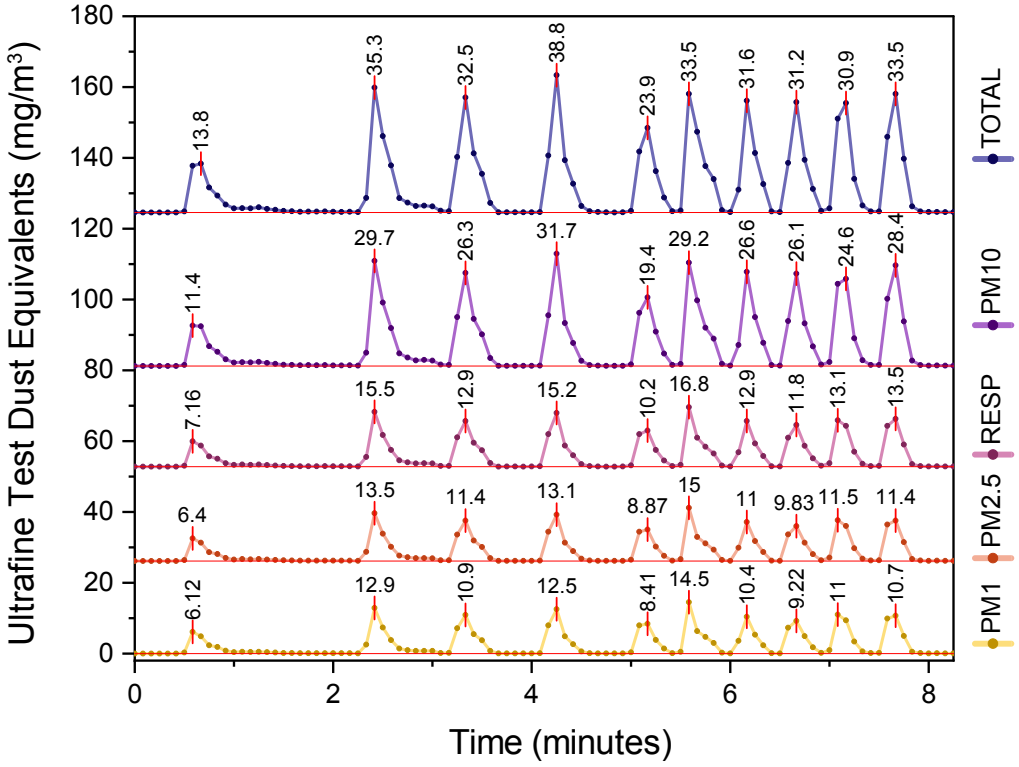


Figure S1. Air sampling positions. (A) at the center of the tube furnace shell opening without the enclosure, (B) directly outside of the enclosure at the level of the center of the tube furnace shell opening, and (C) inside of the enclosure at the center of the tube furnace shell opening. For sampling locations B and C, the furnace was moved to the edge of the enclosure interior to gain access to a handle used for opening and closing the shell. The tubing featured in the bottom left photograph was used to sample the air inside the enclosure for DustTrak measurements.

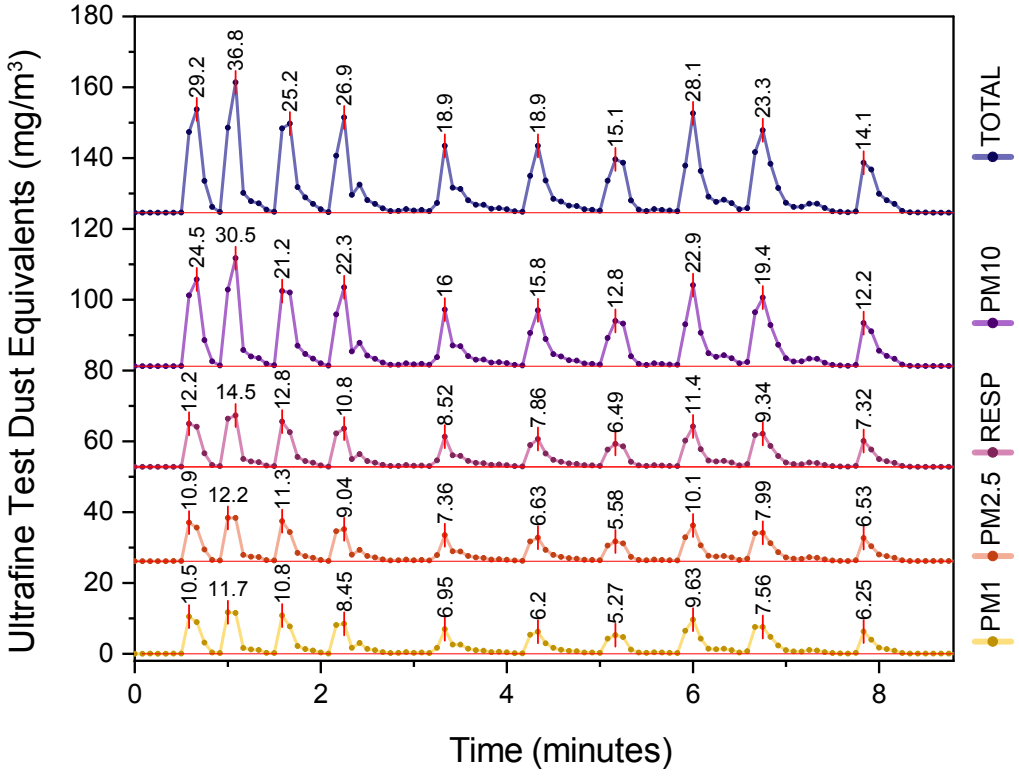
(a)

