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Evaluation of the ICET Test Stand to Assess the Performance of a Range of Ceramic Media Filter Elements in Support of ASME AG-1 Subsection FO

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Disclaimer

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Evaluation of a test stand to assess the performance of a range of ceramic media filter elements

By

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Evaluation of a test stand to assess the performance of a range of ceramic media filter elements

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High Efficiency Particulate Air (HEPA) filters are defined as extended-medium, dry-type filters with: (1) a minimum particle removal efficiency of no less than 99.97 percent for 0.3 micrometer particles, (2) a maximum, clean resistance of 1.0 inch water column (in. WC) when operated at 1,000 cubic feet per minute (CFM), and (3) a rigid casing that extends the full depth of the medium. Specifically, ceramic media HEPA filters provide better performance at elevated temperatures, are moisture resistant and nonflammable, can perform their function if wetted and exposed to greater pressures, and can be cleaned and reused. This paper describes the modification and design of a large scale test stand which properly evaluates the filtration characteristics of a range of ceramic media filters challenged with a nuclear aerosol agent in order to develop Section FO of ASME AG-1.

AUTHOR BIO

The work presented in this text was completed by Andrew L. Schemmel at the Institute for Clean Energy Technology (ICET) at Mississippi State University. The author has completed both his Bachelor's and Master's degrees in Mechanical Engineering at Mississippi State University. Work experience in the nuclear air filtration field has greatly prepared the author for future endeavors in his career as an engineer. In addition to work experience in this field, the author also has past work experience in the manufacturing industry. Much thanks and appreciation are shown to ICET personnel, Dr. Heejin Cho, Dr. Charles Waggoner, and Lawrence Livermore National Lab (LLNL).

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INTRODUCTION

Overview of project

High-efficiency particulate air (HEPA) filters are an important component of nuclear containment facilities, which are used to prevent particulate matter from being released into the environment. In nuclear applications, HEPA filters are used as the last line of defense against airborne particles, which have the potential to greatly affect human life, animal life, and the environment if released into the atmosphere.

The definition of a HEPA filter is found in Section FC Article FC-1000, Paragraph FC-1130 (page 312) of the 2015 American Society of Mechanical Engineers (ASME) Code on Nuclear Gas and Air Treatment (AG-1). It is defined as a "throwaway, extended-media dry type filter with a rigid casing enclosing the full depth of the pleats. The filter shall exhibit a minimum efficiency of 99.97% when tested with an aerosol of 0.3 micrometer (μm) diameter test aerosol particles [1]." Information on different filter types is found within ASME AG-1-2015. Table 1.1 displays the different sections within AG-1, which include finalized sections and in-development sections.

Table 1.1 ASME AG-1 sections.

Section Name	Subject
FA	Moisture Separators
FB	Medium Efficiency Filters
FC	HEPA Filters
FD	Type II Adsorber Cells
FE	Type III Adsorber Cells
FF	Adsorbent Media
FG	Mounting Frames for Air Cleaning
FH	Other Adsorbers
FI	Metal Media Filters*
FJ	Low Efficiency Filters
FK	Special HEPA Filters
FL	Deep Bed Sand Filters
FM	High Strength HEPA Filters*
FO	Ceramic Media Filters*
	*in-development

Conventional nuclear grade HEPA filters are composed of a fibrous glass media with diameters that provide the necessary particle retention efficiency without surpassing the maximum airflow resistance. These fibrous glass filters are one time use filters that must be safely discarded after the usable limit as mentioned in AG-1 [1]. The usable limit of fibrous glass media filters is typically 3 to 5 inch water column (in. WC) greater than the clean differential pressure (dP) as outlined in Chapter 3, Section 3.3.6.1 (page 3-14) of the Nuclear Air Cleaning Handbook [2]. A typical axial-flow HEPA filter from Chapter 1, Section 1.1.3 (page 1-3) of the Nuclear Air Cleaning Handbook is presented in Figure 1.1 [2], and a radial flow HEPA filter is given in Figure 1.2.

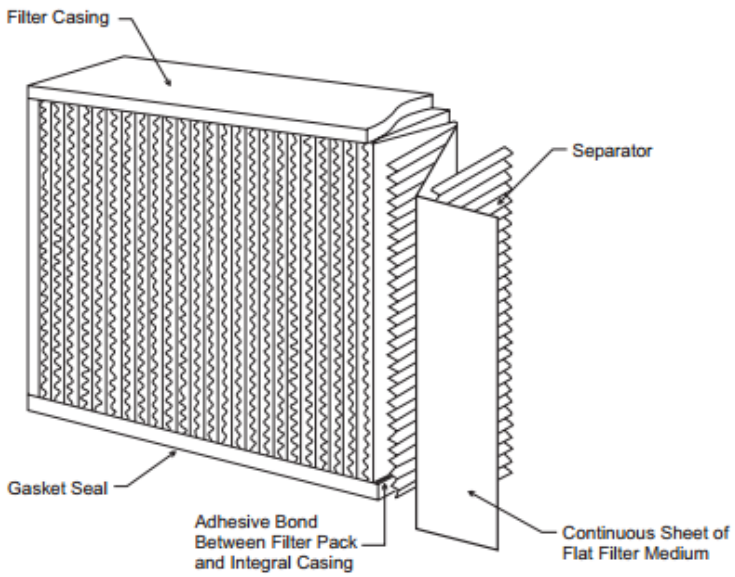


Figure 1.1 Deep-pleat HEPA filter-Type A filter pack.

Figure 1.2 Radial flow HEPA filter.

The filters shown in Figures 1.1 and 1.2 are composed of a fibrous glass media. The two most common types of media used in air filtration include fibrous media and sintered media. Examples of fibrous media include cellulose (wood) fibers, fibrous glass, and plastic fibers. Sintered media is typically comprised of sintered metals and ceramics [4]. The most common type of media used in air filtration is fibrous glass media. This media type typically performs poorly at elevated temperatures and humidity, but shows high filtering efficiency (FE) and low pressure drop at ambient conditions. Alternative media types such as metal and ceramic typically display high pressure drops, but better resistance to elevated temperatures. Figures 1.3 through 1.5 display images of different metal media samples.

