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PERFORMANCE DATA REPORT

FOR

PERFORMANCE EVALUATION OF A FILTRATION SYSTEM

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Acronyms and Abbreviations

Acronym or Abbreviation	Definition
C	Aerosol mass concentration
CFM	Cubic feet per minute
cm	Centimetre
cm ²	Square centimetre
CMD	Count median diameter
DOP	Diocetyl phthalate
FTIR	Fourier Transform Infrared
g	Grams
gsd	Geometric standard deviation
HEPA	High efficiency particulate air
hr	Hour
iwg	Inches water gauge (airflow resistance)
IR	Infrared
L	Liter
L/min	liters per minute
m ²	square meter
m ³	cubic meter
mg	Milligram
mg/m ³	milligram per meter cubed
min	Minute
mL	Milliliter
mm	Millimeter
MPPS	Most penetration particle size
η	Aerosol filtration efficiency
P	Fractional aerosol penetration
PAO	polyalphaolefin
RH	Relative humidity
SMPS	Scanning mobility particle sizer
t	Time
T _b	Breakthrough time (gas life or service life)
T	temperature
UV	Ultraviolet
µm	micrometer
VAC	Volts, alternating current

1.0 INTRODUCTION

1.1 Background

Large-scale (750 to 3,000 m³/hr; [450 to 1,800 CFM]) filtration systems used in scrubbing and air purification applications typically, at a minimum, contain fibrous media for collection and retention of aerosols and contain a sorbent bed, commonly activated carbon granules, to remove nuisance or hazardous gases and vapors. The performance of the filtration system - the efficiency of the filters to remove aerosols and their capacity to adsorb vapors and gases can range greatly depending on the application, operating conditions, and filter design. Battelle was contracted to assess the performance of contract-provided filtration system designs operated at conditions relevant to their intended application.

1.2 Objective

The objective of this effort was to characterize the air purification performance capability of filtration system designs provided by the contract. Three primary types of performance tests were performed, either on the entire filter or a sample of the filter's air purification media:

- Airflow resistance (whole-filter)
- Aerosol filtration (collection) efficiency (whole-filter)
- Gas life (i.e., service life or adsorption capacity) of the adsorbent (carbon only)

Details of the test approach used to generate the data reported here is described in the draft Test Plan delivered on 7 August 2015. A summary of the approach is provided in Section 2.0. Results - performance data - of the unit is provided in Sections 3.0.

2.0 TEST DESIGN AND APPROACH

2.1 Test Item Description

Filtration system has a designated high efficiency particulate air (HEPA) filter that is followed by dual, cylindrical packed carbon beds whereby the inlet airflow splits and effectively flows through the two beds in parallel, then combine within the filter housing to form a single outlet flow of clean air. This filter design is configured such that the unit is oriented in a vertical manner. An annotated photograph depicting the main components of the filter and general flow path is shown in Figure One. (The internal split of the airflow through the two beds is not depicted.)