Without Enclosure

Without Enclosure Replica 1



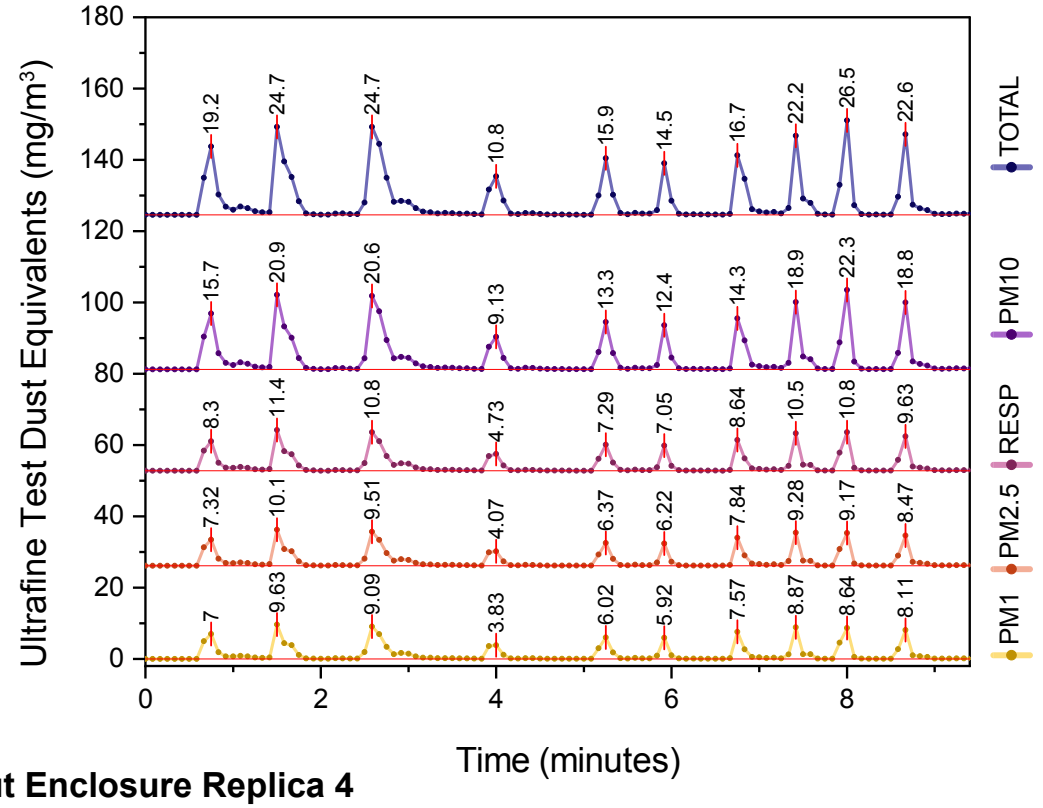
Without Enclosure Replica 2



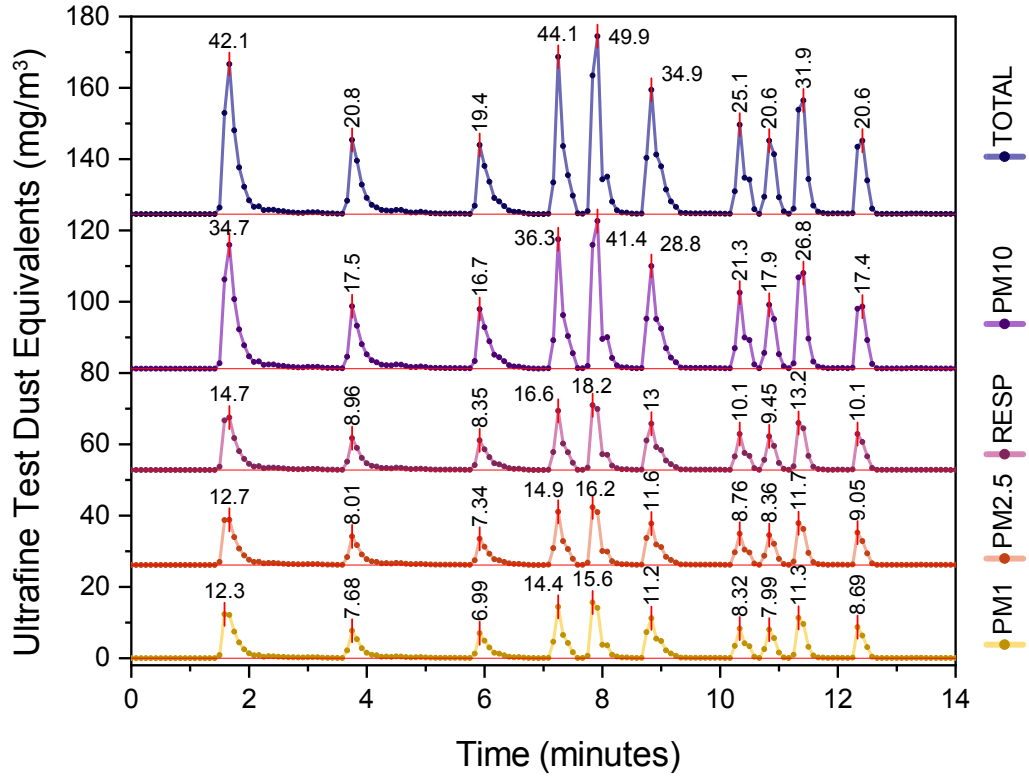
(a)

Without Enclosure

Without Enclosure Replica 3



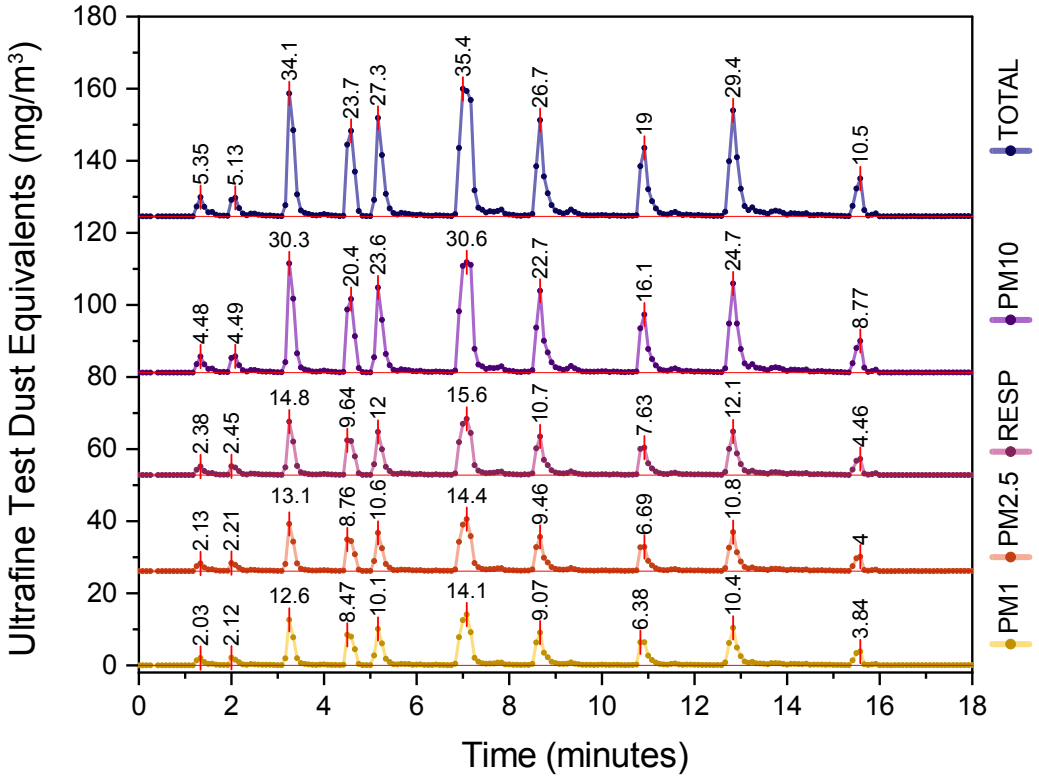
Without Enclosure Replica 4



(a)