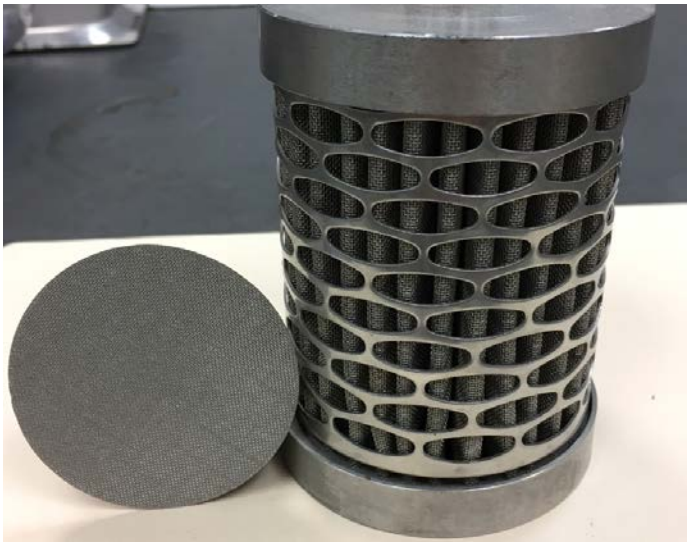


Figure 1.3 Sintered metal media coupon and pleated sintered metal media element.

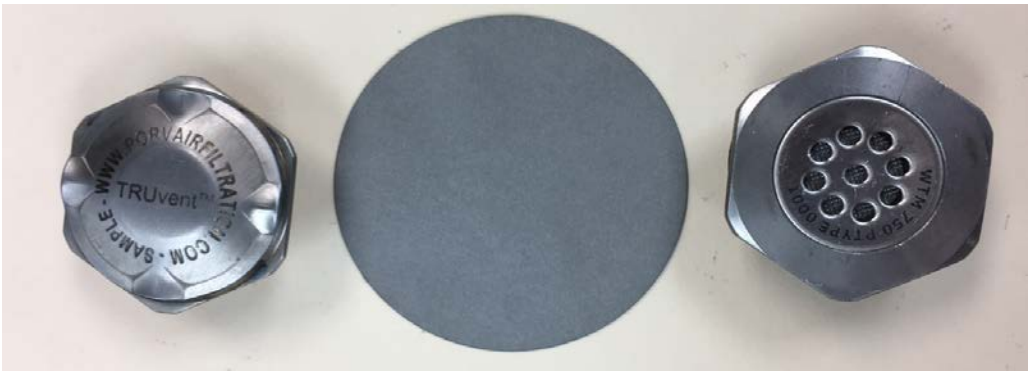


Figure 1.4 Metal fiber medium coupon and a TRUvent cap where the media is inserted.

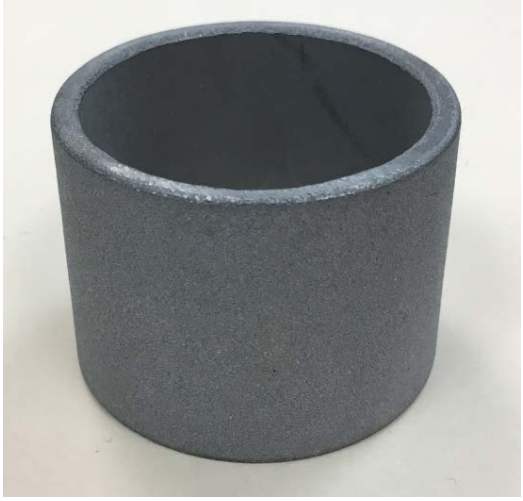


Figure 1.5 Section of a Mott sintered metal powder element.

The media type presented within this project, ceramic, falls under granular media. Ceramic (and metal) media filters are currently considered as advantageous for nuclear and radiological nuclear applications because of their numerous benefits to radiological aerosol filtration in extreme conditions and are in the research and development phase. Figure 1.6 displays a sintered metal media filter containing three filter elements (left) and a powdered metal media filter composed of four filter elements (right).

Figure 1.6 Metal media filter elements.

Figure 1.7 illustrates two ceramic media filter types, both of which, are composed of six filter elements.

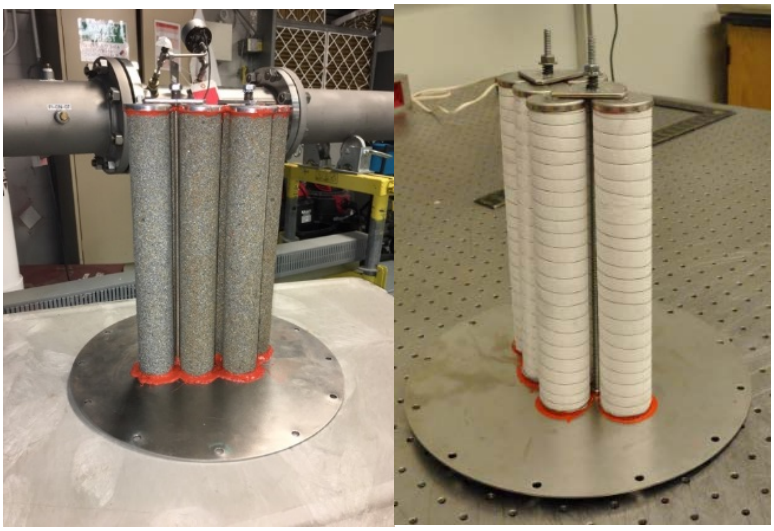


Figure 1.7 Core six-element ceramic filter (left) and Filter Media 1 six-element ceramic filter (right).

Specifically, ceramic media filters have the potential to provide better performance at elevated temperatures, are moisture resistant and nonflammable, can perform their function if wetted and exposed to greater pressures, and can be cleaned and reused. In this project, a range of ceramic media filters are under evaluation. Ceramic media filters pose many potential benefits compared to traditional fibrous glass HEPA filters such as [3]:

1. Better resistance to higher temperatures and fires.
2. Capability to be tested at conditions that simulate an earthquake followed by a fire.
3. Capability to be used in other commercial industries.
4. Potential to be used in applications where thermal and pressure impulses could occur as a result of an explosion.
5. Capability of improving facility safety problems where high temperatures and fires may be more likely to occur.
6. Possibility of providing large life-cycle cost savings for facilities that employ ceramic HEPA filters.
7. Capability of providing continuous ventilation system operation during a fire in facilities.

Statement of need

The Institute for Clean Energy Technology (ICET) at Mississippi State University (MSU) was tasked to develop an infrastructure to qualify a range of ceramic media filters, ultimately, to further enhance Section FO of ASME AG-1. The need for qualification testing procedures and methods stems from the desire to evaluate ceramic media filters as a potential media type to withstand elevated temperatures. Evaluation of ceramic media filters at a higher range of elevated temperatures than metal media (and fibrous glass) filters would greatly help the development of Section FO.

