



**US Army Corps
of Engineers®**
Engineer Research and
Development Center

ERDC
INNOVATIVE SOLUTIONS
for a safer, better world

Laboratory Evaluation of Stainless Steel Filters for Control of Particulate Emissions

Veera M. Boddu, Jessica A. Gilmer, and K. James Hay

June 2011



The US Army Engineer Research and Development Center (ERDC) solves the nation's toughest engineering and environmental challenges. ERDC develops innovative solutions in civil and military engineering, geospatial sciences, water resources, and environmental sciences for the Army, the Department of Defense, civilian agencies, and our nation's public good. Find out more at www.erdcl.usace.army.mil.

To search for other technical reports published by ERDC, visit the ERDC online library at <http://acwc.sdp.sirsi.net/client/default>.

Laboratory Evaluation of Stainless Steel Filters for Control of Particulate Emissions

Veera M. Boddu, Jessica A. Gilmer, and K. James Hay

*Construction Engineering Research Laboratory (CERL)
US Army Engineer Research and Development Center
2902 Newmark Dr.
Champaign, IL 61822-1076*

Final Report

Approved for public release; distribution is unlimited.

Prepared for Headquarters, US Army Corps of Engineers
Washington, DC 20314-1000

Under Work Unit 7360D7

Abstract

This research developed a method to control particulate emissions from Army demilitarization furnaces by developing high temperature filters capable of capturing particulate emissions, including the heavy metal PM_{2.5}. Custom manufactured stainless steel filters were evaluated in a filter test setup based on American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and American Society for Testing and Materials (ASTM) standard protocols used to characterize flat panel filters. Experimental studies using an in-house testing system on pressure drop versus flow rate, particle penetration, and dust holding capacity were performed for each filter. Experimental results showed that, as the quantity of dust increases, pressure drop increases linearly. In the presence of dust, a cake layer forms reducing effective pore size and therefore increasing the filter efficiency. Preliminary results showed that these filters offer a reusable, easily cleanable, cost-effective, and compact particulate filtration system for the Army mobile and stationary combustion systems. Future research is recommended to determine compatibility of the filter material to the operating temperature, pressure, air superficial velocity, and other physicochemical conditions, and whether modifying the filter system by coating with adsorbent material and tack polymers may enhance the separation of metals and other fine particulates.

Executive Summary

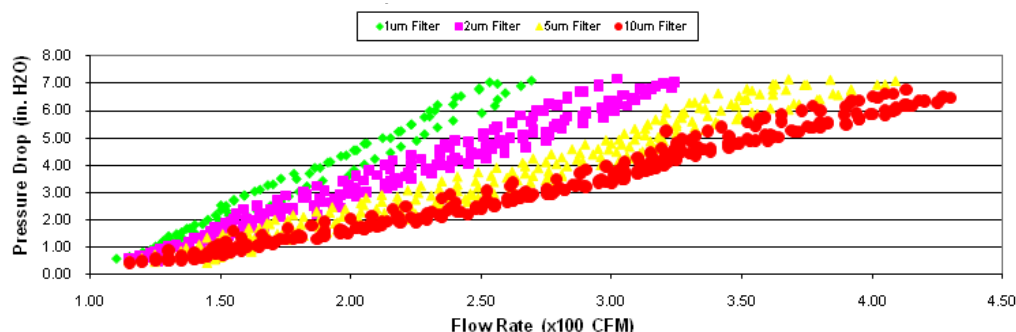
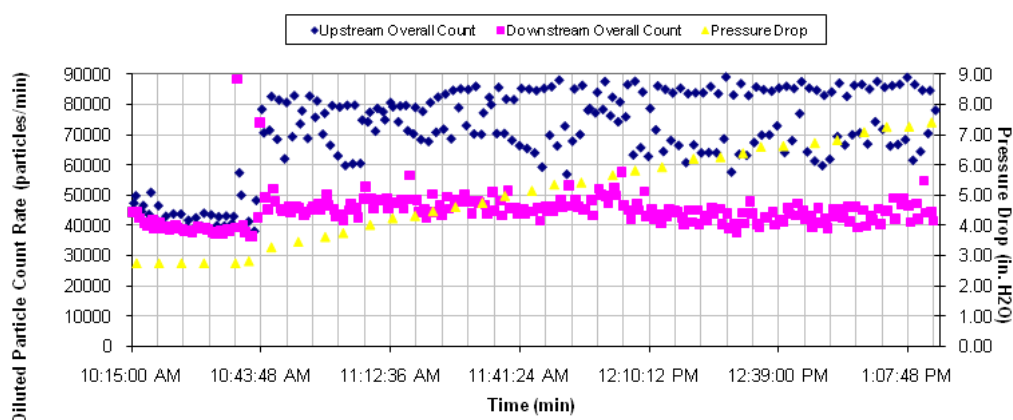
The Army operates and maintains deactivation furnaces for demilitarization operations. These furnaces are subject to the National Emission Standards for Hazardous Air Pollutants (NESHAP) published by the US Environmental Protection Agency in September 1999. The NESHAP include reduction in lead and mercury emissions among various other volatile and semi-volatile metals and toxic organic compounds. For existing incinerators and chemical demilitarization furnaces (CDFs), the lead and cadmium emissions are not to exceed 240 micrograms/dry standard cubic meter ($\mu\text{g}/\text{dscm}$). For new incinerators, the compliance standard is set at 24 $\mu\text{g}/\text{dscm}$. The flue gases released from these facilities are detrimental to the environment and human health. Developing control technologies allows for the use of proven chemical processes while achieving compliance.

The Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) is focused on developing high temperature filters capable of capturing particulate emissions including $\text{PM}_{2.5}$. Custom manufactured stainless steel filters (20-in. diameter) with nominal pore sizes of 1, 2, 5, and 10 microns (μm) are being evaluated in a filter test setup based on standard protocols used to characterize flat panel filters. The purpose of conducting in-place filter testing by this method is to determine penetration of multi-stage installations without individual stage tests. The method and equipment used here can be extended to evaluate filter cloths and materials used in baghouses, respirators and personal protective clothing.

American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) Standard 52.1 states that filter evaluation requires data on efficiency, resistance, dust holding capacity, and the effect of dust loading on efficiency and resistance. Using an in-house testing system, experimental studies on pressure drop versus flow rate, particle penetration and dust holding capacity were performed for each filter.

The pressure drop study is completed on each stainless steel filter by increasing the flow rate step-wise to a maximum operating pressure of 8 in. H_2O (Figure ES1). Air samples upstream and downstream of the filter were analyzed using a Micro laser particle counter to calculate penetration efficiency.

Figure ES1. Pressure drop vs. flow rate for all filters.

Figure ES2. Overall particle count from 0.1–1.5 μm .

DHC test 10-250-3 @ 250 CFM 29Jul03

Figure ES2 represents a typical penetration test performed at a flow rate of 250 cu ft/min (cubic feet per minute, CFM; volumetric flux = 0.582 m/s) using the 10- μm filter showing all particle sizes. Similar graphs are prepared for each of the eight particle size ranges and filter efficiency values are calculated for each (Figure ES2).

When testing the dust loading capacity, ASHRAE standard test dust (72% Arizona road dust, 23% Carbon Black, and 5% cotton lintens) is fed into the system using a hopper, and the mass of the dust collected by the filter is measured. The pressure drop (seen in Figure ES2 represented in yellow) was measured throughout this experiment to determine the effect of dust loading on resistance.

Experimental results show that, as the quantity of dust increases, pressure drop increases linearly. In the presence of dust, a cake layer forms that reduces the effective pore size, which therefore increases the filter efficiency. Based on the preliminary results, these filters offer a reusable, easily cleanable, cost-effective, and compact particulate filtration system for the Army mobile and stationary combustion systems.

Contents

Abstract	ii
Executive Summary	iii
Illustrations	vi
Preface	vii
Unit Conversion Factors	viii
1 Introduction	1
1.1 Background	1
1.2 Objective	2
1.3 Approach	2
1.4 Mode of technology transfer	2
2 Air Filter Testing Plan	3
2.1 Summary of test method	3
2.2 Dust holding capacity test	3
2.3 Equations for particle penetration	4
2.4 Summary of air filter testing plan	6
3 Experimental Setup	8
3.1 Operation of the MYSTAIRe Waterweb Unit	10
3.2 Start-up sequence of the filter test unit	10
3.3 Overview and operation of LAS	11
3.4 Test filter information	13
4 Experimental Procedure	14
4.1 Overview of pressure drop versus flow rate measurement	14
4.2 Overview of dust holding capacity test	15
4.3 Overview of cleaning procedure	16
5 Results	18
5.1 Determining pressure drop versus flow rate correlation	18
5.2 Dust holding capacity test results for 1- μ m filter	18
5.3 Dust holding capacity test results for 2- μ m filter	20
5.4 Dust holding capacity test results for 5- μ m filter	20
5.5 Dust holding capacity test results for 10- μ m filter	23
6 Conclusions and Recommendations	26
References	27
Glossary	28
Acronyms and Abbreviations	29
Nomenclature	30
Report Documentation Page (SF 298)	31

Illustrations

Figures

ES1	Pressure drop vs. flow rate for all filters	iv
ES2	Overall particle count from 0.1–1.5 μm	iv
1	Generalized particle deposition model	5
2	Schematic of air filter testing setup	9
3	Engineering drawing of the skid-mounted MYSTAIRES [®] Waterweb Compact Scrubber	9
4	Comparison of flow rate versus pressure drop data for 1-, 2-, 5-, and 10- μm filters.....	19
5	Efficiency results for 1- μm filter (Experiment 1-150-1).....	19
6	Pressure drop versus flow rate data and particle count data for 1- μm filter pre- and post-dust holding capacity test (Experiment 1-150-1)	20
7	Efficiency results for 2- μm filter (Experiment 2-150-3).....	21
8	Pressure drop versus flow rate data and particle count data for 2- μm filter pre- and post-dust holding capacity test (Experiment 2-150-3)	21
9	Efficiency results for 5- μm filter (Experiment 5-150-2).....	22
10	Efficiency results for 5 μm filter (Experiment 5-150-3).....	22
11	Pressure drop versus flow rate data and particle count data for 5- μm filter pre- and post-dust holding capacity test (Experiment 5-150-3)	23
12	Efficiency results for 10- μm filter (Experiment 10-250-3)	24
13	Efficiency results for 10 μm filter (Experiment 10-150-1)	24
14	Pressure drop versus flow rate data and particle count data for 10- μm filter pre- and post-dust holding capacity test (Experiment 10-150-1).....	25

Preface

This study was conducted for Headquarters, US Army Corps of Engineers (HQUSACE) under Program Element 622720, “Environmental Quality Technology.” The technical reviewer was Dr. K. James Hay, CEERD-CN-E

The work was performed by the Environmental Processes (CN-E) Branch of the Installations Division (CN), Construction Engineering Research Laboratory (CERL). The CERL Principal Investigator was Dr. Veera Mallu Boddu. At the time of publication, Michael Kemme was Acting Chief, CN-E and Dr. John T. Bandy was Chief, CN. The associated Technical Director was Alan Anderson. The Deputy Director of CERL is Dr. Kirankumar V. Topudurti, and the Director is Dr. Ilker R. Adiguzel.