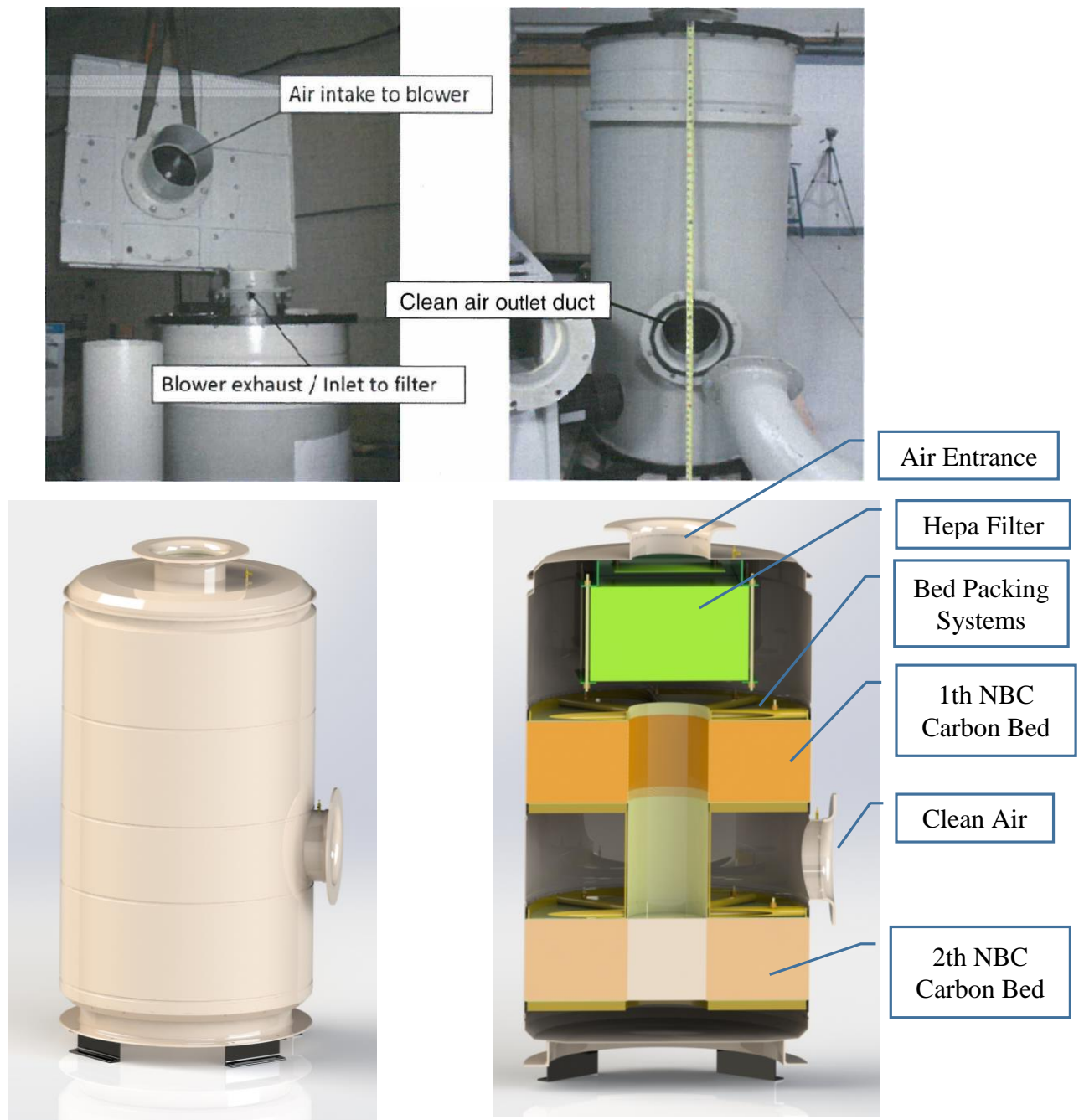


Figure One. Photograph of Vertically Oriented Filter as Received (with Blower Mounted atop the Filter Housing)

Note, the filter was accompanied with a blower, but it was not affixed to the filter housing when received. By inspection of the flow path, the blower was mounted upstream of the filter (as shown in Figure 1) to push contaminated air through the filter and deliver clean air out the side discharge port, which is consistent with its understood use. Also, the blower motor can be operated with either 50 or 60 Hz alternating current. The input voltage range to the blower is 440 to 500 VAC when wired for the Y-configuration, which is the configuration in which it was received. The motor was operated with 50 Hz because that is the expected input it will receive in its installed operation.

2.2 Filtration System Performance Assessment

System performance characterization comprised assessment of the intact, whole-filter while contained within the filtration system and carbon gas life adsorbent recovered from each filtration unit. The airflow rate (Q), airflow resistance (AP), and aerosol filtration efficiency (q) of the whole filter were measured while operating within the complete filtration system. After which, the filtration systems were disassembled to recover granular carbon adsorbent for gas life measurements. (Assessment of the carbon with respect to gas life is a destructive test and therefore requires the carbon to be recovered and tested in small diameter (4.0 cm diameter) carbon test beds with a carbon depth equal to that in the filter.) Samples of the loose carbon were tested for gas life (i,) using airflow conditions equivalent to that which would be experienced in the filter.

Details of the test procedures to measure airflow rate, airflow resistance, aerosol filtration efficiency, and carbon gas life are summarized below.

2.2.1 Whole-Filter Performance Tests

Filtration systems were operated at their rated voltage input and 50 Hz electrical service. Ambient indoor air comprised the make-up to flow through the filter, and as such, the temperature (T) was $23 \pm 3^{\circ}\text{C}$ and relative humidity (RH) was $40 \pm 10\%$. Ambient air temperature and relative humidity was measured, but not controlled, during the whole-filter test.