Objectives

The Institute for Clean Energy Technology (ICET) at Mississippi State University (MSU) was awarded a contract by Lawrence Livermore National Laboratory (LLNL) to assist in the development of test procedures, methodologies, and a test stand to evaluate a range of ceramic media filters to further develop ASME AG-1 Section FO. The large scale test stand at the ICET at MSU was initially designed to evaluate sintered fiber metal media filters (ASME AG-1 Section FI), and requires modification to qualify ceramic media filters. The ceramic media test stand is designed to accommodate for low flowrates (5-25 CFM) to test ceramic filters and to provide elevated temperatures for testing. The ceramic media filters are challenged with dioctyl phthalate (DOP) primarily for FE measurements and potassium chloride (KCl) for solid particle

loading. Filter characteristics are observed through data collection using a laser aerosol spectrometer (LAS) and a scanning mobility particle sizer (SMPS) sampling system. Since ceramic filters have the capability to be washed and reused, a wash tank system is designed in tandem with the filter testing system. For the scope of this project, qualification testing requirements from ASME AG-1-2015 Article FC-5000, Paragraph FC-5100 (page 322) which could not be performed include subparagraphs FC-5130 (Resistance to Rough Handling), FC-5140 (Resistance to Pressure), FC-5150 (Resistance to Heated Air), and FC-5160 (Spot Flame Resistance).

CHAPTER II

AEROSOL CHARACTERISTICS

Physical properties of aerosols

There are many different parameters of interest where aerosol filtration is concerned. Aerosols are defined as two-phase systems, consisting of the particles and the gas in which they are suspended. Examples include mist, smoke, fog, dust, and clouds, which are common components of everyday life.

One of the most important parameters in aerosol science is particle size. The behavior of particles depends on particle size, and it is understood that other aerosol properties are significantly influenced by this characteristic. A few other noteworthy parameters are particle density, aerosol concentration, number concentration (units of number/cm^3), and mass concentration [4].

Particle size statistics

The most common parameters that are used to define different locations of a particle distribution include the mean, mode, median, and geometric mean. These are considered as "averages" of the entire data set when observing a distribution. The mean is defined as the sum of all the particles divided by the number of particles. The median is the diameter at which one-half the total number of particles are smaller and one-half the total number of particles are larger. The mode is the most frequently occurring size, or the diameter that is associated with the highest point on the distribution curve. The median is most commonly used when analyzing skewed particle size distributions.

The geometric mean, d_g, is the Nth root of the product of N values, and is outlined in Equation 2.1.

$$d_g = (d_1 d_2 d_3 \ldots d_N)^{1/N} \tag{2.1}$$

When describing a lognormal distribution, the geometric mean is replaced by the count median diameter (CMD). For a lognormal distribution, d_g is equal to CMD. In addition to count (or number) distributions, there are also mass distributions as functions of particle size. This gives the fraction of the total particle mass contributed by particles in all size ranges. In this type of distribution, the median diameter value is called the mass median diameter (MMD). When observing the lognormal distribution of particle sizes, it is worth noting the definitions that are associated such as the geometric standard deviation (GSD), σ_g, defined in Equation 2.2 [4].

$$\ln \sigma_g = \left(\frac{\sum n_i (\ln d_i - \ln d_g)^2}{N-1}\right)^{1/2} \quad (2.2)$$

Overview of aerosol filtration

Filtration is one of the most common, simple, effective ways of collecting aerosol particle samples. Fibrous filters are commonly used for high-efficiency collection of particles of various sizes. These are arranged so that the fibers are mostly perpendicular to the airflow. Air velocities through high-efficiency filters is typically low, 0.1 m/s (10 cm/s). So, it is necessary to pleat the filter media to increase the effective surface area [4]. The most commonly used filters found in the United States are typically fibrous glass media filters, although these are prone to damage from high temperatures and moisture. An example of the fibers that make up fibrous filters is shown in the scanning electron microscope (SEM) image in Figure 2.1.

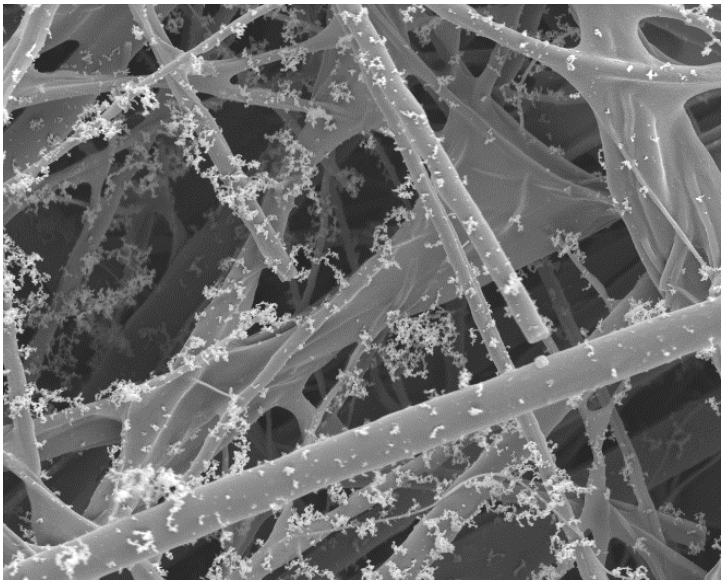


Figure 2.1 SEM image of a flat sheet media sample loaded with soot generated from a propane flame.

This image, magnified at 6000x, displays the individual fibers in a flat sheet media sample that was loaded with propane at ICET. One of the most important parameters that characterize filter performance is the efficiency of collection, or filtering efficiency. This

is simply defined as the ratio of particles that enter to the particles that are retained by the filter. The equation for filtering efficiency is shown in Equation 2.3.

$$E = \frac{N_{in} - N_{out}}{N_{in}} \tag{2.3}$$

It is important to note that this equation can be defined in terms of particle number collection or mass collection. Particle penetration is another important term when discussing aerosol filtration, and it is defined as the fraction of particles hitting the filter that exit or penetrate the filter. Penetration is listed in Equation 2.4.

$$P = \frac{N_{out}}{N_{in}} = 1 - E \tag{2.4}$$

At high efficiencies, a large change in penetration will cause small changes in efficiency. The face velocity, U_0, is the velocity of the air located at the face of a filter right before the air enters the filter and is given in Equation 2.5

$$U_0 = \frac{Q}{A} \tag{2.5}$$

where Q is the volumetric flow rate and A is the effective cross-sectional area of the filter. The solidity, α, is the fraction of the fiber volume to the total volume as defined in

$$\alpha = \frac{\text{fiber volume}}{\text{total volume}} = 1 - \text{porosity} \tag{2.6}$$

Particle penetration (P) decreases exponentially with increasing filter thickness (t) as shown in Equation 2.7.

$$P = e^{-\gamma t} \tag{2.7}$$

The pressure drop, dP, is a property that is influenced by the structure or geometry of a filter. It is the resistance of the air flowing through the filter and is directly proportional to the filter thickness and inversely proportional to fiber diameter (d_f^2). Pressure drop is also proportional to the face velocity, as expected for laminar flow inside the filter. Ideally, a filter will have high filtering efficiency and low pressure drop. Although, a change in any filter property such as solidity, thickness, or face velocity will cause a change in the filtering efficiency for a given particle size and the pressure drop. There are five mechanisms in which particles are deposited onto a filter fiber. The five deposition mechanisms include:

1. Interception
2. Inertial impaction
3. Diffusion
4. Gravitational settling

5. Electrostatic attraction

When discussing the first three deposition mechanisms (interception, impaction, and diffusion), it is important to note that the flow around the individual particle is laminar (Re < 1). Laminar flow is characterized by a smooth pattern of symmetrical streamlines on either side of the particle. Interception occurs when a particle (assuming perfectly) follows the gas streamline, and the streamline comes within one particle radius of the fiber surface so that the particle is removed from the air stream. This is the only mechanism that is not dependent on the flow velocity (U_0). Inertial impaction occurs when the inertia of a particle prevents adjustment to the changing streamlines. The particle crosses over to different streamlines near the filter, and ultimately hits the fiber. This mechanism is governed by the Stokes number. Diffusion is simply the mechanism by which a particle is removed by the fiber as a result of the random path that the particle takes due to Brownian motion. Gravitational settling is controlled by a dimensionless number denoted as G, which is simply the ratio of terminal settling velocity divided by face velocity. The last deposition mechanism is electrostatic deposition. Unless the particles and fibers have been charged in some way, this deposition mechanism is usually neglected [4].

Challenge aerosols

Aerosols, defined previously as a suspension of solid or liquid particles in a gas, come in many different sizes, shapes, and forms. With regards to nuclear aerosol filtration and HEPA filter testing, specific challenge aerosols are used. Article FC-5000, subparagraph FC-5120 Test Aerosol Particle Penetration (page 322) in ASME AG-1-2015 defines acceptable challenge agents for qualification testing using an aerosol with a 0.3 µm particle size from one of the following: dioctylphthalate (DOP), dioctylsebacate (DOS/DEHS), or 4 centistoke polyalphaolefin (PAO) [1]. The most commonly used from the three materials listed is DOP. Filter challenge agents can also be solid particle aerosols or powder aerosols. Examples include NIST A1 Ultrafine Arizona Road Dust, aluminum trihydroxide, and Carbon Black. Tests completed at ICET that utilized these aerosols are illustrated in Figure 2.2, and the statistics are outlined in Figure 2.3 [5].

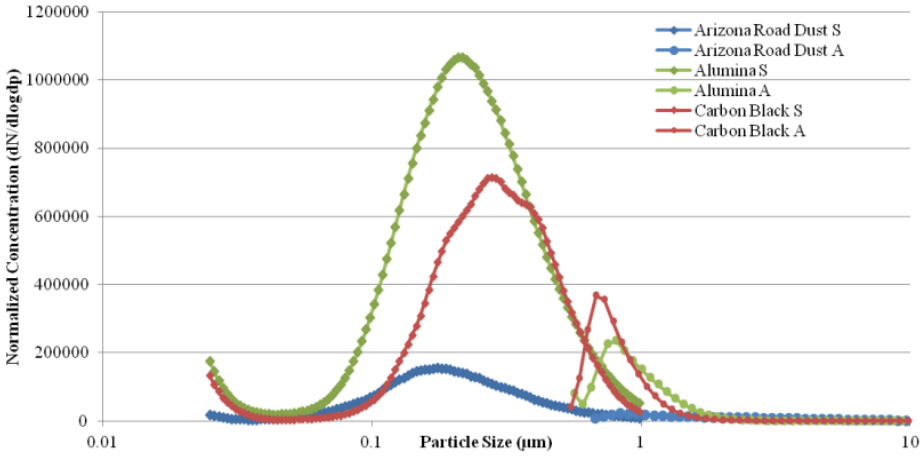


Figure 2.2 Particle size distributions of three dry powder aerosols.

Aerosol	Upstream			
	Number Concentration	CMD	GSD	MMD
Alumina	650,000 #/cc	.185 µm	2.17	0.8 µm
AZ Road Dust	100,000 #/cc	.186 µm	1.86	5 µm
Carbon Black	450,000 #/cc	.250 µm	2.21	1.2 µm

Figure 2.3 Aerosol statistics of three dry powder aerosols.

Aerosol measurement instrumentation

Aerosol measurement instrumentation plays an important role in filtration and the study of aerosol behavior. No single instrument can detect entire ranges of particle sizes, for example, 1 nm to 100 µm. Therefore, multiple instruments must be utilized.

In addition to the Scanning Mobility Particle Sizer (SMPS) and Laser Aerosol Spectrometer (LAS), other aerosol measurement instruments include the Aerodynamic Particle Sizer (APS), Electrical Low Pressure Impactor (ELPI), Laser Particle Counter (LPC), and Pilat Impactor. This section describes some of these instruments' capabilities along with the benefits and drawbacks associated with each one.

One of the most widely used aerosol measurement instruments is the TSI Laser Aerosol Spectrometer (LAS). The model 3340 is used in this project and used for other projects at ICET. This instrument has high sensitivity along with high resolution and can be classified as a "turn on and measure" tool. This instrument utilizes LabView software and offers an on-board PC for easy operation. It also includes the ability to adjust the flowrate in the instrument and contains 100 different particle size channels. The LAS operates based on light scattering techniques where a particle is sized based on how much light is scattered in the laser cavity. The instrument operation is based on the principle that the light scattered by a particle within the laser cavity is a direct function of its size. The particles produce pulses of light during transit through the laser beam. Light pulses are then sensed by a pair of detectors that in turn are

analyzed by four cascading amplifier stages coupled to analog-to-digital converters for sizing. Particles are then aerodynamically focused to a sample stream diameter smaller than the laser beam diameter to avoid edge effects [6]. One drawback includes the use of diluters to dilute the test stand air stream so that the LAS can take samples with an appropriate aerosol concentration. Two TSI Model 3302 diluters are used in this study, which include one 100:1 and one 20:1 diluter. These achieve approximate dilution ratios of 100:1 and 20:1 using the 100:1 and 20:1 capillary tubes, respectively. The diluters are characterized before filter testing with the challenge aerosol that will be used. The LAS is depicted in Figure 2.4, and the diluters are shown in Figure 2.5.

Figure 2.4 Laser aerosol spectrometer.

Figure 2.5 Two TSI diluters.

Another commonly used spectrometer is the TSI Scanning Mobility Particle Sizer (SMPS). The SMPS system is composed of a Differential Mobility Analyzer (DMA), Condensation Particle Counter (CPC), and Electrostatic Classifier (EC). The first two components of the SMPS system are the EC and DMA, which are illustrated in Figure 2.6.