CERL is an element of the US Army Engineer Research and Development Center (ERDC), US Army Corps of Engineers. The Commander and Executive Director of ERDC is COL Kevin J. Wilson, and the Director of ERDC is Dr. Jeffery P. Holland.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic inches	0.00001638706	cubic meters
degrees Fahrenheit	$(5/9) \times (^\circ\text{F} - 32)$	degrees Celsius
degrees Fahrenheit	$(5/9) \times (^\circ\text{F} - 32) + 273.15$	kelvin
feet	0.3048	meters
inches	0.0254	meters
square feet	0.09290304	square meters

1 Introduction

1.1 Background

The US Army operates and maintains incinerators for demilitarization operations. These incinerators are subject to the National Emission Standards for Hazardous Air Pollutants (NESHAP) published in 1999 by the US Environmental Protection Agency (USEPA). The Hazardous Waste Combustor (HWC) NESHAP includes reduction in lead and mercury emissions among various other volatile and semi-volatile metals and toxic organic compounds (e.g., hazardous air pollutants [HAPs] and volatile organic compounds [VOCs]). Army demilitarization facilities need to comply with the HWC NESHAP, which, according to the Army Environmental Center, affects at least 16 Army demilitarization furnaces.

For existing incinerators and chemical demilitarization furnaces (CDFs), the total lead and cadmium emissions are not to exceed 240 micrograms/dry standard cubic meter ($\mu\text{g}/\text{dscm}$). For new incinerators the compliance standard is set at 24 $\mu\text{g}/\text{dscm}$. Similarly, the emission standard for mercury was reduced from 130 $\mu\text{g}/\text{dscm}$ for existing facilities to 45 $\mu\text{g}/\text{dscm}$ for new incinerators. These metals are often present in the form of aerosol particulate materials (e.g., $\text{PM}_{2.5}$) and are difficult to capture even with the conventionally effective technologies such as electrostatic precipitators. The new lower limits are difficult to achieve without adding new control equipment or developing/modifying the existing treatment trains. Therefore, the focus of this effort is to identify, evaluate, and develop promising emission control technologies for Army HWCs. The results of the proposed study provide technical information required for the program management committee to make technically sound decisions in selecting a compliance technology and associated emission control equipment.

HAP and VOC emission control is high priority among US Department of Defense (DOD) facilities since Army incinerators, CDFs, boiler units, and other HWC are subject to the new USEPA regulations. Other power generation units with coal burning boilers will be affected by another NESHAP. This proposed action plan also addresses the Army Environmental Compliance User Requirement A.(2.1.g) Hazardous Air Pollutants and Volatile Organic Compounds Emission Control. The Army will need to be prepared

to meet these regulatory requirements. Developing control technologies will allow for the use of proven chemicals and processes while achieving compliance.

1.2 Objective

The objective of this research was to determine a method to control particulate emissions from Army demilitarization furnaces. The US Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) is focused on developing high temperature filters capable of capturing particulate emissions, including the heavy metal PM_{2.5}.

1.3 Approach

Custom manufactured stainless steel filters (20-in. diameter) with nominal pore sizes of 1, 2, 5, and 10 microns (μm) were evaluated in a filter test setup based on ASHRAE and American Society for Testing and Materials (ASTM) standard protocols used to characterize flat panel filters. The purpose of conducting in-place filter testing by this test method was to determine penetration of multi-stage installations without individual stage tests. The test method and equipment used here can be extended to evaluate filter cloths and materials used in baghouses, respirators, and personal protective clothing.

1.4 Mode of technology transfer

This report will be made accessible through the World Wide Web (WWW) at URL: <http://libweb.erdclib.usace.army.mil>

2 Air Filter Testing Plan

This test plan provides a detailed approach for obtaining technical information on the filters. The experimental tests are based on ASTM test method F1471 and the methods described in the ASHRAE Handbook (2000). These tests included the Dust Holding Capacity Test and the Particle Size Removal Efficiency/Penetration Test.

2.1 Summary of test method

A challenge aerosol produced using polystyrene latex (PSL) is typically injected upstream of the filter system and allowed to mix with the clean air stream. After testing this method it was determined that, when using ambient coarse-filtered air, such PSL beads minimally increase the particle count and do not influence the effectiveness of the filter. For the ERDC-CERL setup, it was determined that using ambient coarse-filtered air can replace the traditional method with unaltered results and lower operational costs. Samples of the air were collected through probes, both upstream and downstream of the filter system.

Using a laser aerosol spectrometer (LAS), the air samples were analyzed to determine penetration for discrete particle sizes. Particle penetration as low as 10^{-8} can be measured by this test method. The penetration of the filter system can be calculated either as a function of particle size or in a particular size of interest. Dilution of the air stream was necessary because the upstream particulate concentration reached levels above the maximum countable value for the LAS. The dilutor must be calibrated appropriately. The dust holding capacity of the filter was evaluated by following the pressure drop as a function of time, composition, and mass balances between successive cleaning of a filter.

2.2 Dust holding capacity test

The pressure drop across the filter and its resistance to flow rises with time as dust is fed into the waste stream. The dust holding capacity test is normally terminated when the resistance reaches the maximum operating resistance set by the manufacturer. Not all filters of the same type retain collected dust equally well, however. The test therefore requires that arrestance be measured at least four times during the dust loading process

and that the test be terminated when two consecutive arrestance values of less than 85%, or one value equal to or less than 75% of the maximum arrestance have been measured (ASHRAE). The ASHRAE dust holding capacity is, then, the integrated amount of dust held by the filter up to the time the dust loading test is terminated. Various parameters that influence the dust holding capacity are:

1. Filter area to gas flow (A/G) ratio
2. Dust particulate concentration in the gas
3. Filter loading
4. Cleaning duration and frequency
5. Temperature
6. Particle size
7. Pressure drop.

The pressure drop, ΔP , in the filter may be estimated by:

$$\Delta P = S_E V + K_2 C_i V^2 t \quad (1)$$

where:

- S_E = effective residual drag of the filter
- V = velocity
- K_2 = specific resistance coefficient of the dust
- C_i = concentration of the dust in the gas stream
- t = filtration time.

The specific resistance coefficient, K_2 , is a characteristic of the dust and should be measured for a given particulate stream. Similarly, the drag is a property of the filter, which may be obtained from the manufacturer or can be measured. In this setup, the pressure drop across the filter is simply measured by a Dwyer Photohelic gauge capable of measuring 0–10 inches of water (in. of H_2O) with an accuracy ± 0.1 in. of H_2O . As can be concluded from equation (1), the pressure drop across the filter increases with time as the dust builds up in the filter.

2.3 Equations for particle penetration

The equations for determining particle penetration are derived (Calvert and Englund 1984) in terms of the variables:

- u_g = gas velocity, cm/sec
- L = collector length, cm
- H_f = flow stream height, cm

u_d = deposition velocity, cm/sec

W = flow stream width

Q = volumetric flow rate = $u_g H_f W$

n = particle concentration averaged across a plane normal to the flow, cm^{-3}

n_d = particle concentration at deposition plane, cm^{-3}

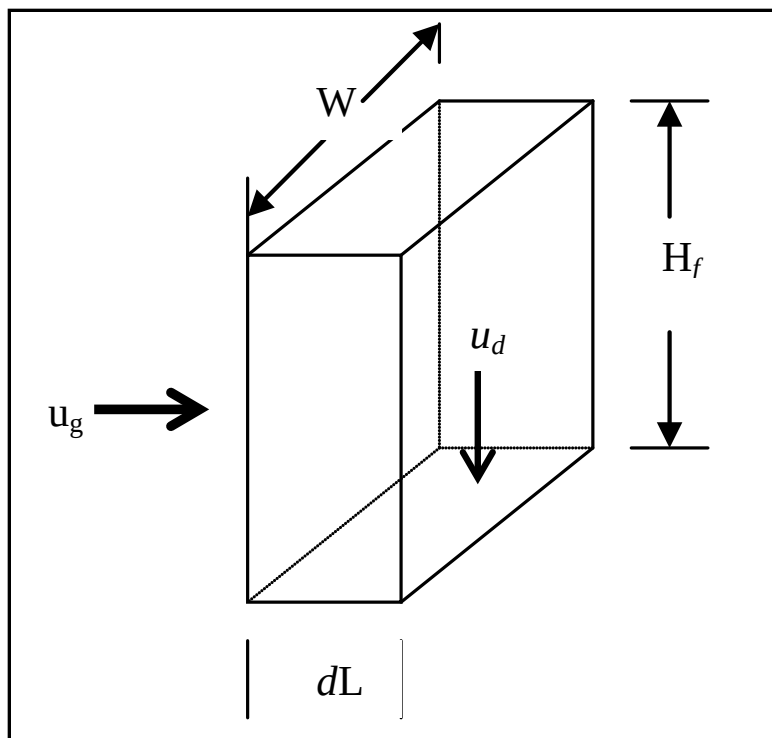
Figure 1 shows a generalized particle deposition model based on the equations for determining particle penetration.