Without Enclosure

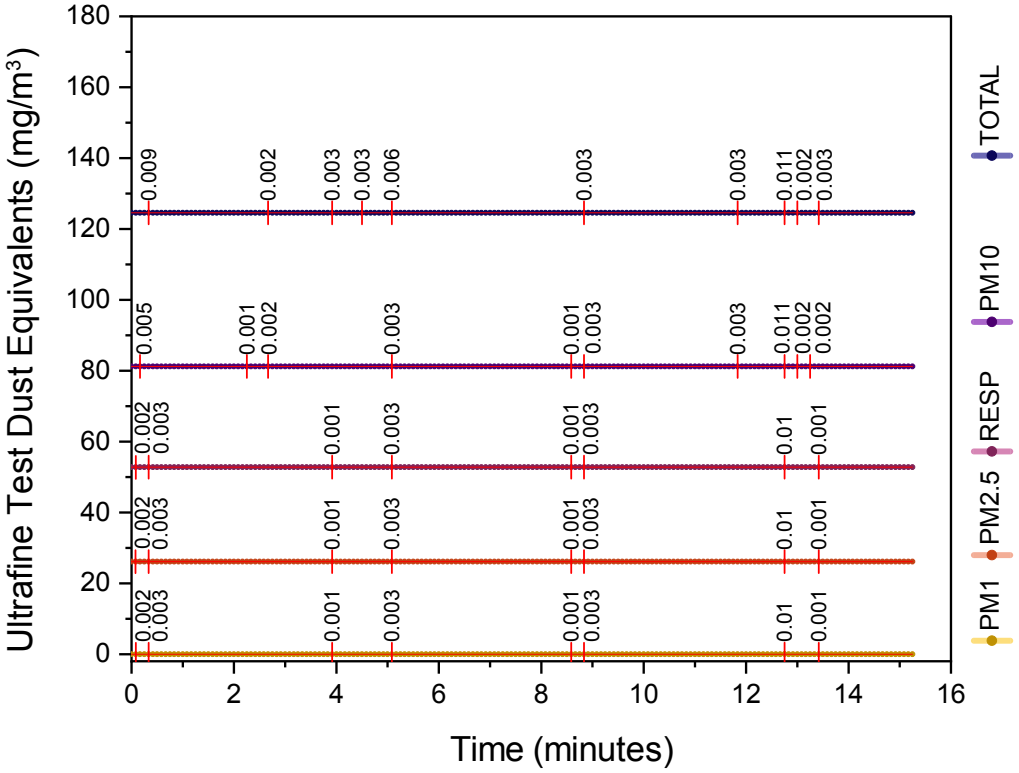
Without Enclosure Replica 5



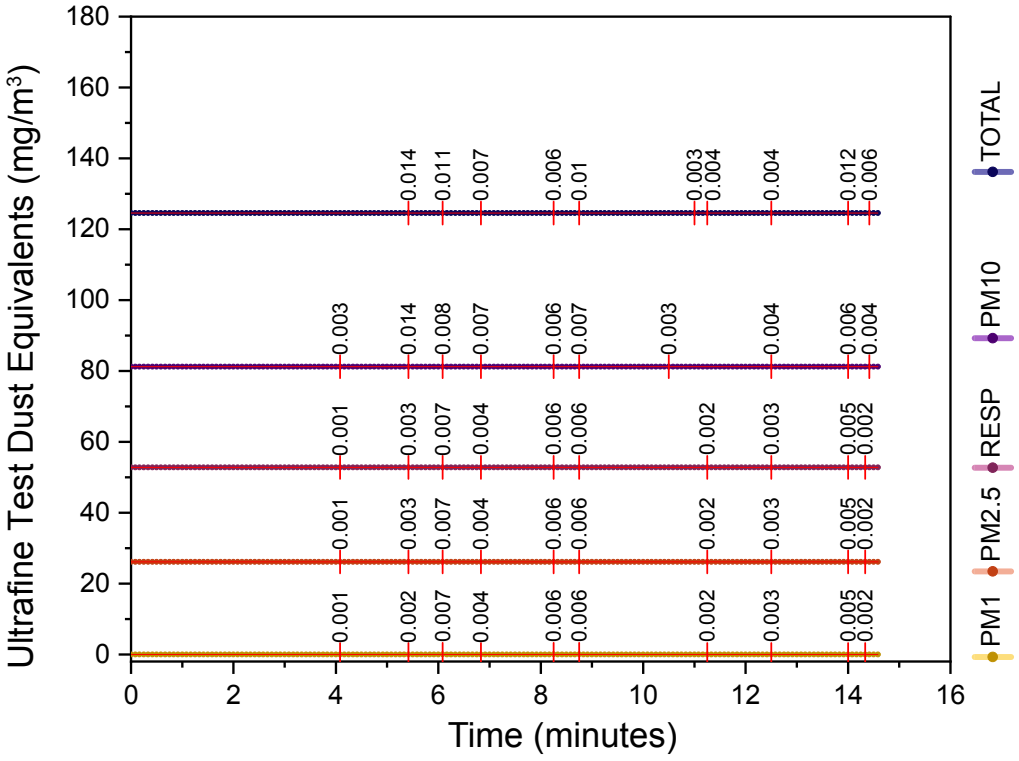
(b)

With Enclosure

With Enclosure Replica 1



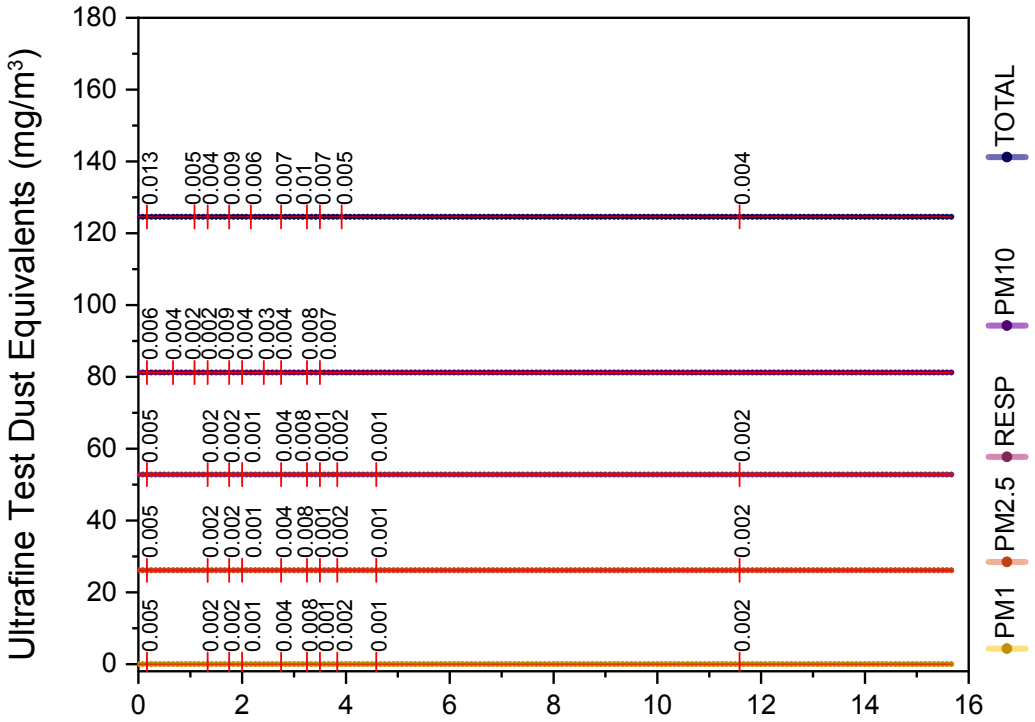
With Enclosure Replica 2



(b)