Figure 2.6 Scanning Mobility Particle Sizer (SMPS).

The principle of operation of the EC and DMA is based on the monotonic relationship between electrical mobility and particle size with singly charged particles. The EC separates particles based on the mass to charge ratio. A polydisperse aerosol enters the EC and passes through a neutralizer (Krypton-85), which exposes the aerosol to large concentrations of bipolar ions. Particles reach a state of equilibrium, in which they then carry a bipolar charge distribution. The charged aerosol then travels into the 24 inch (61 cm) DMA column. It is important to note the length of the DMA column since it determines the upper end of the range of particle sizes. Both the polydisperse aerosol and the sheath air are introduced at the top of the classifier. They travel downward between the two concentric cylinders within the DMA with no mixing of the two laminar streams. Since the inner cylinder (collector rod) is maintained at a controlled negative voltage and the outer cylinder is grounded, an electric field is generated between the cylinders. This electric field causes positively charged ions to be attracted to the collector rod. Particles with high electrical mobility are precipitated along the upper portion of the rod, and particles with low electrical mobility are collected on the lower portion of the rod. So, the DMA column operates based on the principle that the rate of diffusion of particles through air toward accelerating electrodes is a function of both particle size and mass to charge ratio. Ultimately, the particles within a narrow range of electrical mobility exit with the monodisperse airflow through the bottom of the collector rod to the CPC for particle concentration determination [7]. The minimum particle size detection is dependent upon the CPC connected to the EC. The final component of the SMPS system is the CPC, which is shown in Figure 2.7.

Figure 2.7 Condensation Particle Counter (CPC) on SMPS system.

The aerosol sample from the DMA column is transferred to the CPC and drawn through a heated saturator. Butanol is vaporized and diffuses into the sample stream. The aerosol sample and butanol vapor pass into a condenser where the butanol becomes supersaturated and ready for condensation. Particles that are present in the sample stream act as condensation nuclei, and the butanol condenses on the surfaces of the particles. After the condensation process begins, particles that are larger than a threshold diameter grow into larger droplets. They pass through the optical detector and are then counted. This detector counts individual pulses produced as each droplet passes through the sensing zone [8]. The CPC communicates with the EC to provide a count rate for each bin assigned to a particle size.

The ELPI is a real-time particle size analyzer, which consists of a cascade impactor and an aerosol charger. This instrument is capable of detecting particles in the size range of 0.03 – 10 µm and up to concentrations of 10^7 particles/cm^3 at 10 L/min. It also contains 12 different channels. A cascade impactor is used for particle size fractionating (size classification), which utilizes 12 different electrically insulated stages. The corona charger is the component that charges the particles going through the system. It uses corona discharge to produce ions that transmit their charge to passing particles. Very small particles are removed through a trap voltage that is found after the corona discharge area inside the charger. The trap voltage causes an electric field to remove charged molecule groups and particles smaller than the lowest stage cutpoint. Once the particles have passed through the corona charger, they travel down through

the impactor where they are separated based on their electrical charges. The electrometers are small, needle-like components located behind the impactor that are used to measure the current signals from the 12 impactor stages. During testing, samples are continuously taken by the ELPI and separated onto each of the 12 impactor stages, providing real-time data throughout the entire test. The ELPI software is capable of giving number, diameter, mass, current, area, and volume as functions of aerodynamic diameter. Figure 2.8 displays the ELPI system that is used on the test stand for the project testing activities [9].

Figure 2.8 Electrical Low-Pressure Impactor (ELPI) system.

For clarification, Table 2.2 is generated to summarize the characteristics among the LAS, SMPS, and APS instruments.

Table 2.1 Aerosol measurement instrumentation summary.

Instrument	Concentration Range (#/cc)	Minimum concentration (#/cc)	Particle Size Range (μm)
TSI Model 3340 LAS	$1.8x10^4$ at 10 cm^3/min $3.6x10^3$ at 50 cm^3/min $1.8x10^3$ at 95 cm^3/min	< 0.02	0.09-7.5
TSI SMPS • Model 3080 Electrostatic Classifier (EC) • Model 3081 Differential Mobility Analyzer (DMA)	$1x10^8$ $1x10^4$	2 0	0.01-1.0 0.01- >3

Table 2.1 (Continued)

• Model 3772 Condensation Particle Counter (CPC)			
TSI Model 3321 APS	$1x10^3$ ($1x10^5$ with TSI Model 3302A Diluter)	1	0.3-20

CHAPTER III

FILTRATION USED IN NUCLEAR CONTAINMENT VENTILATION

Standards involving nuclear HEPA filters

The industry of nuclear aerosol filtration includes many codes and standards for nuclear containment ventilation. Some of the most important resources include the Nuclear Air Cleaning Handbook, the American Society of Mechanical Engineers (ASME) Code on Nuclear Air and Gas Treatment (AG-1), and ASME Quality Assurance Requirements for Nuclear Facility Applications (NQA-1). These, along with other resources, help assure the quality of work in nuclear facilities and when qualifying HEPA grade filters for nuclear applications.

The Nuclear Air Cleaning Handbook contains information on systems used in nuclear facilities to contain and control radioactive particulate matter and gases, which was developed by the U.S. Department of Energy (DOE). It is intended to be utilized for nuclear applications within the U.S. DOE and the National Nuclear Security Administration (NNSA). This resource is divided into 11 chapters, which cover material dealing with the history and development of nuclear aerosol filtration, cleaning system considerations, HEPA filters, housing design, glovebox filtration, testing, and many more areas [2]. The ASME Code on Nuclear Air and Gas Treatment (AG-1) was organized in order to develop and implement codes and standards on design, fabrication, inspection, and testing of air cleaning and conditioning components used in nuclear facility safety systems. It contains information relating to mandatory requirements, prohibitions, and nonmandatory requirements for construction activities involved with nuclear facilities. The AG-1 Code is divided into four divisions including General Requirements, Ventilation Air Cleaning and Ventilation Air Conditioning, Process Gas Treatment, and Testing Procedures. These divisions are broken down further into sections. The sections are divided into articles, subarticles, paragraphs, subparagraphs, and sub subparagraphs. Section FC and FK are two noteworthy sections, which discuss HEPA filters and special HEPA filters, respectively. Another important document in nuclear filtration is ASME NQA-1 Quality Assurance Requirements for Nuclear Facility Applications. In 1975, the ASME Committee on Nuclear Quality Assurance was created and operated under the ASME Procedures for Nuclear Projects. Currently, the Committee operates under the ASME Operating Procedures and Practices for Nuclear Codes and Standards Development Committees. This Committee generated ASME NQA-1, Quality Assurance Program Requirements for Nuclear Power Plants. Since the NQA-1 standard was issued, it has been revised numerous times, and the latest edition was published in 2015. NQA-1 includes 18 different criterion or requirements, which include the following sections [10]:

1. Organization
2. Quality Assurance Program
3. Design Control
4. Procurement Document Control
5. Instructions, Procedures, and Drawings
6. Document Control
7. Control of Purchased Items and Services
8. Identification and Control of Items
9. Control of Special Processes
10. Inspection
11. Test Control
12. Control of Measurement and Test Equipment
13. Handling, Storage and Shipping
14. Inspection, Test and Operating Status
15. Control of Nonconforming Items
16. Corrective Action
17. Quality Assurance Records
18. Audits

Overview of ASME code on nuclear air and gas treatment (ASME AG-1-2015)

ASME AG-1-2015 contains invaluable information regarding HEPA filters, special HEPA filters, structural design, filter qualifications, and much more information concerning nuclear filtration systems. The purpose of AG-1 is to provide requirements and non-mandatory guidelines on the design, fabrication, testing, and overall development of a nuclear containment system. The document is divided into many different sections. The sections that contain information on different filter types are included in the following [11]:

- Section FA- Moisture Separators
- Section FB- Medium Efficiency Filters
- Section FC- HEPA Filters
- Section FD- Type II Adsorber Cells

- Section FE- Type III Adsorber Cells
- Section FF- Adsorbent Media
- Section FG- Mounting Frames for Air Cleaning
- Section FH- Other Adsorbers
- Section FI- Metal Media
- Section FJ- Low Efficiency Filters
- Section FK- Special HEPA Filters
- Section FL- Deep Bed Sand Filters
- Section FM- High Strength HEPA Filters
- Section FO- Ceramic Filters

Overview of ASME AG-1 Sections FC and FK

Two important sections in ASME AG-1-2015 are Section FC and FK. They outline the requirements for a filter to be considered acceptable in nuclear applications and are the most developed sections within AG-1. Section FC (page 312) is the most developed and one of the most significant sections within AG-1. It includes the requirements for design, performance, testing, fabrication, inspection, and quality assurance of HEPA filters used in nuclear containment facilities. This section applies to dry-type filters for use in air and gas streams operating at a maximum of 250 °F (121.111°C) continuous temperature and with size and ratings found in Table FC-4110 within Section FC. It also includes several other requirements such as Materials, Design, Inspection, Fabrication, Packaging, Shipping, and Storage, Quality Assurance, and Nameplates. In addition to these, a mandatory appendix for fire resistant, high efficiency filters and a nonmandatory appendix for division of responsibility is also included. Most of the sections currently in development are modeled after Section FC. Section FK (page 457) is a recent addition to AG-1. It contains a very similar structure to Section FC. This section outlines the requirements of odd-shaped or unique HEPA filter types. Three types of special HEPA filters in this section include:

- Type 1- Radial flow filters
- Type 2- Axial flow circular filters
- Type 3- (deleted)
- Type 4- Axial flow rectangular filters that are size variations of those addressed in Section FC

Two important articles within Section FC include Article FC-4000 (Design) and Article FC-5000 (Inspection and Testing). Article FC-4000 (page 316) contains design specifications for the HEPA filters such as filter case, filter pack, gaskets, separators, and much more information. Further into Article 4000, Table FC-4110 contains significant information on how HEPA filters should be constructed. The table lists the nominal sizes and ratings for filter physical dimensions, minimum rated airflow, and maximum resistance. Article FC-5000 (page 322) overviews the HEPA filter qualification testing requirements to be accepted for nuclear containment facilities and inspection requirements. The structure of these two articles in AG-1 are significant for new section development and pose as guidelines to how filters should perform. Article 5000 is particularly important to the content presented in this project since the objective is to initialize development of qualification procedures for ceramic media filter testing. In other words, Article 5000 establishes the performance envelope for HEPA filters, which is a very important resource when developing test procedures and test frameworks for ceramic media filters. Qualification testing (Paragraph FC-5100 on page 322), is divided into seven subparagraphs, which are outlined in Table 3.1 [1].

Table 3.1 Subparagraphs of Paragraph FC-5100

Subparagraph	Title
FC-5110	Resistance to Airflow
FC-5120	Test Aerosol Penetration
FC-5130	Resistance to Rough Handling
FC-5140	Resistance to Pressure
FC-5150	Resistance to Heated Air
FC-5160	Spot Flame Resistance
FC-5170	Structural Requirements

These subparagraphs describe in detail what testing is required to determine if a filter can be used in nuclear containment facilities. It is imperative that the AG-1 code be understood when developing other sections of AG-1, such as Section FO or FI. All newly developed sections should conform to the specifications and requirements listed in Article 4000 and 5000 as well.

Status of ceramic media filter research

To better understand what has been completed and what still needs further research, the following section summarizes work that has involved ceramic media filters.

As discussed in [12], a silicon carbide (SiC) “dead-end” monolithic ceramic filter with a glass-frit-bonded zirconium silicate coating retained 99.97% or greater retention after repeated plugging and cleaning cycles. This paper also includes a review of literature, in which it describes evidence that SiC had been used in nuclear applications. It was also determined that this type of robust filter reduced the potential of HEPA filter failure due to high moisture content or elevated temperatures. Adamson mentions that the ceramic single element filter could potentially be used as a pre-filter, and it operated well in a high humidity setting. Another

conclusion from this paper is that the ceramic filter did not regenerate well after being plugged with road dust. This study shows that ceramic-based filters are not only robust media types, but they also can maintain characteristics similar to those of traditional HEPA grade filters.

The versatility of ceramic filters is also illustrated in [2]. In the 1950s, Hurlbut Paper Company and the Hollingsworth and Vose Company generated a filter paper that was composed of Fiberfrax fibers. These fibers were made of silicon oxide-aluminum hydroxide and could be exposed to temperatures of up to 2000°F (1093.33°C) for extended amounts of time and over 3000°F (1648.889°C) for a shorter amount of time. Flanders Filters, Inc. eventually combined this filter paper and Fiberfrax fibers to generate an all-ceramic filter, which was capable of performing at temperatures over 2,000°F (1093.33°C). These filters were also very resistant to heat shock. Ultimately, the use of these filters diminished because it was not possible to produce fibers fine enough to generate filter efficiencies that fibrous glass media could maintain.