The particle collection can be estimated under two situations: (1) no mixing of particles normal to the flow axis in the gas stream, and (2) complete mixing. When there is no mixing, n_d remains constant at n (inlet concentration) until it abruptly becomes zero.

The likelihood that a particle may penetrate through the filter is referred to as penetration, P_t , which is calculated as $P_t = 1 - \eta$. The filter penetration efficiency, P_η , expressed in percent is;

$$P_\eta = 100 \left[\frac{\text{Downstream concentration}}{\text{Upstream concentration}} \right] \quad (2)$$

Figure 1. Generalized particle deposition model.



This expression suggests that measurements required for obtaining the penetration are only upstream and downstream particle concentrations, which are measured by light-scattering photometer or by a laser particle counter.

$$\eta = \frac{n_{in} - n_{out}}{n_{in}} \quad (3)$$

The ability to collect particles is usually expressed in terms of an efficiency of collection, η , the fraction of entering particles that are retained by the filter. This efficiency can be expressed either in terms of particle (or count) collection efficiency, η , or mass collection efficiency, η_m . The latter refers to the fraction of the entering mass that is retained by the filter. Generally, mass efficiency is higher than count efficiency.

2.4 Summary of air filter testing plan

The tests included both the Dust Holding Capacity Test and Particle Size Removal Efficiency/Penetration Test. The initial installation and calibration of various components followed the procedures described in the equipment manual. These calibration tests included:

1. LAS calibration
2. Aerosol Dilutor
3. Aerosol Mixing Uniformity Tests
4. Airflow velocity
5. Temperature
6. Pressure measurement.

The calibrations were performed according to ASTM test method F1471 (ASTM 2009). To calculate the penetration of the filter system for each discrete particle size, the equation holds for each specific particle size diameter as:

$$P = \left[\frac{C_d - C_b}{C_u D} \right] \quad (4)$$

where:

- P = penetration
- C_d = particle counts downstream
- C_b = particle counts background
- C_u = particle counts upstream, and
- D = dilution ratio

To calculate the uncertainty of the upstream and downstream penetration measurements, a theoretical value (based on standard propagation-of-error techniques neglecting covariance terms and using Poisson statistics to estimate uncertainties) was used in the following equation:

$$CV_p = [(PNT_d)^{-1} + (D/(NT_u)) + CV_D^2]^{1/2} \quad (5)$$

where:

CV_p = coefficient of variation for penetration,

P = aerosol penetration

N = undiluted upstream count rate, counts/s

T_d = downstream counting time, s

D = dilution ratio

T_u = upstream counting time, s, and

CV_D = coefficient of variation for dilution ratio*

Data required for characterization of the filters for filtration of particulate material shall be documented in tables and presented for easy comparison.

* Note that, since the manufacturer did not provide a CVD value, the value of CVD for the calculations shown was assumed to be zero.

3 Experimental Setup

The filter test setup included the following major components:

- filter housing,
- particle counter/size analyzer,
- aerosol generator,
- dilutor and
- gas analyzer.

Provisions for measuring temperature, air stream velocity, and pressure drop were made. Figure 2 shows various components of the filter testing.

The components of the experimental setup are also described in Figure 2. The system includes a two-stage compact Waterweb Scrubber housing, a fan, and instrumentation. The filter housing is a skid-mounted MYSTAIRE Two-stage Compact Waterweb Scrubber supplied by MISONIX, Inc. The scrubber is customized to accommodate different filters. The body of the housing is made of 304L stainless steel to be compatible with the intended high temperature operation of the equipment. The nominal diameter of the intake section is 9 in. while the filter scrubbing section is about 21 in. in diameter. The downstream section is connected to a 3 horsepower blower with a digital speed control drive. The blower is rated for 500 acfm (actual cubic feet per minute), and the whole unit is rated for operating at a maximum temperature of 500 °F.

Proper installation of the MYSTAIRE Compact Waterweb Scrubber and proper ductwork, plumbing, and electrical connections are described in the installation and operation manual. Brief discussions of the operation of the unit are described below. Depending on the application, the filters may be subjected to liquid spray where gaseous contaminants can also be removed. The liquid spray can be collected at the bottom drains. During filter evaluation, particulate removal efficiency and other filter characteristic information can be collected. Figure 3 shows details of the filter housing.

Figure 2. Schematic of air filter testing setup.

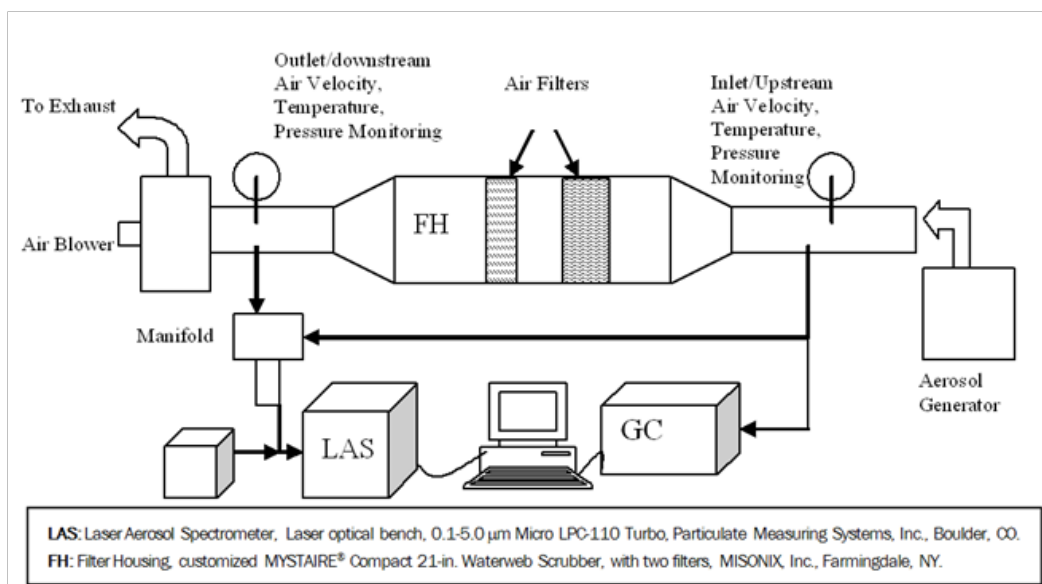
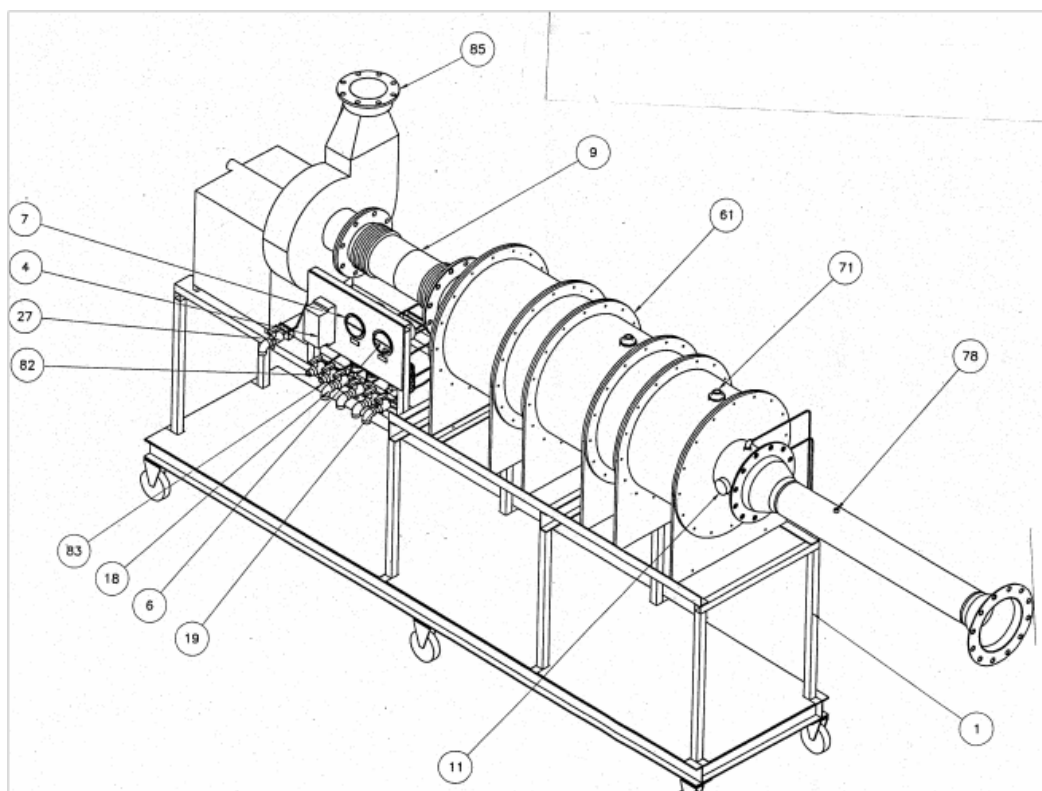


Figure 3. Engineering drawing of the skid-mounted MYSTAIRES® Waterweb Compact Scrubber.