A schematic of the test system for whole-filter performance tests is shown in Figure two

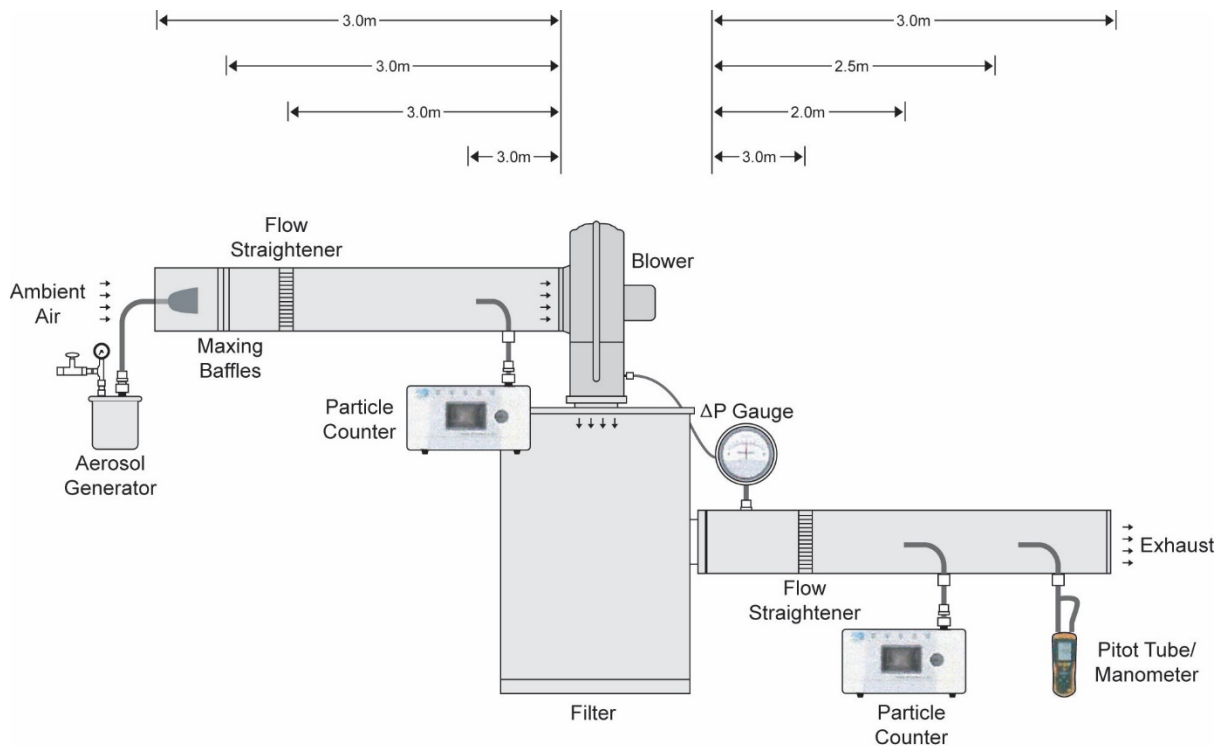


Figure Two . Schematic of Whole-Filter System Aerosol Filtration and Airflow Resistance Test Fixture (Vertical Filtration System Shown)

Pressure taps located at the blower exhaust and outlet airflow duct were connected to a Series 477 Digital Manometer (Dwyer Instruments, Inc., Michigan City, IN) to measure the pressure drop (airflow Resistance) across the filter. The pressure differential across the filter was measured independently three times. For each measurement, the blower was initially off, turned on and allowed to reach steady flow (stable blower Speed.)

A traverse pitot tube array (Series DS-400 Flow Sensor, Dwyer Instruments, Inc., Michigan City, IN) was located 0.5 m upstream from the distal end of the downstream duct to measure the volumetric airflow rate. The traverse pitot tube array is factory calibrated to convert the velocity pressure created by the airflow in the duct to a volumetric airflow rate. This measurement method is a common approach and practice used in the HVAC and chemical processing industry.