With Enclosure

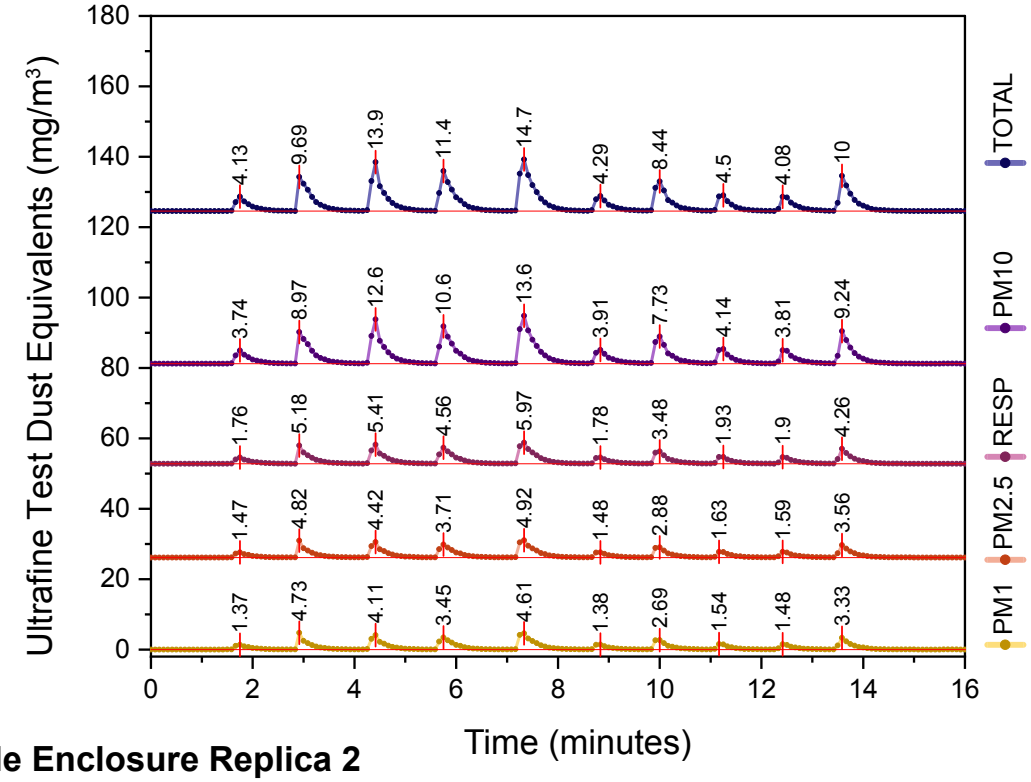
With Enclosure Replica 3



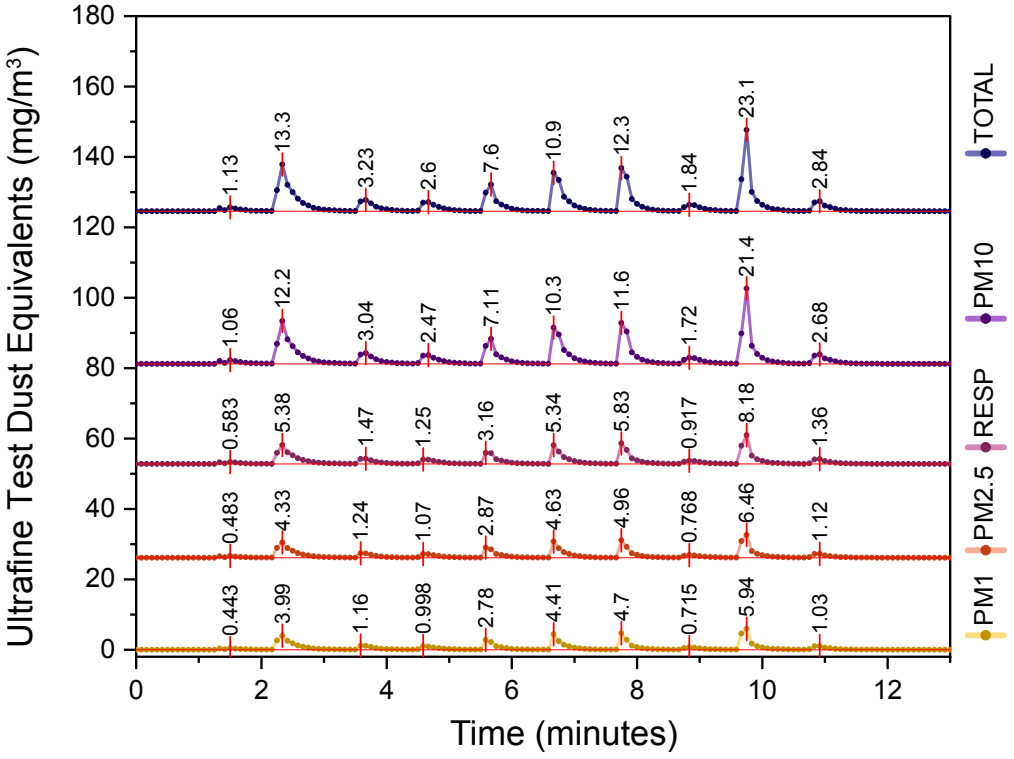
(c)

Inside Enclosure

Inside Enclosure Replica 1



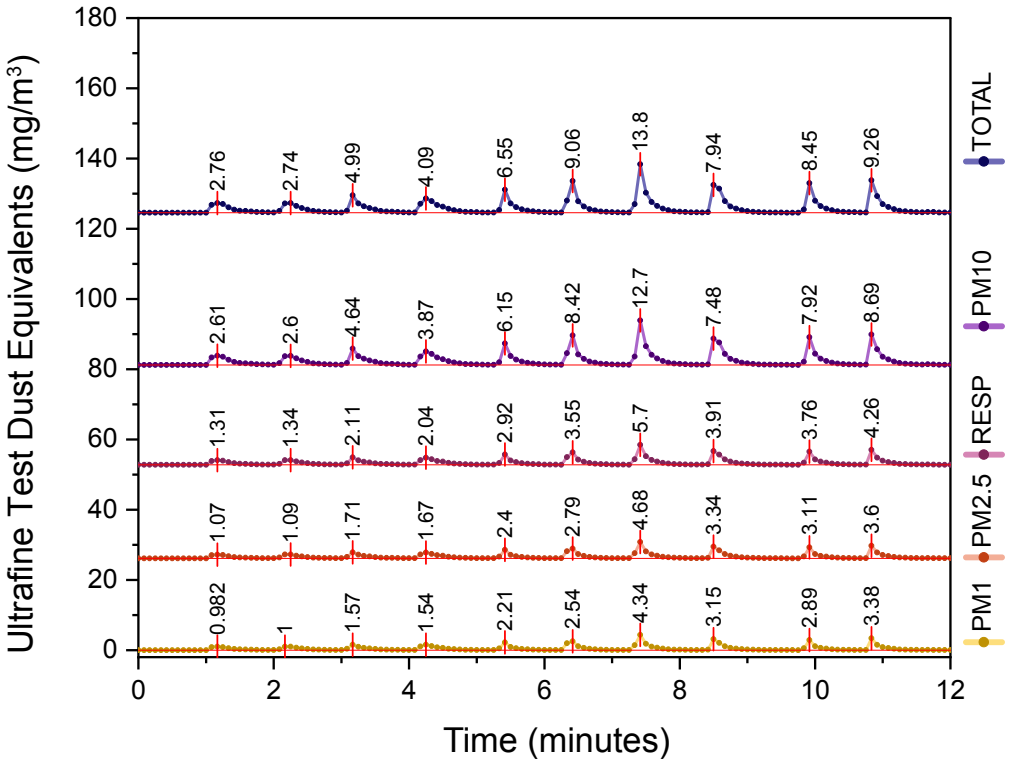
Inside Enclosure Replica 2



(c)

Inside Enclosure

Inside Enclosure Replica 3



Inside Enclosure Replica 4

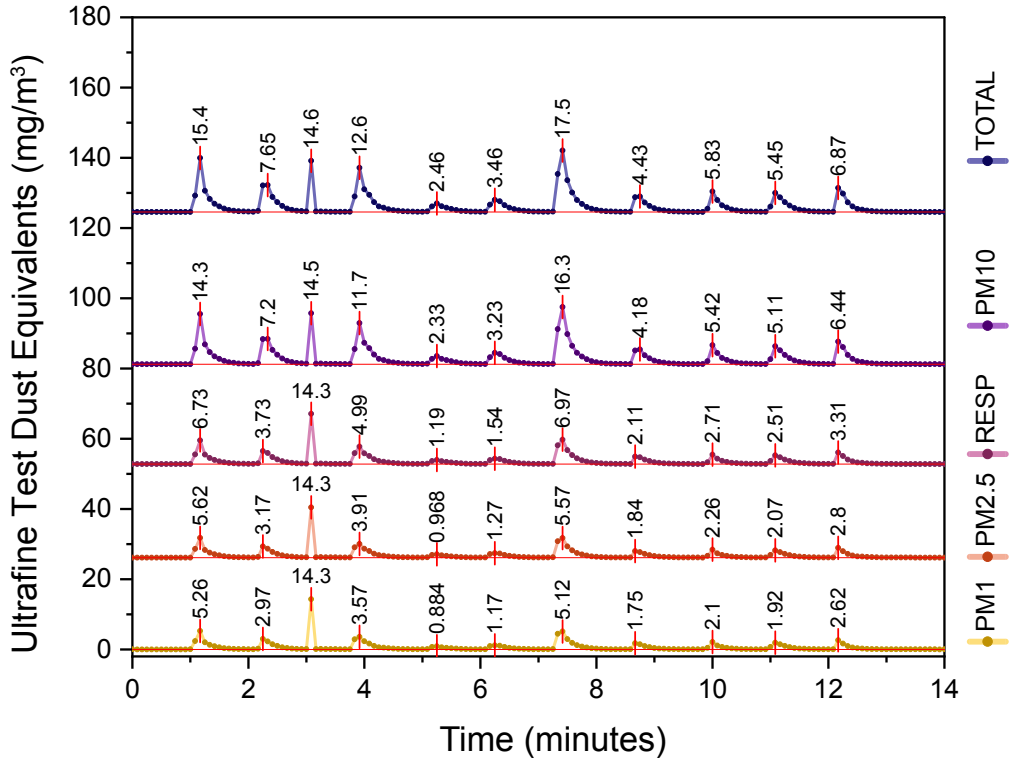


Figure S2. Furnace insulation real-time aerosol measurements. Particle mass concentration measured by DustTrak DRX via continuous air sampling under conditions (a) without the enclosure, (b) with the enclosure, and (c) inside of the enclosure (see Figure S1 for details). Each peak represents a furnace insulation agitation event; each agitation event consisting of opening and closing the furnace ten times; each experiment consists of ten agitation events; experimental replicas of each condition are numbered. Under condition (B), there are no discernable peaks corresponding to the release of furnace insulation particles upon agitation; in this case the ten peaks with the largest peak heights are identified.