Work completed in [13] shows that ceramic filters have a potential to be used in many different areas of study. In this paper, monolithic ceramic media is tested to see if it can filter trace amounts of solid carbon particles generated as a side product from the conversion of methane to acetylene and hydrogen. The filter tested in this study was a diesel engine particulate filter (DPF) or a monolithic porous media filter, which is composed of either cordierite or aluminum titanate. In order to see the regeneration effects, the carbon-loaded filter was placed in a laboratory furnace and heated to temperatures between 752°F (400°C) and 1652°F (900°C) for six hours. The test results showed that the filter initially produced a low pressure drop at 11 Pa, but after approximately six hours of operation, the pressure drop accelerated to a rate of 0.00042 psi (2.9 Pa/min) all the way up to 0.00159 psi (200 Pa). Regeneration methods were successful on this filter. No leftover particles were found on the filter face surface or in the entrance of the cells. The results also prove that the high temperature oxidation of the carbon is a feasible method for regeneration.

Arunkumar tested a porous ceramic support coated with a filtration membrane in [14]. In this study, the ceramic filter was evaluated after several loading and washing cycles. Results from the loading cycles showed that the projected mass loadings ranged from 9.7 mg to 34.8 mg. Loading curves displayed filtering efficiencies of approximately 98% at 15 inches of water and efficiencies above 99.97% at 25 inches of water. It was also determined that the ceramic filters showed good regenerative ability through multiple cleaning cycles using a 10% nitric acid solution. The differential pressures after three load/wash cycles were essentially the same as the initial differential pressures measured, which was 1.5 inches water column at a rated media velocity of 5 feet/min.

Bishop describes testing completed on a membrane-coated porous ceramic honeycomb monolith filter (CeraMem HEPA filter). This filter was altered so that it could be used as a dead-end, wall-flow filter. Part one of the test utilized an elevated temperature HEPA filtration/catalytic oxidation process to decrease dioxin and furan emissions from incinerator off-gas streams. The second part included the use of ceramic HEPA filters as pre-filters to fibrous glass HEPA filters to reduce the levels of radioactive particulate calcine in a pneumatic

transport system. Results indicate that the clean pressure drop of these ceramic filters are approximately six times the pressure drop of pleated, fibrous glass HEPA filters, but the ceramic filters are valuable in that they can be cleaned by water flushing and backpulse cleaning using compressed gas. Through these two tests, the ceramic filters proved to be useful as either primary filters or pre-filters, which ultimately depends on the application that the filters are used in [15].

A paper by Fukushima overviews a study in which open-cell SiC foams were used as a component in a high efficiency air filter. Ceramic nanowires (NWs) were grown on the surfaces by placing a preceramic polymer coating with a cobalt or copper-based catalyst and heating in N_2 at 2642°F (1450°C). Two NWs (Si_2N_20 and Si_3N_4) were formed onto the surface of the ceramic struts through a catalyst assisted pyrolysis procedure. Collection efficiency tests were performed on the ceramic filters using an SMPS, and an aqueous sodium chloride (NaCl) solution was used to produce nanoparticles. Results from testing proved that the NWs improved the particle removal in the entire size range. Although this was the case, the pressure drop of the filters coated with NWs was around two orders of magnitude higher than the one measured with no NWs. It was also determined that the NW filters displayed equivalent performance to that expected of HEPA filters, which confirms that these ceramic filters could be used as high efficiency filters. The final conclusions from this paper are that the NW filters can be operated at high temperatures because of the ceramic material. Also, they can accommodate higher loads of collected aerosol particles because of their geometry and, in principle, they can be cleaned and used for an extended period of time [16].

One area of concern is the possibility for fires in nuclear facilities. This is the largest potential threat to areas surrounding a facility that contains and handles radioactive materials. Because of the materials they are constructed with, HEPA filter installations can be damaged relatively easily given an elevated temperature scenario. Exposure to filter media in the temperature range of approximately 700-750 °F (371.11-398.889°C) for only five minutes can greatly reduce the FE. If a fire reaches metal materials in a facility, specifically, a nuclear facility, flame temperatures can reach up to several thousand degrees [17]. This information raises concern regarding the design of fire containment systems and the types of filter media needed to suppress a fire in these types of situations. A recent study of realistic fire scenarios for non-reactor nuclear facilities indicates a maximum air temperature of 500°C for Ultra-Fast Fires [29]. A desirable characteristic of ceramic media filters is the ability to withstand high temperatures (400^{o}C and 500^{o}C), which would be useful to incorporate into fire containment systems either as pre-filters or the primary filters.

CHAPTER IV

TEST STAND DESCRIPTION

One of the first steps to evaluate ceramic media filters is to create a qualification test stand for filter testing. In a previous research project at ICET, a large scale test stand was designed and built to test sintered and powdered metal media filters [18]. The design of the metal media test stand includes three main sections: the upstream, housing (middle), and downstream. The upstream and downstream sections are both composed of 6 inch diameter 304L stainless steel piping, and the housing section is 12 inch diameter 304L stainless steel pipe. The housing section needed to be able to hold up to three radial flow metal media filter elements, which are four inches in diameter and 2.6 meters long. Also included in the test stand design are a number of flanges and ports located in all three sections. Flanges were added so that there could be areas for aerosol sampling, aerosol injection sites, and filter imaging equipment. Ports and couplings on the test stand are included to allow for temperature, relative humidity, static pressure, and differential pressure readings. A blower and claw compressor provided a positive pressure airflow system for the test stand. The downstream section includes a venturi flowmeter and the test stand exit pipe, which opens to the atmosphere outside of the highbay. A complete drawing of the metal media test stand design is illustrated in Figure 4.1.

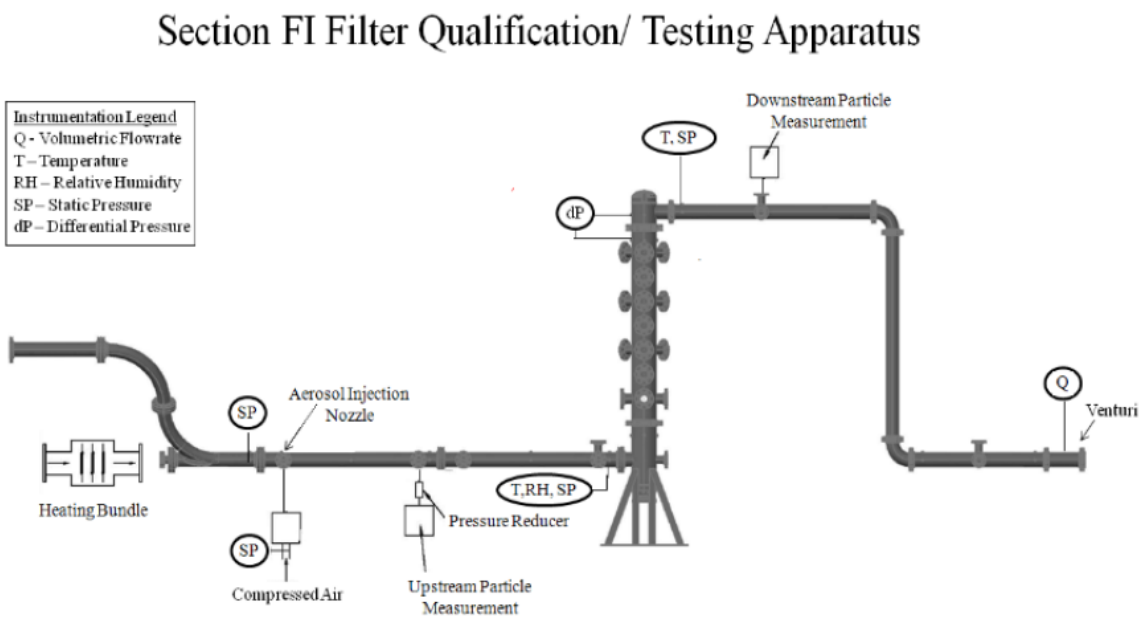


Figure 4.1 Metal media filter test stand design.