3.1 Operation of the MYSTAIRE Waterweb Unit*

1. After completing all equipment and component connections, prepare to run the unit with air for 2 minutes. Nitrogen or helium may be used to purge the unit of air. This will allow time for familiarization with the complete system and to work any bugs, which might upset the operation. Also before shutting down the unit, purge the entire system and connecting ductwork with nitrogen. Between runs, bleed in a low flow of nitrogen upstream of the scrubber in order to maintain the inert atmosphere.
2. Turn on the blower, resulting in airflow through the system.
3. Verify that the blower drain is clear. Drain any accumulated liquid. Particulate matter may accumulate in the reservoir either by removal from the gas stream or because of neutralization reactions. In a "Once Through Scrubbing Mode" of operation, this presents no problem. In recycled systems, the particulate matter could clog the nozzles and damage the pump. A filtration system is necessary for continued operation. Solid contaminant compounds such as BCl₃ and other trichlorides, sulfur trioxides, and silicon compounds may build up in the inlet by impingement or hydrolysis adhesion.
4. Check for signs of fatigue, cracks, or leaks.
5. Check that the electric motors are dry and secure. Periodically check the motor amperage.

3.2 Start-up sequence of the filter test unit

1. Make sure all equipment is installed and piped.
2. Make sure all gaskets are suitable for high temperature if running combustion gases. The gaskets purchased for low temperature testing are Sealex Thermaseal ¼-in. gaskets and are replaced after each use or when they no longer provide good seal.
3. Make sure all valves are in their appropriate positions and drain valves are closed.
4. Drain valves street (straight) elbows to prevent HOT liquids spraying out. The Magnahelic and Photohelic pressure gauges (see the equipment manuals) are protected with a cooling coil and any condensate should be drained from them frequently to prevent damage to the instrument.
5. Make sure inlet and outlet ducting are open to atmosphere.
6. Turn on the fan; make sure the damper is mostly closed to put resistance on the fan; verify that the fan ON pilot light is illuminated when the fan is running.

* Note that most of the following will be useful for further applications, but was not used in the dry air filter testing.

3.3 Overview and operation of LAS

The laser particle counter, PMS* Model Micro LPC-110 Turbo, with an active cavity, is an aerosol counter designed for clean room monitoring, gas sampling, and filter testing. It sizes particles from 0.1 to 5.0 μm and greater in diameter in seven size classes plus an oversize class simultaneously with differential and accumulative populations in each class. An active cavity laser is the source for particle illumination. The laser tube has one sealed mirror and one Brewster's window. An additional external mirror defines the active cavity.

The collecting optics include four Mangin mirrors mounted at right angles to the laser beam imaging particles passing through the laser beam onto two solid-state photodetectors (one strip detector and one 20-element array). The mirrors provide a one-to-one magnification relay system from the laser beam to the detectors. The mirrors and the detectors are dielectrically coated for minimal light loss.

A self-contained flow system including pump, filters, flow meter, inlet jet, and outlet jet is used to provide a flow, which allows for 1 CFM to be sampled. A purge flow (factory adjusted) is used to keep the laser optics clean while sampling. The purge flow is set at 10 cc/s. The sample flow meter is factory adjusted to correct for this additional flow.

The signals from the detectors are amplified and sent to the pulse height analyzer where the particle size is determined. The particles are counted in an eight channel accumulating memory with 17-million population capacity per channel.

This instrument incorporates a means of reducing noise by using an imaging system and detector array to reduce the background light from molecular scattering to manageable levels. An open cavity laser beam illumination system is configured similarly in other PMS instruments except that the detector is a linear array of rectangular elements. These array elements view corresponding volumes within the laser beam. Light scattering from a particle is imaged onto a single element as a bright image along with a background of diffuse molecular scattering produced by all of the air molecules in a particle element's sensitive volume. Thus, the amount of background molecular scattering is reduced by the number of elements

* Particle Measurement Systems, Inc., Boulder CO.

selected for the array. For light noise sources other than those described by Shott noise, there is also a direct reduction in noise in direct proportion to the number of array elements. For Shott noise sources, the noise reduction is proportional to the square root of the number of array elements.

Because there are now “ n ” independent detectors, their signals must be individually interrogated to determine when a particle image has been observed by any one element. An overview of the operation is as follows: Each preamplifier develops an amplified signal of the noise and particle event. The peak amplitude of each element’s amplified signal is compared to a threshold equal to the peak amplitude of $0.1\text{ }\mu\text{m}$ particles. This comparison provides an indication of a particle being larger than $0.1\text{ }\mu\text{m}$. The comparator outputs are OR’ed together to provide a particle transit-time pulse. The transit time is used to determine if the event is a valid particle.

For sizes larger than $0.2\text{ }\mu\text{m}$, the strip photodiode detector output is used. Using two separate gain stages, the signals are passed to a conventional pulse height analyzer. The $0.2\text{ }\mu\text{m}$ threshold level is sufficiently higher than the $0.1\text{ }\mu\text{m}$ level that the summed noise is now smaller than the threshold for $0.2\text{ }\mu\text{m}$ particles. Each signal processing circuit, in conjunction with threshold detectors, determines when a particle event has occurred and the magnitude of the scattered light.

The final gain for the summed output signals from the preamplifier is provided on the pulse height analyzer (PHA) module. The PHA, as constructed, has eight voltage comparators and latches. The reference voltage, which inputs to the PHA comparators, is derived by sensing light leakage through the external laser mirror, using a photodiode and appropriate amplifiers. Because the reference voltage is derived from the source of illumination, the entire system has an effective automatic gain control (AGC).

The laser used in the laser optical bench Micro LPC-110 Turbo. is a 2 mW He-Ne tube. The tube operates in a low order multimode. The laser beam is approximately 2.0 mm diameter. Particles passing through the laser beam in the sampling aperture scatter energy into the optics. The amount of scattering for a given particle size is a function of the laser mode as well as the exact radial transect through the beam. Because low order multimode is used, there is a probability distribution for a particle intersecting with the maximum intensity in the beam. In order to provide for uniform

illumination of particles within a low order multimode laser beam, the sample volume is confined to the central 50% of the beam width.

In summary, a laser cavity of several Watts power is directed through the sensing region, and particles flow through the sensing region at 1.0 CFM flow rate. Each element of the array of detectors monitors a predetermined volume of the sensing region, senses detectable light scattering within the monitored portion, and provides an electrical output signal indicative of the amount of light scattering (along with signals caused by background noise). The electrical output signals are parallel processed and the peak amplitudes sensed for sizes above 0.1 μm . Simultaneously, particles larger than 0.2 μm are sensed by a strip detector and the scattering amplitudes sized by a PHA.

3.4 Test filter information

Four filters were evaluated in the initial phase of identifying filters for $\text{PM}_{2.5}$. Stainless steel filters fabricated from a 2- μm sieve were custom manufactured to fit into the MYSTAIRe filter tester. These filters were designed to have pore sizes of 1, 2, 5, and 10 μm .

4 Experimental Procedure

To date, a general start-up and data collection procedure has been followed for every experiment to prepare the equipment. This start-up is valid any time the system is run and it should be understood that this sequence is interjected in every procedure mentioned below at the appropriately noted time. The equipment start-up consists of:

1. Make sure that the fume hood is on and closed to regulation height. The hood minimizes backpressure and results in the minimum amount of flow rate fluctuation.
2. Make sure the inlet butterfly valve is completely open. No tests have been done to date with the valve less than fully open. In addition, look over the system and make sure all probe valves are open completely and facing horizontally.
3. Start the blower. Set the electronic display to a desired setting or set according to pressure drop of flow rate.
4. Five minutes after turning the blower on, power on the LAS particle counter, the manifold pump and the computer connected to the LAS. Open the program Facility Net and open a sensor table and a plot. In the plot, select an hour sampling time and choose the Diluted Upstream 1, Diluted Upstream 2, Diluted Downstream 1, and Diluted Downstream 2 values to display. This will allow monitoring of data trends as they are collected.
5. The Facility Net program is set to sample each stream for 20 seconds with a 5 second delay between sample streams. The system and data collection software are now prepared for the appropriate test. From this point, choose the procedure associated below with the desired test results.

4.1 Overview of pressure drop versus flow rate measurement

Studies were done to appropriately determine the relationship between pressure drop and flow rate for each filter. The procedure consists of:

1. The scrubber is opened and the appropriate filter is securely tightened in the filter housing. Disposable gaskets are placed on the filter housing, front and back, in two concentric circles to ensure no leakage around the bolts. The filter housing is lifted and reattached to the scrubber by tightening 16 bolts and nuts on both the front and back of the filter housing connection.
2. The start-up sequence is followed. The Facility Net program is started.

3. The electronic display is set to setting 15. Every 5 minutes, after allowing time to equilibrate, collect pressure drop, flow rate, and temperature readings and increase the setting by five units. This process continues until the setting reaches 60, the display maximum, or the pressure drop reaches a maximum running value of 8 in. of H₂O. This results in a gradual increase in flow rate and pressure drop.
4. The Facility Net program is stopped and a CSV with the appropriate data is made. The particle counter, manifold pump, blower and hood are turned off.
5. The data for pressure drop are plotted. This process is repeated for all filters three times to compile a set of average data.