The aerosol collection efficiency was measured using a test method based on established filter test methods used in industry for HEPA filter testing for air purification in applications such as respiratory protection, emissions control and/or indoor air quality. The test aerosol for filtration efficiency testing was polyalpha olefin (PAO) oil, an inert test aerosol that is commonly used in place of dioctyl phthalate (DOP) in filtration test methods. The challenge aerosol size was predominantly between 0.1 and 0.3 μm on a count basis with a count median diameter within that range, also. The target challenge aerosol median size of 0.1 to 0.3 μm is within the range of the generally accepted most penetrating particle size (MPPS) for HEPA filters and consistent with common industry standards for testing filter efficiency.

The aerosol generator was an oil aerosol generator (Part No. 1080604, TSI, Inc., Shoreview, MN) that is designed to produce a $\sim 0.2 \mu\text{m}$ CMD aerosol of PAO for filter testing applications. The measured

number size distribution was measured using a Scanning Mobility Particle Sizer (SMPS, TSI, Inc., Shoreview, MN).

The primary instrument to quantify aerosol concentration for filtration efficiency measurements was the DustTrak™ II (Model 8530, TSI, Inc., Shoreview, MN). The DustTrak™ II is a light scattering laser photometer that measures the total aerosol mass concentration of particles ranging from 0.1 to 10 µm and such instruments are commonly used for filtration efficiency measurements of this type. It can measure aerosol mass concentrations ranging from >100 mg/m³ to 0.001 mg/m³, giving it the dynamic range needed to measure HEPA filtration efficiency. Samples collected upstream and downstream of the filter were used to quantify fractional penetration (P), calculated as the ratio of challenge aerosol concentration measured downstream of the filter (C_D) to the particle number concentration measured upstream of the filter (C_U), as shown in Equation 1. Similarly, fractional collection efficiency, $1 - P$, will be calculated.

$$\text{Equation 1. } P = \frac{C_D}{C_U}$$

The percent penetration is obtained by multiplying the fractional penetration by 100%. The aerosol filtration efficiency (η) is given by:

$$\text{Equation 2. } \eta = (1 - P) \times 100\%$$

2.2.2 Carbon Gas Life Tests

Carbon was recovered from throughout the bed depth and various points along the circumference of the vertical filtration system. (It was assumed that the carbon in the two beds of the vertically-oriented system are the same, and because of ease of access (without physically destroying the filter) carbon was recovered from the top bed only.) All carbon recovered from the filter was stored in a sealed container to minimize uptake of moisture or other trace organics present in the ambient air. The carbon container was retained in a laboratory or storage room maintained at room temperature.

The measured bed depth of the vertical filter was 20.3 cm (depth of a single bed since the two beds function in parallel). The available cross-sectional surface area available for the airflow to pass was 8,800 cm² for the vertical filter systems. The measured volumetric airflow rate was 980 m³/hr (580 CFM) through the vertical filter. Based on those measured airflow rates and cross-sectional areas, the equivalent airflow velocity to match in the loose carbon tube tests was 31 and 36 cm/s, which corresponds to a target volumetric airflow rate through the loose carbon bed tubes of 23 and 27 L/min.

The carbon gas life was measured for nine test vapors/gases at the target test conditions summarized in Table 1. The test chemicals represent a range of chemical classes such as organic vapors, acid gases, halogens, basic gases, and hydrides so that the performance can be assessed over a broad range of potential chemicals of

interest. Humidity is known to often affect, beneficially and adversely, depending on the adsorbent/adsorbate interaction, performance and thus dry and humid conditions are included in the matrix. (Humid conditions are not included for hydrochloric acid and chlorine gases because of the gas phase interactions at humid conditions.) The challenge concentrations in Table 1 are within the range of concentrations used within industry for various air purification applications, which vary across countries and intended applications. The general concept was to test using concentrations that yielded a test that concluded within a reasonable test duration (< 6 hrs). Likewise, the breakthrough concentration for each test gas can be different for different standards and applications, but those used here are within a range found within the air purification industry for various applications. They often are concentrations in the range associated with little or no adverse health effect.