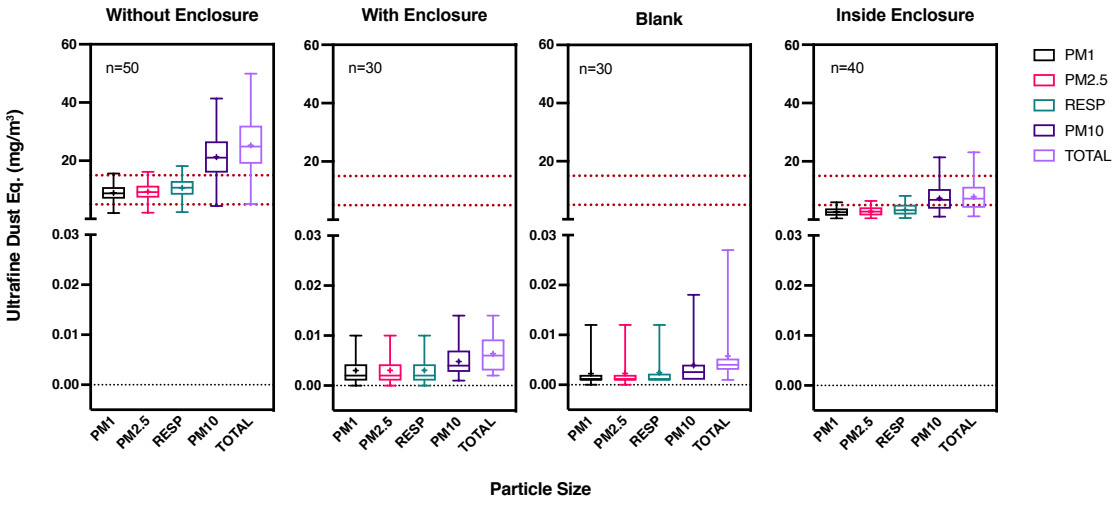


Figure S3. Aerosol generated and contained by enclosure. RCF aerosol concentration mitigated by enclosure particle concentration was measured with DustTrak DRX in ISO 12103-1 A1 ultrafine test dust equivalents. Red dotted lines denote the OSHA PEL (8-hour TWA) for total nuisance dust (15 mg/m^3) and respirable fraction of particulates not otherwise regulated (PNOR) or nuisance dust (5 mg/m^3).

Materials List for Benchtop Split- Tube Furnace Enclosure

Part Number	Description	Qty	Unit Price		Sub-total
McMaster-Carr					
57485K75	Set Screw Shaft Collar for 20 mm Diameter, Black-Oxide 1215 Carbon Steel	4 pc.s	$3.74	ea.	$14.96
9422K22	Rod-Sealing Wiper for 3/4" Rod Diameter	1 pc	$5.95		$5.95
9307K874	Buna-N Rubber Push-In Grommet for 3/4" ID and 1/4" Material Thickness, 5/16" ID, MS-35489-97	1 pk	$6.33		$6.33
9307K69	Buna-N Rubber Push-In Grommet for 1" ID and 1/4" Material Thickness, 11/16" ID, MS-35489-106	1 pk	$9.54		$9.54
93565K63	Super-Cushioning Polyethylene Foam Strip, Adhesive-Back, Extra Soft, 1/2" Wide, 3/16" Thick	1 pc	$6.30		$6.30
93275K22	Resilient Polyurethane Foam Strip, Adhesive-Back, Extra Soft, 1/2" Wide, 3/16" Thick	1 pc	$27.52		$27.52
Amazon					
SBR20-1000mm	Linear Rail	2 pc.s	$36.48	ea.	$72.96
4SBR20UU	Bearing Block	4 pc.s	$18.24	ea.	$72.96
Other:					
	Clear Acrylic Box and Door	1 pc	$1,806.00		$1,806.00
	Water-Jet Aluminum Side Lift Plates	2 pc.s	$32.50	ea.	$65.00
				Total	**$2,087.52**

Table S1. Enclosure cost and materials list.

Descriptive Statistics

Without Enclosure

	Ultrafine Dust Equivalents (mg/m^3)				
Particle Size Bins (um)	**PM1**	**PM2.5**	**RESP**	**PM10**	**TOTAL**
n	50	50	50	50	50
Minimum	2.030	2.130	2.380	4.480	5.130
Maximum	**15.600**	**16.200**	**18.200**	**41.400**	**49.900**
Range	**13.570**	**14.070**	**15.820**	**36.920**	**44.770**
10% Percentile	5.335	5.644	6.546	11.480	13.830
25% Percentile	6.980	7.335	8.338	15.950	18.975
Median	**8.780**	**9.225**	**10.750**	**21.050**	**24.900**
75% Percentile	10.925	11.425	13.025	26.650	32.050
90% Percentile	12.870	13.460	15.470	30.590	36.660
95% CI of median					
Actual confidence level	96.72%	96.72%	96.72%	96.72%	96.72%
Lower confidence limit	7.990	8.360	9.450	17.900	20.800
Upper confidence limit	10.400	10.800	12.100	24.500	29.200
Mean	**8.964**	**9.375**	**10.677**	**21.245**	**25.306**
Std. Deviation	**3.042**	**3.136**	**3.546**	**7.922**	**9.553**
Std. Error of Mean	0.430	0.444	0.501	1.120	1.351
Lower 95% CI of mean	8.100	8.484	9.669	18.994	22.591
Upper 95% CI of mean	9.829	10.266	11.685	23.497	28.021
Coefficient of variation	**33.93%**	**33.45%**	**33.21%**	**37.29%**	**37.75%**

With Enclosure

	Ultrafine Dust Equivalents (mg/m^3)				
Particle Size Bins (um)	**PM1**	**PM2.5**	**RESP**	**PM10**	**TOTAL**
n	30	30	30	30	30
Minimum	0.000	0.000	0.000	0.001	0.002
Maximum	**0.010**	**0.010**	**0.010**	**0.014**	**0.014**
Range	**0.010**	**0.010**	**0.010**	**0.013**	**0.012**
10% Percentile	0.001	0.001	0.001	0.002	0.003
25% Percentile	0.001	0.001	0.001	0.003	0.003
Median	**0.002**	**0.002**	**0.002**	**0.004**	**0.006**
75% Percentile	0.004	0.004	0.004	0.007	0.009
90% Percentile	0.007	0.007	0.007	0.009	0.012
95% CI of median					
Actual confidence level	95.72%	95.72%	95.72%	95.72%	95.72%
Lower confidence limit	0.002	0.002	0.002	0.003	0.004
Upper confidence limit	0.003	0.003	0.003	0.006	0.007
Mean	**0.003**	**0.003**	**0.003**	**0.005**	**0.006**
Std. Deviation	**0.002**	**0.002**	**0.002**	**0.003**	**0.003**
Std. Error of Mean	0.000	0.000	0.000	0.001	0.001
Lower 95% CI of mean	0.002	0.002	0.002	0.004	0.005
Upper 95% CI of mean	0.004	0.004	0.004	0.006	0.008
Coefficient of variation	**81.18%**	**80.05%**	**80.05%**	**63.66%**	**54.37%**