4.2 Overview of dust holding capacity test

Studies were performed to appropriately determine the effect of atmospheric dust, typically accumulated on an air filter over time, at an accelerated rate using ASHRAE test dust. From these tests, conclusions can be made about dust holding capacity, the effect of dust loading on pressure drop and the estimates on the appropriate cleaning schedule. The test procedure consists of:

1. The scrubber is opened and the appropriate CLEAN filter (see section 4.3 for cleaning procedure) is securely tightened in the filter housing. Disposable gaskets are secured and the filter housing is placed back into the system (see above section for details).
2. Fill the hopper with at least 5 lb of ASHRAE 52.1 test dust. Set the dust feeder to a setting that may yield the desired flow rate. The desired flow rate should provide a concentration of approximately 12 CFM per 1 g of dust. Run the hopper at said setting for 30 minutes and calculate the actual flow rate. Adjust the hopper setting and retest until the appropriate setting is determined. Repeat this setting test, and if the hopper produces the dust at approximately the same rate ($\pm 5\%$), then the setting is ready. This test is necessary every time a test is run because humidity and temperature effect the flow properties of the ASHRAE test dust.
3. An airflow rate is chosen that has a relatively low starting pressure to allow for the build-up of pressure across the filter as the dust cake forms. For most tests, a setting yielding an airflow rate of 150 CFM is ideal.
4. The start-up sequence is followed. Begin data collection using the Facility Net program.
5. Adjust the setting as appropriate to acquire the desired flow rate and run the system at this setting to establish a background set of data (background data used for penetration test) before the introduction of dust. Af-

- ter collecting background data for 30 minutes, the dust hopper is switched on. From this point forward pressure drop and flow rate are frequently monitored. Pressure drop and flow rate data are recorded every 2-10 minutes, depending on the temperature, humidity and filter pore size, followed by a setting adjustment to maintain the ideal flow rate. It is necessary to maintain the flow rate to simulate field conditions.
6. Once the pressure drop reaches 8 inches of H₂O, the maximum pressure drop allowed in this system, the dust holding capacity test is terminated. The Facility Net program is stopped and a CSV with the appropriate data is made. The particle counter, manifold pump, blower, hopper, and hood are turned off.
 7. The filter housing is opened and the filter is exposed. To get the data necessary, a collection bag is weighed. The filter is brushed off, and all the loose dust is collected. The bolts and nuts are removed, and the filter is agitated to release the majority of dust collected inside the filter. The collection bag is reweighed and the difference of the weight is the approximate dust holding capacity. The filter is then cleaned. The inside of the system is vacuumed and then washed with a damp rag to minimize residual dust for future runs.
 8. The data for pressure drop are plotted versus the flow rate. The CSV containing particle size distribution and their respective counts is copied into an Access database that was created to organize the CSV data into usable data columns. These data are then transferred into Excel where a template was created to calculate filter efficiencies based on each of the eight particle size ranges. For both the background and dust run data, graphs are plotted for ease of data comparison.

4.3 Overview of cleaning procedure

After performing a dust holding capacity test, the filter was cleaned to remove dust particulates that were not dislodged during agitation. To determine whether a filter has been adequately cleaned, an experiment is performed to measure how pressure drop is affected by increasing the flow rate. These data were then compared with the initial flow rate versus pressure drop data to determine if the same relationship applies. If deviation was more than 10% from the initial clean data, the filter was cleaned again and the process repeated.

Initially, a simple soapy soak was attempted. The filter was placed in a large soapy tub and allowed to soak for a few hours. A brush was then used to agitate the filter surface and remove any loose dust. For the first several

attempts, this approach yielded results within the range deemed suitable for a clean filter. After several dust tests, however, the filters were not responding to such cleaning and the pressure drop was much higher at a given flow rate than was seen with the clean filter. After some research, Waste Management and Research Center in Champaign, IL was contacted. Dr. William M. Nelson was asked to test the effectiveness of using sonication to clean the filters. After cleaning with sonication, the pressure drop lowered again, although not always within the desired range, and the dust testing continued. The following is the cleaning summary supplied by Dr. Nelson:

The Waste Management and Research Center (WMRC) has been studying ultrasonic aqueous cleaning in its Alternative Cleaning Technologies Laboratory (ACTL) as a means for cleaning filters provided by US Army CERL. This evaluation has included:

- Comparative testing of ultrasonic cleaning with other types of cleaning methods,
- Determination of various factors that influence the effectiveness of ultrasonic cleaning, and
- Testing the ability of ultrasonic cleaning to clean spaces with tight tolerances.

The results of the present study show that the use of aqueous cleaning coupled with ultrasonics and membrane filtration is an option for the optimal filter cleaning methodology. Evaluations were conducted at WMRC to determine optimum temperatures and operating times for four different detergents:

- Brulin 815GD, manufactured by Brulin Corporation,
- Daraclean 236A, manufactured by W. R. Grace,
- HurriSafe Hot Immersion Degreaser, manufactured by Hurri Clean Corporation, and
- SWROne, manufactured by SWR Corporation.

Preliminary tests were conducted by ACTL to determine if any obvious relationships existed between the operating parameters and effectiveness of the detergents. These tests consisted of (1) determining cloud points for each of the four detergents being tested, (2) determining cavitation properties as a function of temperature, and (3) conducting cleaning analyses of the detergents as a function of concentration and temperature. The four detergents selected for testing appeared to operate well within the 5 to 15% concentration range. A Ney SweepSonic Ultrasonic device was used, operating between 1 and 100 kHz. Optimally, a frequency range of 30 to 70 kHz was used with a bath temperature of 45 to 55 °C.

5 Results

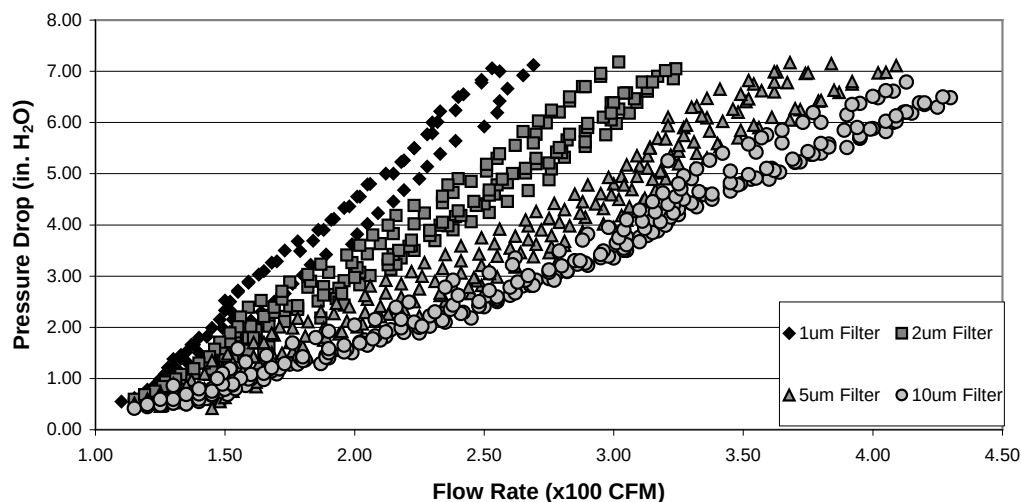
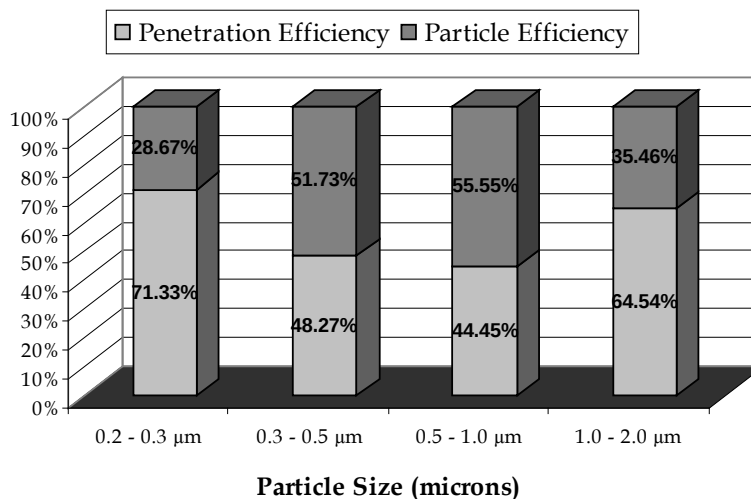
ASHRAE Standard 52.1 states that filter evaluation requires data on efficiency, resistance, dust holding capacity, and the effect of dust loading on efficiency and resistance. Using an in-house testing system, experimental studies on pressure drop versus flow rate, particle penetration and dust holding capacity were performed for each filter. Studies were performed to appropriately determine the relationship between pressure drop and flow rate for each filter. Additional studies were performed to appropriately determine the effect of atmospheric dust, typically accumulated on an air filter over time, at an accelerated rate using ASHRAE test dust. From these tests, conclusions can be made about dust holding capacity, the effect of dust loading on pressure drop, and the estimates on the appropriate cleaning schedule. The background data collected for each dust holding capacity test were then used to calculate penetration efficiencies. The following sections summarize the results for each filter to date. Note that the results for the 0.1–0.2 μm data range and $>2 \mu\text{m}$ range for all filters provide data that do not appropriately represent actual results and should be disregarded.

5.1 Determining pressure drop versus flow rate correlation

Studies of pressure drop versus flow rate were performed to establish a relationship between the data and to determine, for use in field studies, under what conditions a given filter can perform. All four filters were tested using the procedure described above; Figure 4 shows the results. The dilution ratio for every test to date is 1/100. The results shown in Figure 4 were used in subsequent cleaning tests to determine if a newly cleaned filter fell within the necessary range determined normal for each filter. A filter was deemed sufficiently clean if a chosen pressure drop value was within $\pm 10\%$ of these ranges.