Table 1. Carbon Gas Life Test Matrix and Conditions

Test Gas	Target [Challenge] (mg/m ³)	[Breakthrough] (mg/m ³)	Relative Humidity (%) Precond ^(a) /Test	Replicates
Ammonia (NH ₃)	1,750 ± 175	9	AR/15	3
			80/80	3
Chlorine (Cl ₂)	2,000 ± 200	1.5	AR/15	3
Cyanogen Chloride (CK)	750 ± 75	5	AR/15	3
			80/80	3
Cyclohexane	8,930 ± 900	34	AR/15	3
			80/80	3
Hydrogen Chloride (HCl)	2,000 ± 200	7	AR/15	3
Hydrogen Cyanide (AC)	1,040 ± 100	5.2 (AC + NCCN)	AR/15	3
			80/80	3
Hydrogen Sulfide (H ₂ S)	1,390 ± 140	7	AR/15	3
			80/80	3
Phosphine (PH ₃)	420 ± 42	0.4	AR/15	3
			80/80	3
Sulfur Dioxide (SO ₂)	3,930 ± 390	13	AR/15	3
			80/80	3

^(a) Preconditioned for at least 6 hrs at specified humidity and T = 23±3°C; AR = as-received and requires no preconditioning; T = 23 ± 3°C for all tests and preconditioning.

Q = 23 L/min, equivalent superficial velocity of 31 cm/s experienced at rated flow and carbon volume in vertical filter.

Tests were performed in triplicate for each of the unique test conditions (sixteen unique test conditions exist) specified in Table 1. The carbon gas life was measured by filling cylindrical tubes with a 4.0 cm inner diameter with carbon recovered from the whole filter to a bed depth equivalent to that in the whole filter. Consequently, the test matrix in Table 1 was repeated for carbon recovered from filter with the bed depth and airflow velocities unique to their respective filter. A representative schematic of the basic carbon gas life test system is shown in Figure Three.

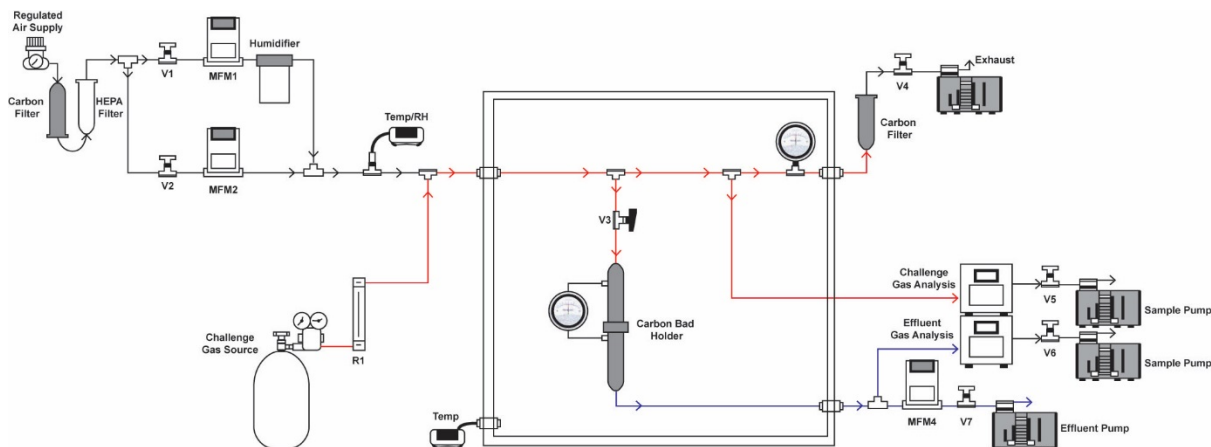


Figure Three. Diagram of the Nominal Test System used for Gas Life Testing

Nominally, the maximum planned test duration was 360 min. If breakthrough was not detected within 360 min, the test was halted and the gas life reported as >360 min. The reason the tests were stopped before Breakthrough was measured in these instances was that testing cannot operate unattended, and in some cases, cannot be conducted outside of normal business hours for safety considerations.

Each sample was weighted to the nearest 1 g. Since the packing density was not known, the carbon Mass required to fill a carbon bed with 20.3 or 8.8 cm bed depth was determined prior to breakthrough testing. The carbon was loaded into the filter holder using a “snow storm” method to uniformly distribute the carbon in He holder.(The carbon is gravity fed through a series of wire meshes to randomize the filling of the bed resulting In a uniform distribution throughout the bed.)

All test gases, except cyclohexane and hydrogen cyanide, were generated by bleeding a controlled flow From a compressed gas cylinder that then was diluted with environmentally conditioned air. Liquid cyclohexane And hydrogen cyanide were evaporated at a constant rate and mixed with environmentally controlled dilution air To generate the challenge concentration. Control of generation and dilution flow rates were used to achieve the Target concentration.