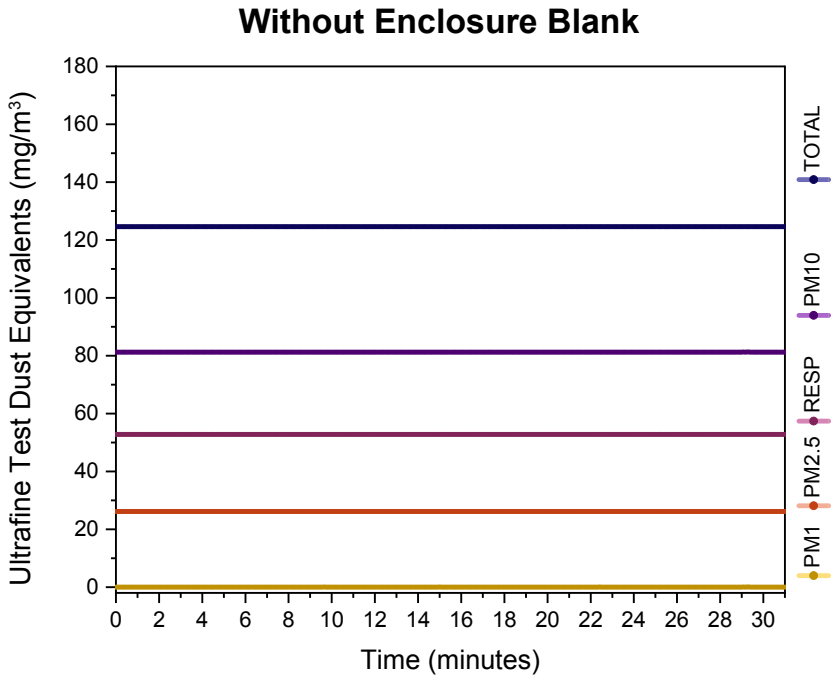
Blank

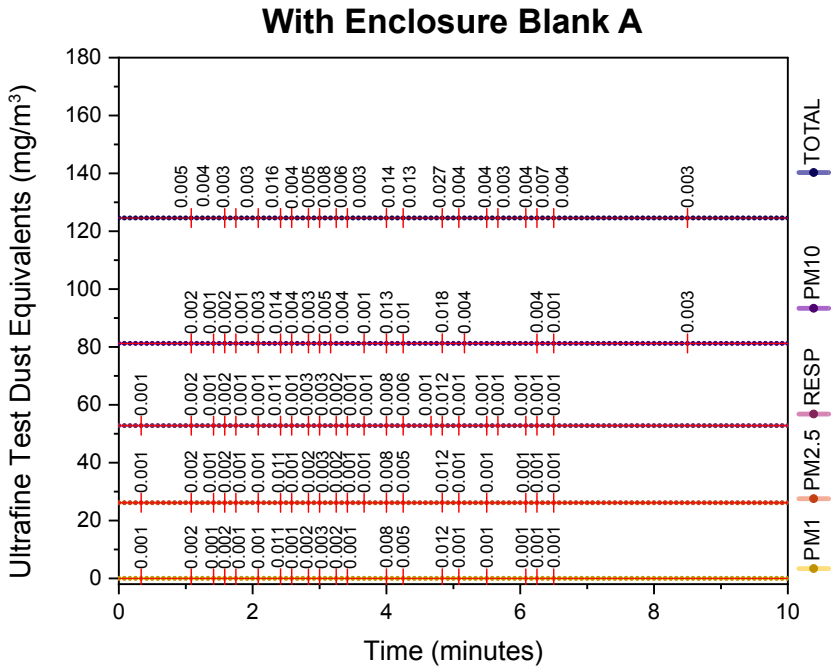
Particle Size Bins (um)	Ultrafine Dust Equivalents (mg/m^3) PM1	PM2.5	RESP	PM10	TOTAL
n	30	30	30	30	30
Minimum	0.000	0.000	0.001	0.001	0.001
Maximum	**0.012**	**0.012**	**0.012**	**0.018**	**0.027**
Range	**0.012**	**0.012**	**0.011**	**0.017**	**0.026**
10% Percentile	0.000	0.000	0.001	0.001	0.002
25% Percentile	0.001	0.001	0.001	0.001	0.003
Median	**0.001**	**0.001**	**0.001**	**0.003**	**0.004**
75% Percentile	0.002	0.002	0.002	0.004	0.005
90% Percentile	0.008	0.008	0.008	0.013	0.014
95% CI of median					
Actual confidence level	95.72%	95.72%	95.72%	95.72%	95.72%
Lower confidence limit	0.001	0.001	0.001	0.001	0.003
Upper confidence limit	0.002	0.002	0.002	0.004	0.005
Mean	**0.002**	**0.002**	**0.002**	**0.004**	**0.006**
Std. Deviation	**0.003**	**0.003**	**0.003**	**0.004**	**0.005**
Std. Error of Mean	0.001	0.001	0.001	0.001	0.001
Lower 95% CI of mean	0.001	0.001	0.001	0.002	0.004
Upper 95% CI of mean	0.003	0.003	0.004	0.005	0.008
Coefficient of variation	**133.39%**	**130.53%**	**120.51%**	**110.51%**	**92.85%**

Inside Enclosure

Particle Size Bins (um)	Ultrafine Dust Equivalents (mg/m^3) PM1	PM2.5	RESP	PM10	TOTAL
n	40	40	40	40	40
Minimum	0.443	0.483	0.583	1.060	1.130
Maximum	**5.940**	**6.460**	**8.180**	**21.400**	**23.100**
Range	**5.497**	**5.977**	**7.597**	**20.340**	**21.970**
10% Percentile	0.984	1.070	1.256	2.483	2.614
25% Percentile	1.373	1.473	1.765	3.758	4.083
Median	**2.580**	**2.795**	**3.235**	**6.775**	**7.235**
75% Percentile	3.885	4.225	5.133	10.525	11.275
90% Percentile	4.727	4.956	5.956	13.510	14.620
95% CI of median					
Actual confidence level	96.15%	96.15%	96.15%	96.15%	96.15%
Lower confidence limit	1.540	1.670	2.040	4.140	4.430
Upper confidence limit	3.330	3.560	4.260	8.690	9.260
Mean	**2.646**	**2.834**	**3.410**	**7.330**	**7.882**
Std. Deviation	**1.485**	**1.585**	**1.930**	**4.589**	**4.966**
Std. Error of Mean	0.235	0.251	0.305	0.726	0.785
Lower 95% CI of mean	2.171	2.327	2.792	5.863	6.293
Upper 95% CI of mean	3.120	3.341	4.027	8.798	9.470
Coefficient of variation	**56.13%**	**55.93%**	**56.60%**	**62.61%**	**63.01%**

Table S2. Summary tables of peak statistics presented in Figure S3.


Without Enclosure Blank
Ultrafine Test Dust Equivalents (mg/m3)
Time (minutes)
TOTAL
PM10
RESP
PM2.5
PM1


With Enclosure Blank A
Ultrafine Test Dust Equivalents (mg/m3)
Time (minutes)
TOTAL
PM10
RESP
PM2.5
PM1