5.2 Dust holding capacity test results for 1- μm filter

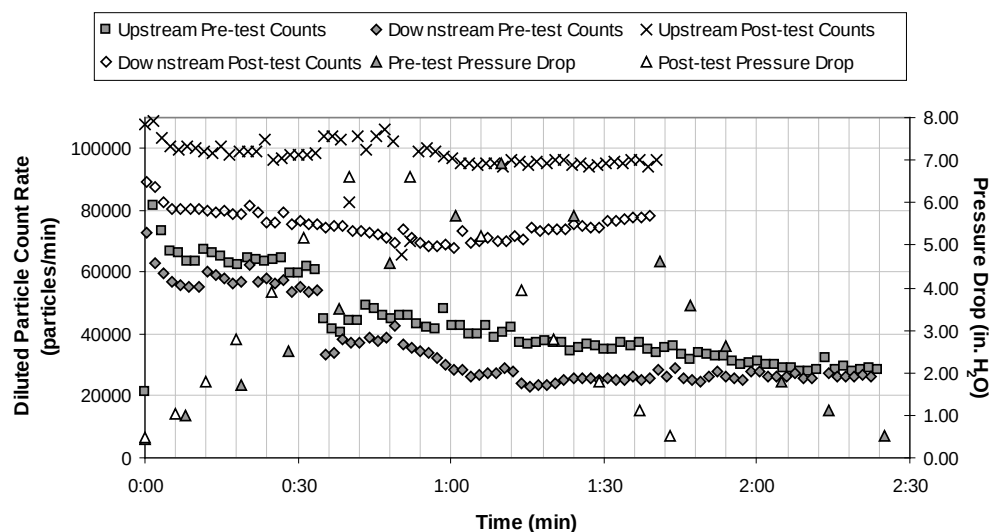
For the 1- μm filter, only one successful dust holding capacity test has been completed to date. The blower was set for an airflow rate of 150 CFM (volumetric flux = $0.349\text{m/s} = 1.15\text{ ft/s}$). The internal and external temperatures were recorded as 75 and 67°F, respectively. The internal and external relative humidity averaged 21.9 and 21.5%, respectively.

Figure 4. Comparison of flow rate versus pressure drop data for 1-, 2-, 5-, and 10- μ m filters.Figure 5. Efficiency results for 1- μ m filter (Experiment 1-150-1).

The dilution ratio for every test to date is 1/100. The dust holding capacity was determined to be 5.42 g. The 1- μ m filter efficiency reached a maximum of 55.55% in the particle size range 0.5–1.0 μ m. Figure 5 shows the efficiencies for each of the eight particle size ranges. The average coefficient of variation for penetration is 9.92×10^{-5} .

For each filter tested after 24 November 2003, graphs were plotted to determine the relationship between pressure drop and flow rate and to display the effect a dust cake has on filter efficiency. Figure 6 shows the increased pressure drop in the presence of dust, and qualitative data to show the difference in filter efficiency for the 1- μ m filter.

Figure 6. Pressure drop versus flow rate data and particle count data for 1- μm filter pre- and post-dust holding capacity test (Experiment 1-150-1).



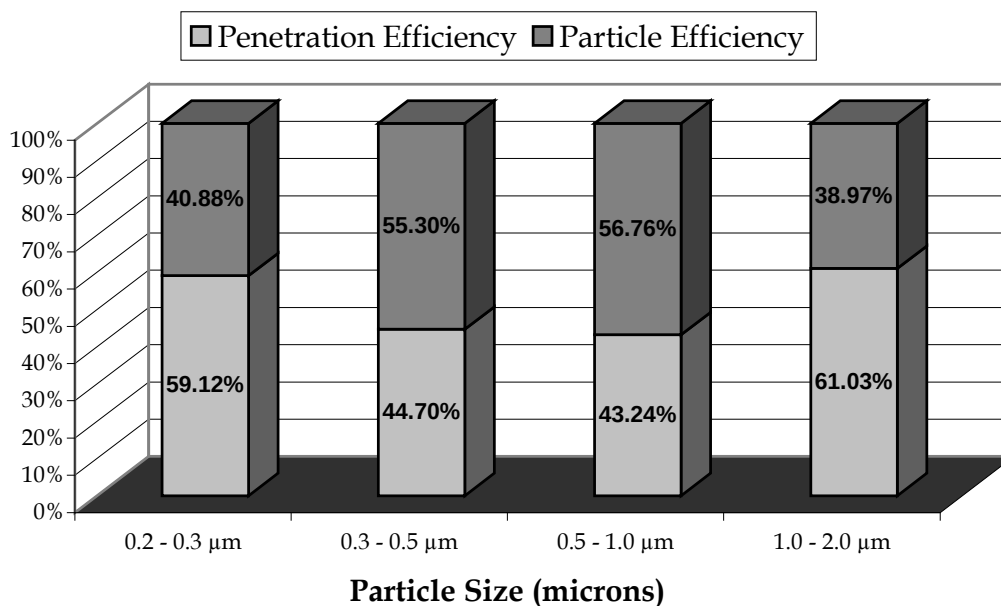
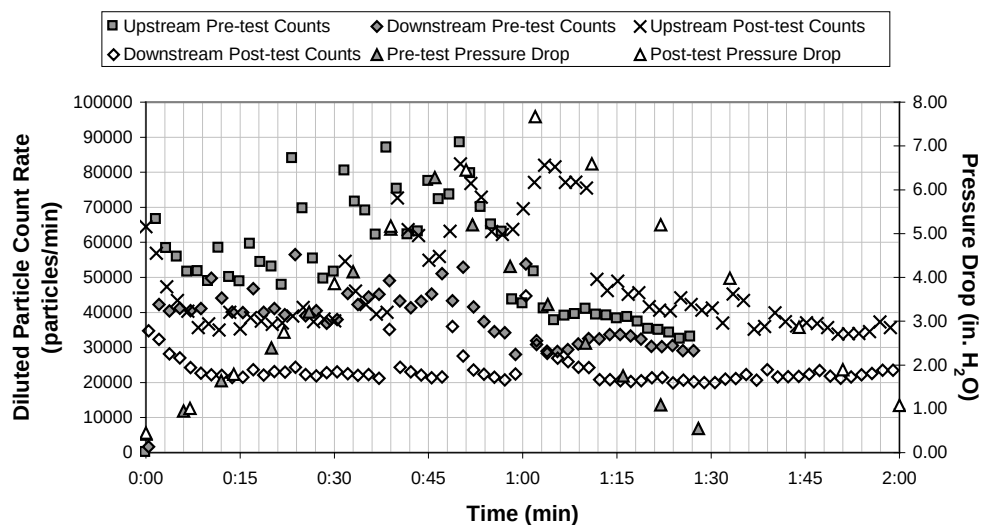
5.3 Dust holding capacity test results for 2- μm filter

For the 2- μm filter, only one successful dust holding capacity test has been completed to date. The blower was set for an airflow rate of 150 CFM (volumetric flux = $0.349 \text{ m/s} = 1.15 \text{ ft/s}$). The internal and external temperatures were recorded as 78 and 66 °F, respectively. The internal and external relative humidity averaged 24.3 and 36.9%, respectively. The dust holding capacity was determined to be 5.48 g. The 2- μm filter efficiency reaches a maximum of 56.76% in the particle size range 0.5–1.0 μm . Figure 7 displays the efficiencies for each of the eight particle size ranges. The average coefficient of variation for penetration is 5.24×10^{-4} .

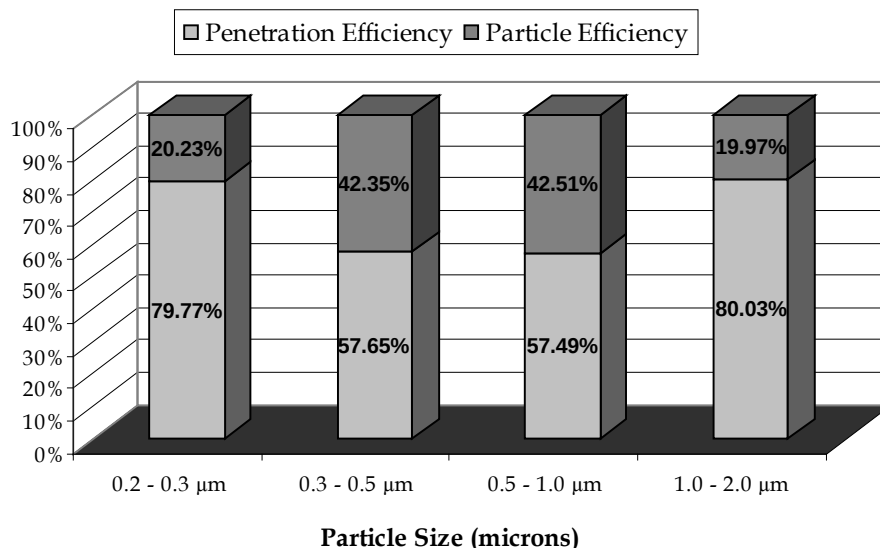
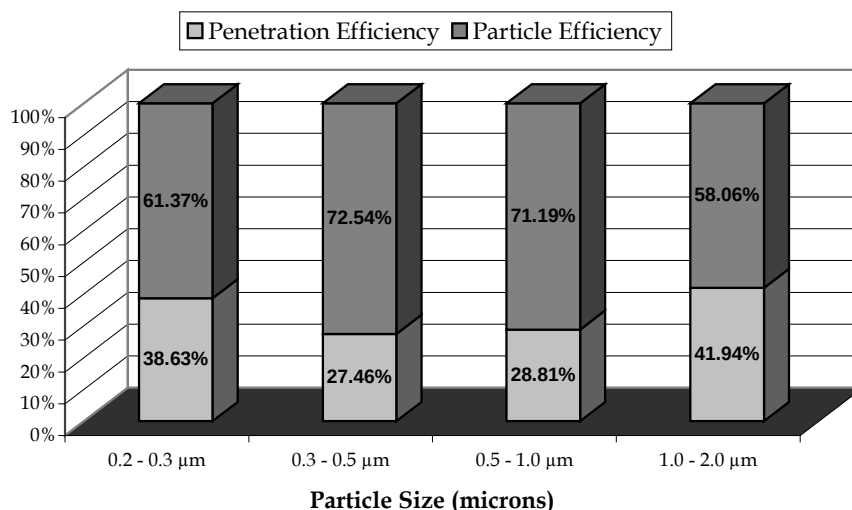
For each filter tested after 24 November 2003, graphs were plotted to determine the relationship between pressure drop and flow rate and to display the effect a dust cake has on filter efficiency. Figure 8 shows the increased pressure drop in the presence of dust, and qualitative data to show the difference in filter efficiency for the 2- μm filter.