The analytical methods for the challenge and effluent depended on the challenge gas, challenge Concentration, and breakthrough (carbon bed effluent) concentration. Analysis by direct gas sensing, near real-time was completed for all the chemicals. A gas chromatograph (GC) equipped with a flame ionization detector (FID), electron capture detector (ECD), or flame photometric detector (FPD) was used for cyanogen chloride, Cyclohexane, hydrogen cyanide, hydrogen sulfide, and phosphine. Method runtime for GC analysis chemical Dependent, but a concentration measured was made typically every 3 to 5 min. The challenge and effluent Ammonia concentrations were measured continuously in real-time using MIRAN® SapphIRe infrared analyzer (Thermo Scientific, Waltham, MA), one instrument dedicated to the challenge and one for the effluent.

Electrochemical cells (Draeger MiniWarn® and Honeywell EC-P2) were used for chlorine and hydrogen Chloride. A real-time ultraviolet(UV)analyzer (Model921, Ametek Process Instruments, Calgary, Alberta) was

used for SO₂.

Per the test matrix, preconditioning of the carbon at the environmental conditions of the gas life test was required for some samples (i.e., those tested at 80/80). Carbon samples were preconditioned with humidified air (T = 23 ± 3° C, flow rate of 23 L/min for the carbon from the vertical filter and conditioning duration was at least 6 hr.

The measured gas life analysis calculated arithmetic averages and standard deviations of the three replicates for the breakthrough times to give an indication of the reproducibility. Arithmetic average of the equally-spaced challenge concentration measurements was calculated to obtain the average challenge concentration. Similarly, the average temperature and relative humidity were calculated and reported.

The breakthrough time was obtained directly from the effluent concentration time plot. When a GC was used to quantify the effluent gas concentration, the breakthrough time was determined by interpolating between the time of sample collected immediately preceding and proceeding the breakthrough concentration.

Since the breakthrough time is directly dependent upon the challenge concentration and the average challenge concentration varied within the acceptable target range, the breakthrough time was normalized based on the average challenge concentration by the relationship:

$$t'_{\text{breakthrough}} = t_{\text{breakthrough}} * \left(\frac{C_{\text{chal}}}{C_{\text{Target}}} \right)$$

Where $t'_{\text{breakthrough}}$ = normalized breakthrough time; $t_{\text{breakthrough}}$ is the measured breakthrough time; C_{chal} is the average challenge concentration measured; and C_{Target} is the target challenge concentration. This normalization allows a more accurate comparison of the replicates.

3.0 RESULTS

The measured average delivered airflow rate, airflow resistance, and aerosol filtration efficiency are:

- $Q = 980 \text{ m}^3/\text{hr}$ (580 CFM)
- $AP = 11 \text{ iwg}$
- $\eta = 99.7 \%$

The measured aerosol filtration efficiency is less than that required of a HEPA filter but it should be noted that careful inspection of the filter uncovered damage to the HEPA filtration medium. The damage, evident only with careful inspection, occurred prior to the system's delivery to Battelle. The initial filtration efficiency measurement was made prior to removing the HEPA filter to access carbon for gas life testing.

The measured carbon gas life for all sixteen test conditions given in the test matrix of Table 1 are summarized in Table 2 along with the average measured test conditions.

A few comments regarding the measured gas lives are appropriate to fully describe the results.

- Several gas and test conditions resulted in the test being stopped before breakthrough was detected.
 - In all cases, those results are represented with the ">" prefix. For these the average and standard deviation were not calculated. Rather, the minimum measured gas life of the three replicates is reported.
 - Some of those tests were operated as long as could safely be operated within a normal working day. Hence, the reported ">" value sometimes exceeds 360 min.
- There were cases when the measured gas life exceeded 360 min because those tests were able to run longer to completion before having to stop for safety purposes.
- The measured gas life for phosphine is correctly reported for the 80/80 % RH condition. In all three replicates, phosphine was detected downstream of the carbon bed immediately after the start of challenge phosphine gas. In the first two trials, it was temporarily (<10 min) above the breakthrough criterion of 0.4 mg/nr on the initial effluent sample analysis and then continued to drift below the 0.4 mg/nr criterion, but then gradually increased to above the breakthrough criterion. In those instances, the reported gas life is when the effluent exceeded breakthrough concentration during the gradual increase in effluent concentration. Otherwise, those two tests would have a breakthrough time of <3 min. In the third trial, phosphine was detected immediately; however, it was below ($\sim 0.2 \text{ mg/m}^3$) the breakthrough concentration. The effluent concentration gradually decreased to approximately 0.06 mg/m^3 after 60 min, then very gradually increased to the breakthrough concentration at 139 min. This behavior of gradual decrease at the onset of testing and then gradual increase in effluent concentration had a relatively large effect on reported gas life.