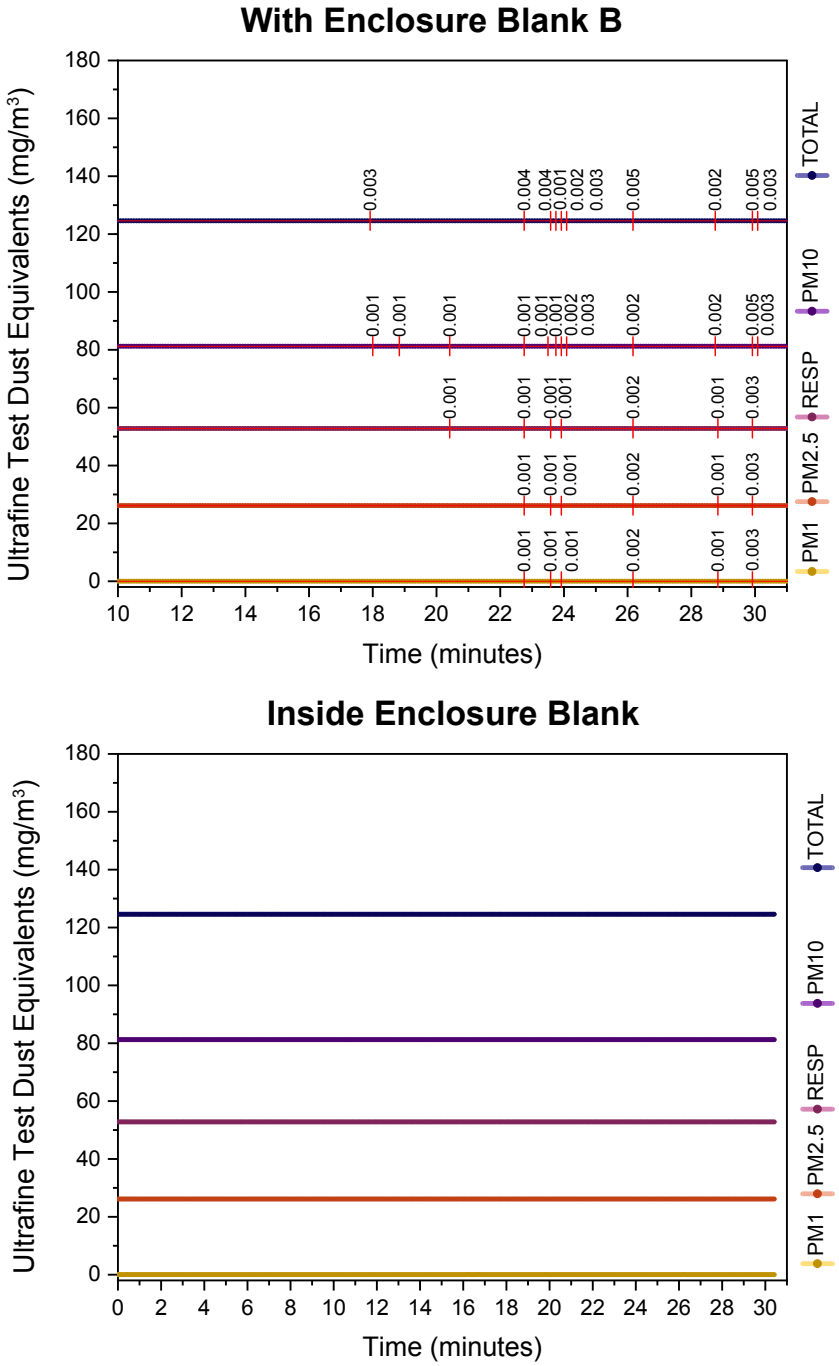


Figure S4. Real-time background room dust. Particle concentrations measured by DustTrak DRX via continuous air sampling under conditions (A) without the enclosure, (B) with the enclosure, and (C) inside of the enclosure (see Figure S1 for details) without any furnace insulation agitation. Sampling condition (B) with the enclosure plot is shown in two separate plots for clarity.

DustTrak DRX particle size segregation bins in micrometers:

PM1 = PM2.5 – PM1-2.5

PM2.5 = Photometric signal x calibration factor

Respirable / PM4 = PM2.5 + PM2.5-4

PM10 / Thoracic = PM4 + PM4-10

TPM = PM10 + PM>10

Peak finding and filtering criteria (in Origin)

1. *Furnace Insulation Aerosol Sampling/ Measurements:* Peak finding criteria was set to local maximum method with 2 local points. Peak filtering was set to 10 peaks per experiment for every particle size bin. Except for (B) "with enclosure" Replica 1, PM1, PM2.5, RESP, where an additional peak was identified in each size bin by lowering the peak local maximum finding criterial to 1 local point. Lowering the criteria allowed for identification of 8 peaks per size bin (instead of 7 peaks per size bin). Peak filtering was set to 11 peaks per experiment for (C) "inside enclosure" Replica 4, where an anomalous single point peak ~ 3 min was removed in the statistical analysis.
2. *With Enclosure Blank*: Peak finding criteria was set to local maximum method with 1 local point. Peak filtering was set to 30 peaks for every particle size bin.

When fewer than the expected number of peaks are found in a particular experiment, zero value peak heights are added to the statistical analysis until the appropriate comparable sample size is reached (i.e., "with enclosure" Replica 1, PM1, PM2.5, RESP 2 zero peaks added, "with enclosure" blank PM1 4 zero peaks added, "with enclosure" blank PM2.5 3 zero peaks added).

Peak fiber concentration calculation

Sample fiber masses were calculated for a subset of fibers sampled without the enclosure. Only fibers, which met the following criteria: >5 µm long, <3 µm diameter, and with an aspect ratio ≥5:1 were used to calculate statistics on fiber mass. Only "whole" fibers were considered, i.e., fibers for which both ends were visible while measuring their dimensions under TEM. The volume of each fiber was calculated from a measured length and width, and the fiber was assumed to be cylindrical. Using the density of the fiber, the mass of individual fibers was calculated. As airborne dusts consist of a wide distribution of fiber masses, the estimated peak fiber concentration (Table 2) remain constrained by the sample fiber masses used herein. A total of 85 fibers were analyzed. The standard deviation of the sample fiber masses was greater than the mean mass, indicating a skewed distribution. Therefore, the median mass along with a 97% confidence interval of the median (upper and lower limits) and the range were used to approximate the mass of a single particle.

	Length (um)	Width (um)	Mass (ng)
Mean	15.21	1.07	0.05
Standard Deviation	8.72	0.54	0.08
Coefficient of variation	57%	50%	150%

We note that while the standard deviation of the lengths and widths is lower than that of the mean values, the standard deviations are still over 50% of the means, respectively.