5.4 Dust holding capacity test results for 5- μm filter

For the 5- μm filter, two successful dust holding capacity tests have been completed to date. The blower was set for an airflow rate of 150 CFM (volumetric flux = $0.349 \text{ m/s} = 1.15 \text{ ft/s}$).

Figure 7. Efficiency results for 2- μm filter (Experiment 2-150-3).Figure 8. Pressure drop versus flow rate data and particle count data for 2- μm filter pre- and post-dust holding capacity test (Experiment 2-150-3).

The external temperature was recorded as 80 °F. The dust holding capacity was determined to be 11.32 g. The 5- μm filter efficiency reaches a maximum of 42.51% in the particle size range 0.5–1.0 μm . Figure 9 displays the efficiencies for each of the eight particle size ranges. The average coefficient of variation for penetration is 1.42×10^{-4} . At the time in which this experiment was completed, post-data were not yet collected to determine the effect a dust cake has on pressure drop and filter efficiency.

Figure 9. Efficiency results for 5- μ m filter (Experiment 5-150-2).Figure 10. Efficiency results for 5 μ m filter (Experiment 5-150-3).

With the second experiment, 5-150-3, there were no problems with the run. The blower was set for an airflow rate of 150 CFM (volumetric flux = $0.349 \text{ m/s} = 1.15 \text{ ft/s}$). The internal and external temperatures were recorded as 75 and 72 °F, respectively. The internal and external relative humidity averaged 49.5 and 32.6%, respectively. The dust holding capacity was determined to be 6.72 g. The 5- μ m filter efficiency reaches a maximum of 72.54% in the particle size range 0.3–0.5 μ m. Figure 10 displays the efficiencies for each of the eight particle size ranges. The average coefficient of variation for penetration is 1.08×10^{-4} .

For each filter tested after 24 November 2003, graphs were plotted to determine the relationship between pressure drop and flow rate and to display the effect a dust cake has on filter efficiency. Figure 11 shows the increased pressure drop in the presence of dust, and qualitative data to show the difference in filter efficiency for the 5- μm filter.

5.5 Dust holding capacity test results for 10- μm filter

For the 10- μm filter, two successful dust holding capacity tests were completed to date. The blower was set for an airflow rate of 250 CFM (volumetric flux = 0.582 m/s = 1.91 ft/s). The external temperature was recorded as 88 °F. The dust holding capacity was determined to be 3.88 g. The 10- μm filter efficiency reached a maximum of 84.28% in the particle size range 0.5–1.0 μm . Figure 12 displays the efficiencies for each of the eight particle size ranges. The average coefficient of variation for penetration is 1.33×10^{-4} . At the time this experiment was completed, post-data were not yet collected to determine the effect a dust cake has on pressure drop and filter efficiency.

Figure 11. Pressure drop versus flow rate data and particle count data for 5- μm filter pre- and post-dust holding capacity test (Experiment 5-150-3).

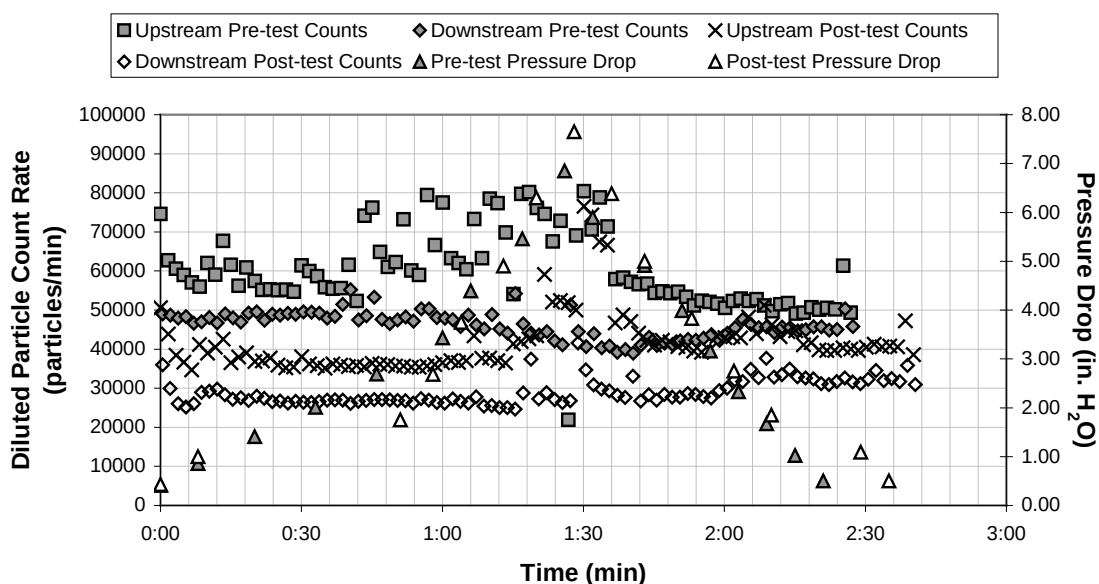
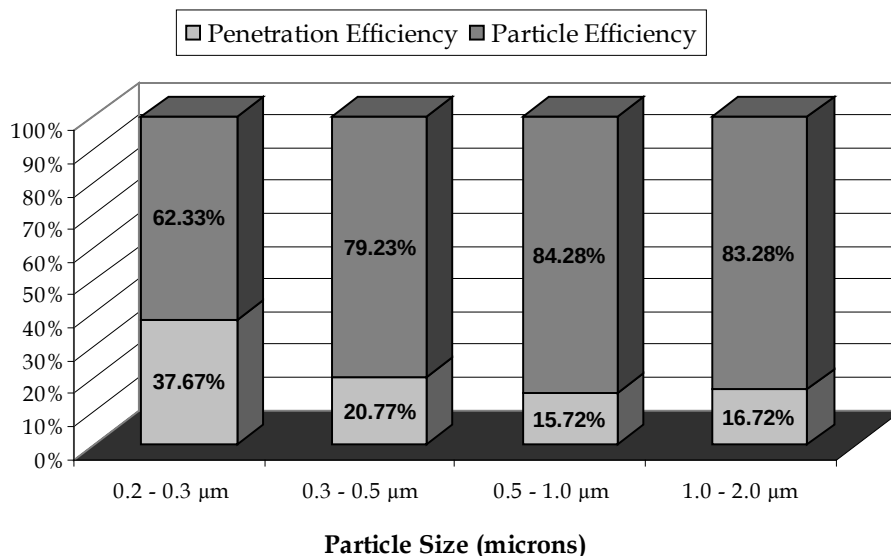
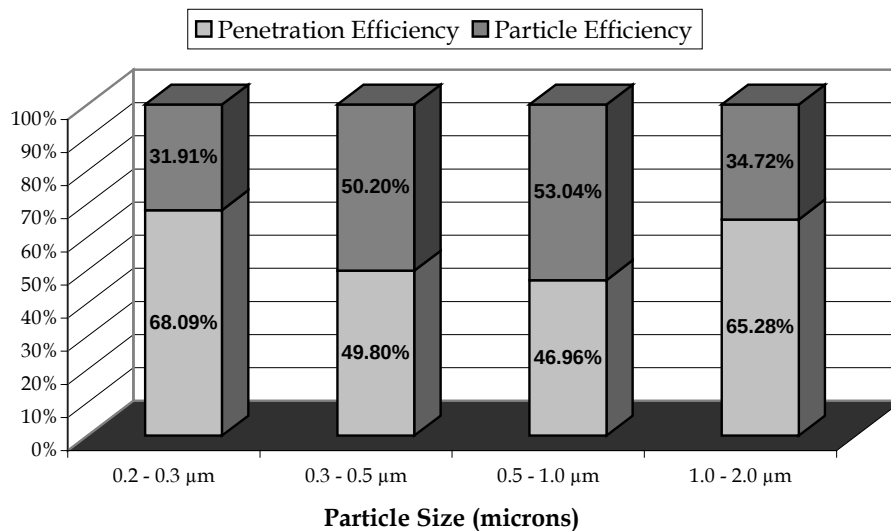
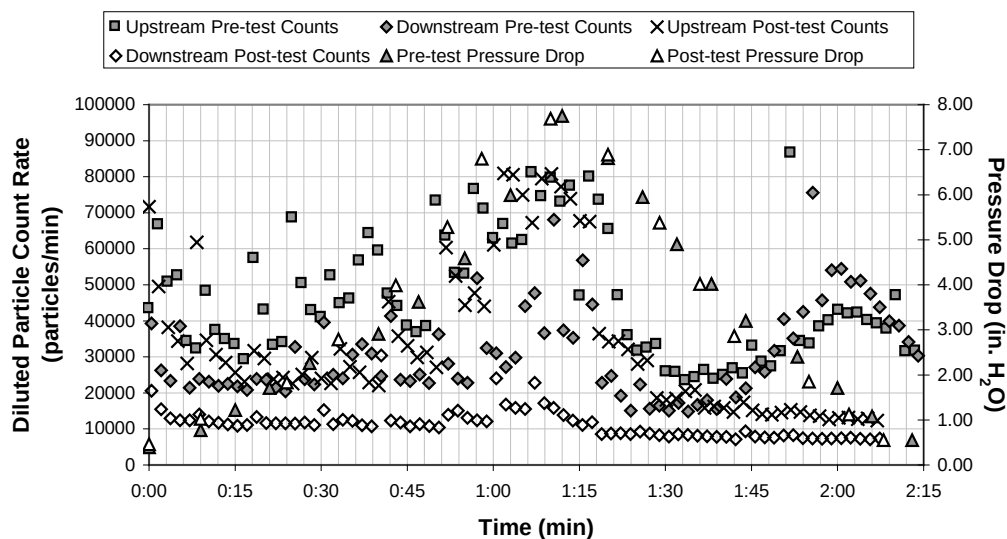


Figure 12. Efficiency results for 10- μ m filter (Experiment 10-250-3).Figure 13. Efficiency results for 10 μ m filter (Experiment 10-150-1).