Table 2. Measured Individual and Average Gas Life and Average Test Conditions for the Carbon Recovered from the Vertical Filtration System

Chemical	Target [Chal] (mg/m ³)	Target RH (%)	Sample ID	Avg T (°C)	Avg RH (%)	Avg [Chal] (mg/m ³)	t _b ¹ (min)	Avg t _b ^{1,2} (min)
Ammonia	1,750 ± 175	AR/15	V-NH3-15-T01	21	18	1,900	38	36 ± 2
			V-NH3-15-T02	22	16	1,900	35	
			V-NH3-15-T03	22	16	1,900	35	
		80/80	V-NH3-80-T01	23	78	1,900	31	31 ± 1
			V-NH3-80-T02	21	79	1,700	30	
			V-NH3-80-T03	22	81	1,800	32	
Chlorine	2,000 ± 200	AR/15	V-CL2-15-T01	25	17	2,100	170	171 ± 2
			V-CL2-15-T02	26	14	2,100	169	
			V-CL2-15-T03	26	16	2,100	174	
Cyanogen Chloride	750 ± 75	AR/15	V-CK-15-T01	24	17	730	>374	>361
			V-CK-15-T02	24	13	760	>361	
			V-CK-15-T03	24	13	760	>361	
		80/80	V-CK-80-T01	25	78	740	>369	>369
			V-CK-80-T02	24	79	750	>391	
			V-CK-80-T03	24	79	750	>391	
Cyclohexane	8,930 ± 900	AR/15	V-CYC-15-T01	22	17	8,600	66	67 ± 3
			V-CYC-15-T02	22	17	8,700	64	
			V-CYC-15-T03	22	17	8,700	70	
		80/80	V-CYC-80-T01	23	81	8,500	<3	<3
			V-CYC-80-T02	23	81	7,800	<3	
			V-CYC-80-T03	23	80	8,400	<3	
Hydrogen Chloride	2,000 ± 200	AR/15	V-HCl-15-T01	25	15	2,000	431	>420
			V-HCl-15-T02	25	15	2,000	420	
			V-HCl-15-T03	25	15	2,000	>480	
Hydrogen Cyanide	1,040 ± 100	AR/15	V-AC-15-T01	24	14	990	226	235 ± 14
			V-AC-15-T02	23	16	1,100	251	
			V-AC-15-T03	23	16	1,100	229	
		80/80	V-AC-80-T01	25	76	1,000	210	219 ± 8
			V-AC-80-T02	25	76	1,000	225	
			V-AC-80-T03	24	80	1,000	221	
Hydrogen Sulfide	1,390 ± 140	AR/15	V-H2S-15-T01	24	16	1,400	>396	>378
			V-H2S-15-T02	24	15	1,400	>390	
			V-H2S-15-T03	24	14	1,400	>378	
		80/80	V-H2S-80-T01	24	79	1,400	>360	>333
			V-H2S-80-T02	24	80	1,400	333	
			V-H2S-80-T03	24	81	1,400	379	
Phosphine	420 ± 42	AR/15	V-PH3-15-T01	22	16	420	360	402 ± 59
			V-PH3-15-T02	22	16	420	377	
			V-PH3-15-T03	22	16	450	469	
		80/80	V-PH3-80-T01	22	83	430	93	119 ± 23
			V-PH3-80-T02	22	82	460	125	
			V-PH3-80-T03	22	80	410	139	
Sulfur Dioxide	3930 ± 390	AR/15	V-SO2-15-T01	21	17	3,500	67	67 ± 2
			V-SO2-15-T02	23	17	3,600	69	
			V-SO2-15-T03	23	17	3,700	64	
		80/80	V-SO2-80-T01	22	80	3,600	82	90 ± 7
			V-SO2-80-T02	23	80	3,600	95	
			V-SO2-80-T03	23	81	3,600	92	

¹ Breakthrough time normalized to the target challenge concentration.

² Average of three trials at specific condition; ± indicates value of one standard deviation.



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