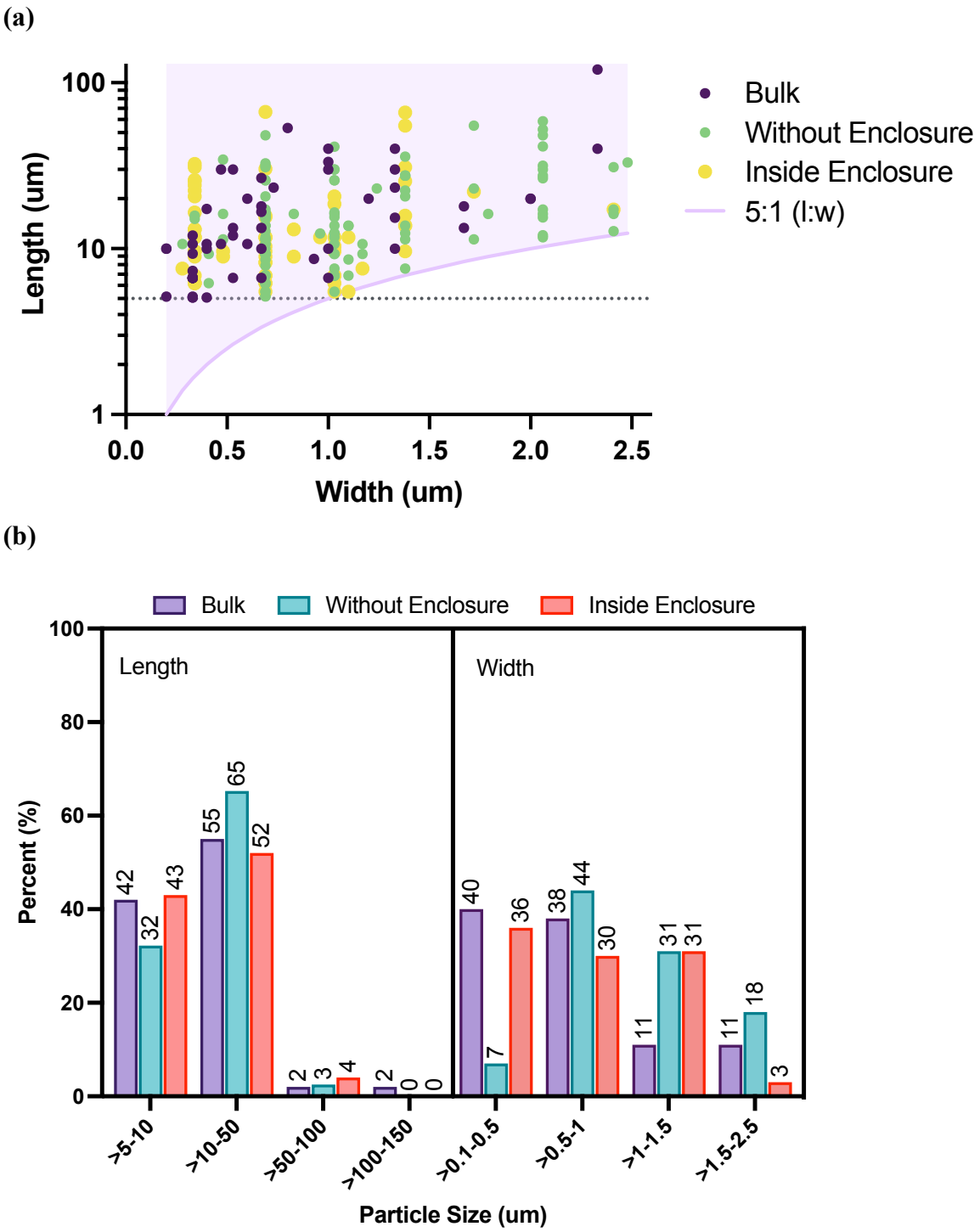
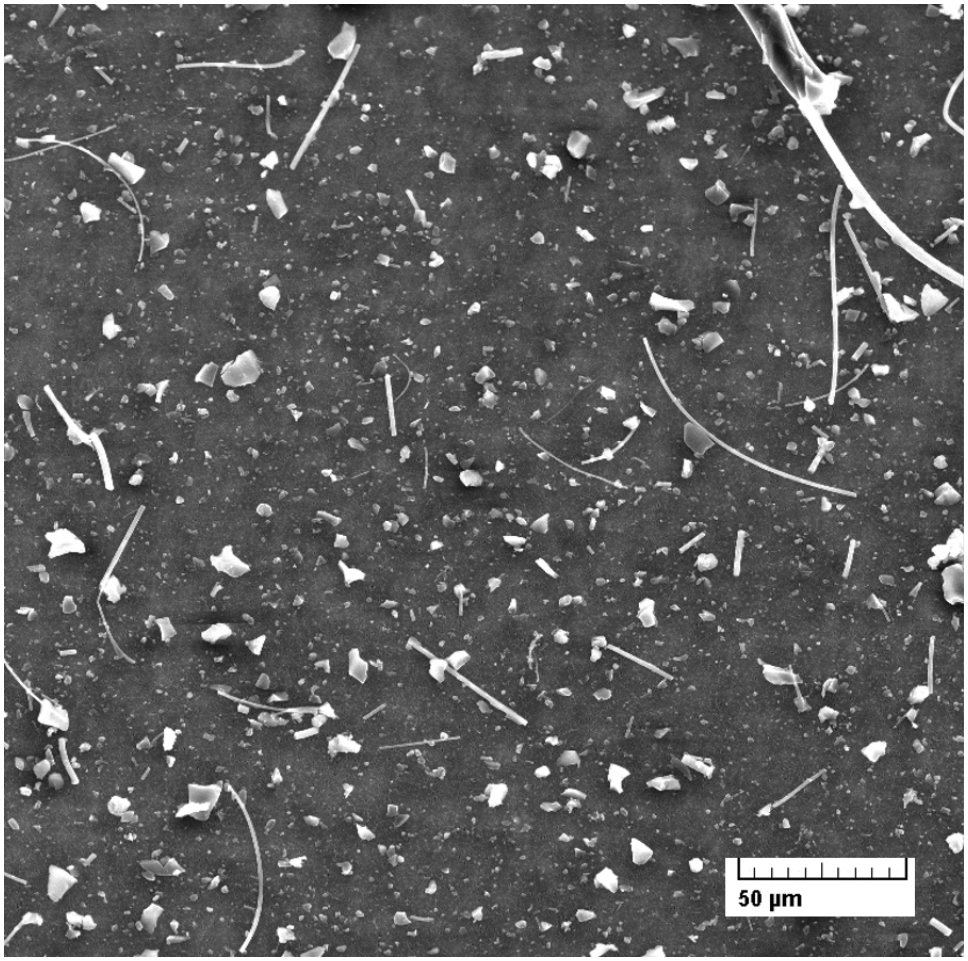
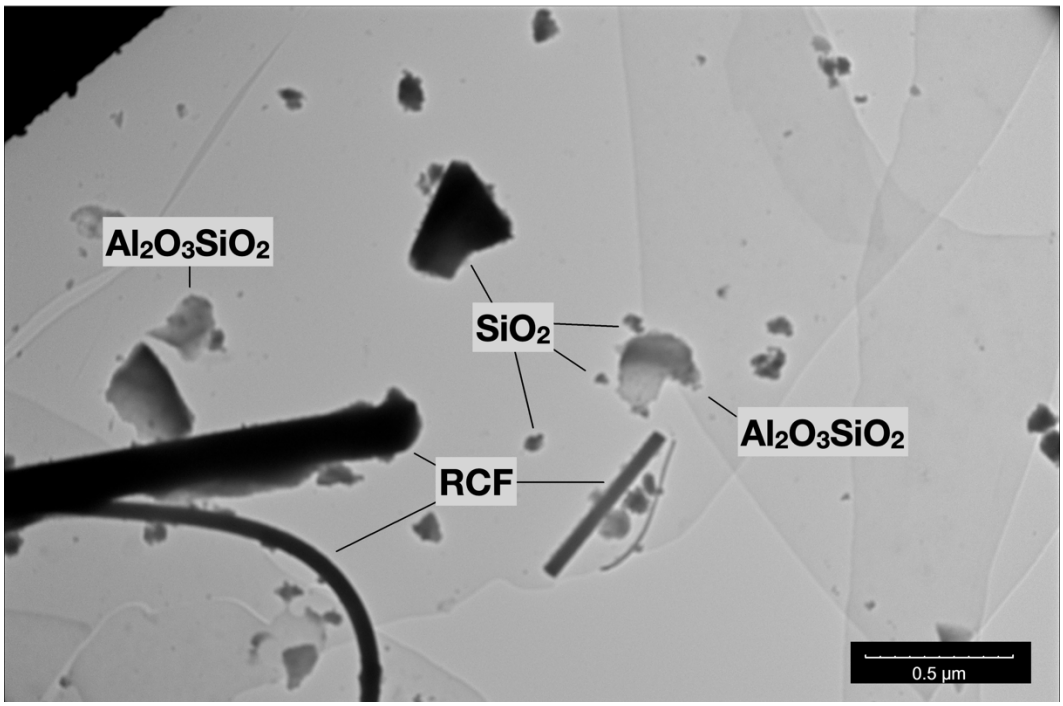


Figure S5. Aerosol and bulk fiber size distribution (including 0.5 fiber counts). RCFs greater than 5 µm in length, less than 3 µm in width, and with a > 5:1 length:width aspect ratio, are counted by TEM. (a) Grey dotted line highlights the 5 µm length minimum; purple curve represents 5:1 length:width aspect ratio for each measured particle width. (Includes ½ fiber counts—see methods).

(a)



(b)



(c)

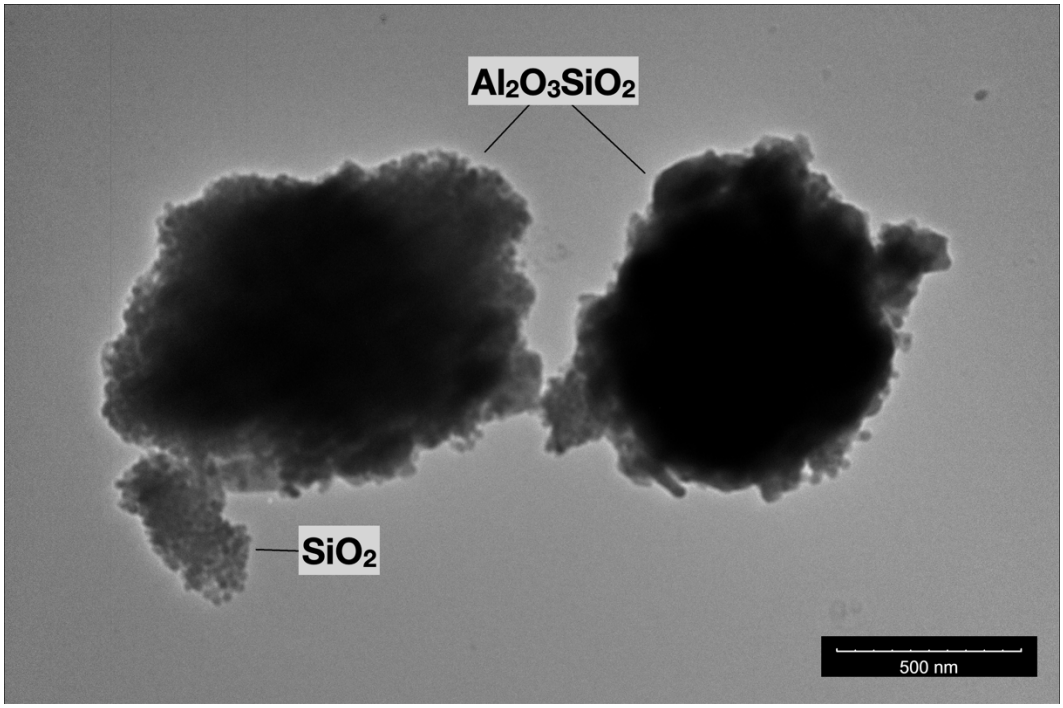


Figure S6. Bulk material images and chemical composition. SEM (a) and TEM (b, c) images of bulk RCF material.