With the second experiment, 10-150-1, there were no problems with the run. The blower was set for an airflow rate of 150 CFM (volumetric flux = $0.349 \text{ m/s} = 1.15 \text{ ft/s}$). The internal and external temperatures were recorded as 72 and 48.4 °F, respectively. The internal and external relative humidity averaged 31.0 and 37.0%, respectively. The dilution ratio for every test to date is 1/100. The dust holding capacity was determined to be 13.54 g. The 10- μ m filter efficiency reaches a maximum of 53.0% in the particle size range 0.5–1.0 μ m. Figure 13 displays the efficiencies for each of the eight particle size ranges. The average coefficient of variation for penetration is 1.49×10^{-4} .

For each filter tested after 24 November 2003, graphs were plotted to determine the relationship between pressure drop and flow rate and to display the effect a dust cake has on filter efficiency. Figure 14 shows the increased pressure drop in the presence of dust, and qualitative data to show the difference in filter efficiency for the 10- μm filter.

Figure 14. Pressure drop versus flow rate data and particle count data for 10- μm filter pre- and post-dust holding capacity test (Experiment 10-150-1).



6 Conclusions and Recommendations

ASHRAE Standard 52.1 states that filter evaluation requires data on efficiency, resistance, dust holding capacity, and the effect of dust loading on efficiency and resistance. Using an in-house testing system, experimental studies on pressure drop versus flow rate, particle penetration, and dust holding capacity were performed for each filter. Experimental results show that, as the quantity of dust increases, pressure drop increases linearly. In the presence of dust, a cake layer forms reducing effective pore size and therefore increasing the filter efficiency. Based on the preliminary results, these filters offer a reusable, easily cleanable, cost-effective, and compact particulate filtration system for the Army mobile and stationary combustion systems. Compatibility of the filter material to the operating temperature, pressure, air superficial velocity, and other physicochemical conditions shall be tested in field studies and considered in the design process of the filter system.

Modifying the filter system by coating with adsorbent material (e.g., Bromine, Chitosan) and tack polymers may enhance the separation of metals and other fine particulates. Future research and development of such filters is recommended.

References

- American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). 2000. *ASHRAE Systems and Equipment Handbook(SI)*. Atlanta, GA: ASHRAE.
- _____. 1999. *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*. Standard 52.2. Atlanta, GA: ASHRAE
- American Society for Testing and Materials (ASTM). 2009. *Standard Test Method for Air Cleaning Performance of a High-Efficiency Particulate Air- Filter System*. ASTM F1471 – 09. West Conshohocken, PA: ASTM.
- Calvert, S., and H. M. Englund (Editors). 1984. *Handbook of Air Pollution Control Technology*. New York: John Wiley & Sons.
- Hinds, W. C. 1982. *Aerosol Technology, Properties, Behavior, and Measurement of Airborn Particles*. New York: John Wiley & Sons.
- Institute of Environmental Sciences and Technology (IEST). 1992. *Testing ULPA Filters*. IES RP-CC 007.I. Mount Prospect, IL: IEST.
- _____. 1993. *HEPA and ULPA filters*. IES RP-CC 0013.I. Mount Prospect, IL: IEST.
- Liu, B. Y. and K. L. Rubow. 1986. Air filtration by fibrous filter media. *Fluid-Filtration: Gas*. ASTM STP973. Philadelphia, PA: ASTM.
- Shah, J. K. 1999. Surrogate burns in deactivation furnace system, *J. of Hazardous Materials*.
- MYSTAIRES. Undated. Equipment Manual for Laser Aerosol Spectrometer (LAS). MYSTAIRES: Creedmoor, NC.
- _____. Undated. Equipment Manual for Gas Chromatograph (GC). MYSTAIRES: Creedmoor, NC.

Glossary

ASHRAE Synthetic Test Dust

Standardized artificial loading dust used to simulate atmospheric dust loading. This dust is composed, by weight, of 72% standardized air cleaner test dust, fine; 23% powdered carbon; and 5% cotton lintens.

CFM Volumetric flow rate expressed as cubic feet per minute (cu ft/min)

Dilution Ratio (D)

Using a diluter, the air stream is split and only a percentage of the original stream enters the particle counter. In this application, the dilution ratio = 1/100.

Downstream concentration.

The number of particles counted downstream of the filter.

Dust Holding Capacity (DHC)

ASHRAE defines DHC as the amount of a particular type of dust that an air cleaner can hold when it is operated at a specific airflow rate to some maximum resistance value (ASHRAE Standard 52.1)

Flux

The rate of flow of fluid, particles, or energy through a given surface (www.dictionary.com). The units are distance per time.

Penetration efficiency

The penetration efficiency is the ratio of the downstream concentration to the upstream concentration expressed as a percentage.

Particle efficiency

The particle efficiency, or filter efficiency, is defined as 100 - Penetration Efficiency.

Pressure drop

Used interchangeably with resistance to airflow, it is defined as the static pressure drop across the filter at a given airflow rate.

Relative humidity (Rh)

Ratio of amount of water in the air at a specific temperature to the maximum amount that the air could hold at that temperature, expressed as a percentage (dictionary.com). Rh is measured, internally and externally, via Fisher Scientific digital hygrometer.

Room temperature (Tr)

Usually defined as 300K. The internal temperature is measured at the beginning of each experiment via Fisher Scientific digital hygrometer.

Upstream concentration: The number of particles counted upstream of the filter.

Acronyms and Abbreviations

Term	Definition
ACTL	Alternative Cleaning Technologies Laboratory
AGC	automatic gain control
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
CEERD	US Army Corps of Engineers, Engineer Research and Development Center
CERL	Construction Engineering Research Laboratory
CFM	cubic feet per minute
CSV	Comma Separated Values
DC	District of Columbia
DHC	Dust Holding Capacity
ERDC	Engineer Research and Development Center
GC	Gas Chromatograph
HAP	Hazardous Air Pollutant
HEPA	high-efficiency particulate air
HQUSACE	Headquarters, US Army Corps of Engineers
HWC	Hazardous Waste Combustor
IENT	Institute of Environmental Sciences and Technologies
LAS	Laser Aerosol Spectrometer
LPC	Laser Particle Counter
NESHAP	National Emission Standards for Hazardous Air Pollutants
PHA	pulse height analyzer
PMS	Particle Measurement System
PSL	polystyrene latex
SI	Système Internationale
TR	Technical Report
ULPA	Ultra-Low Particulate Air
URL	Universal Resource Locator
US	United States
USEPA	US Environmental Protection Agency
VOC	volatile organic compound
WMRC	Waste Management and Research Center
WWW	World Wide Web

Nomenclature

Scientific Terms

Cb	background particle counts
Cd	downstream particle counts
Ci	concentration of the dust in the gas stream
Cu	upstream particle counts
CVD	coefficient of variation for dilution ratio
CVp	coefficient of variation for penetration
D	dilution ratio
Hf	flow stream height, cm
K2	specific resistance coefficient of the dust
L	collector length, cm
N	undiluted upstream count rate, counts/s
n	particle concentration averaged across a plane normal to the flow, particles/cm-3
nd	particle concentration at deposition plane, cm-3
P	particle penetration
P η	filter penetration efficiency
Q	volumetric flow rate = $u_g H_f W$
R _{hint}	internal (room) relative humidity, %
R _{hext}	external relative humidity, %
SE	effective residual drag of the filter
Td	downstream counting time, s
T _{ext}	external temperature, °F
T _r	room temperature, °F
Tu	upstream counting time, s
t	filtration time
ud	deposition velocity, cm/sec
u _g	gas velocity, cm/sec
W	flow stream width

Greek letters

ΔP	filter pressure drop
η	particle collection efficiency
η_m	mass collection efficiency

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 15-06-2011		2. REPORT TYPE Final		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Laboratory Evaluation of Stainless Steel Filters for Control of Particulate Emissions				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT 622720	
6. AUTHOR(S) Veera M. Boddu, Jessica A. Gilmer, and K. James Hay				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Engineer Research and Development Center (ERDC) Construction Engineering Research Laboratory (CERL) PO Box 9005 Champaign, IL 61826-9005				8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/CERL TR-11-17	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Headquarters, US Army Corps of Engineers 441 G St., NW Washington, DC 20314-1000				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT This research developed a method to control particulate emissions from Army demilitarization furnaces by developing high temperature filters capable of capturing particulate emissions, including the heavy metal PM2.5. Custom manufactured stainless steel filters were evaluated in a filter test setup based on American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and American Society for Testing and Materials (ASTM) standard protocols used to characterize flat panel filters. Experimental studies using an in-house testing system on pressure drop versus flow rate, particle penetration, and dust holding capacity were performed for each filter. Experimental results showed that, as the quantity of dust increases, pressure drop increases linearly. In the presence of dust, a cake layer forms reducing effective pore size and therefore increasing the filter efficiency. Preliminary results showed that these filters offer a reusable, easily cleanable, cost-effective, and compact particulate filtration system for the Army mobile and stationary combustion systems. Future research is recommended to determine compatibility of the filter material to the operating temperature, pressure, air superficial velocity, and other physicochemical conditions, and whether modifying the filter system by coating with adsorbent material and tack polymers may enhance the separation of metals and other fine particulates.					
15. SUBJECT TERMS air pollution control, emissions, filters, demilitarization					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 42	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code)