This test stand has the potential to produce a large range of parameters as outlined in Table 4.1.

Table 4.1 Actual performance capabilities of metal media test stand.

Capacity	House up to three 8-foot-long filter elements
Flow	Produce 50-160 ACFM of airflow at pressures up to 10 psi (68947.6 Pa)
Test Conditions	Capability of maintaining 60-80 °F (15.556-26.667°C), 40-60% RH, up to 10 psi (68947.6 Pa)
Test Stand Data Measurements	Continuous measurement and recording of static pressure, temperature, differential pressure, relative humidity, and flow rate
Aerosol Measurement	Continuous measurement and recording of particle concentration and particle size
High Temperature	Separate test stand design which requires further work
High Pressure	Separate test stand design which requires further work

All design considerations and calculations are found in [18]. The metal media test stand is equipped with sensors to monitor parameters such as temperature, relative humidity,

differential pressure, static pressure, and air flowrate. Data collected from the sensors are continuously logged in the test stand computer and software. Table 4.2 displays information about the sensors found on the test stand.

Table 4.2 Metal media test stand sensor information.

Sensor Type	Manufacturer	Model Number	Sensor Ranges
Temperature Transmitter	Omega	TX-M12-RTD-C	N/A
Temperature RTD Probe	Omega	PR-22-3-100-B-1/4-0900-M12	-122 – 932°F (-50 - 500°C)
Relative Humidity and Temperature Transmitter	Vaisala	HMT338	0 – 100 %
Differential Pressure	Omega	PX409-2.5DDUI PX409-0005DDUI PX409-015DDUI	0 - 2.5 psig (0 – 17236.9 Pa) 0 - 5 psig (0 – 34473.8 Pa) 0 - 15 psig (0 – 103421 Pa)
Static Pressure	ProSense	SPT25-20-0030D	0 - 30 psig (0 – 206843 Pa)
Venturi Flowmeter	Primary Flow Signal	6” HVT-FV	50 - 375 CFM

The locations of the sensors on the metal media test stand are illustrated in Figure 4.2.

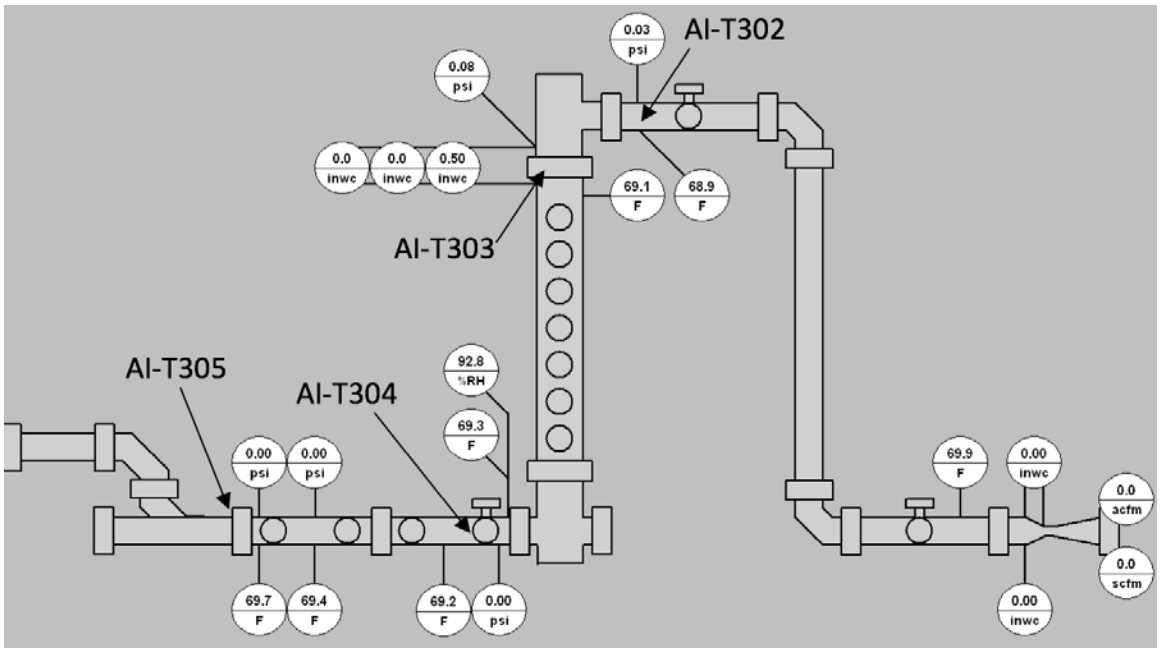


Figure 4.2 Sensor locations on the metal media test stand.

The sensor locations ensure optimal data measurement for each test stand section. Differential pressure sensors are located right before and after the filter. Flow rates greater than 50 CFM are controlled using the venturi flowmeter. Static pressure and temperature sensors are found in all three sections, while the relative humidity sensor is located in the upstream section right before the housing. Two different air supply systems were used on the metal media test stand for positive pressure airflow. First, two Spencer vortex blowers arranged in series were used to push air through the test stand, which provided flowrates up to 133 ACFM at 6 inch water column (in. WC). The second set of tests utilized an Elmo-Rietschle claw compressor that provided flowrates from 20 to 160 ACFM and pressures up to 10 psi (68947.6 Pa). The findings from [18] indicate that the vortex blowers maintained a smoother flow than the claw compressor and are recommended for testing small filter elements that require lower flowrates and differential pressure.

Ceramic media test stand description

In order to better understand the test stand design requirements for the metal media test stand and the ceramic media test stand, Figure 4.3 displays a size comparison of the metal media and ceramic media filter elements.

Figure 4.3 Comparison of ceramic media and metal media filters.

The ceramic media filter is composed of six elements that are significantly shorter than the three metal media filter elements. The metal media test stand is designed to house filter elements up to two meters long, while the ceramic media test stand is designed to house filter elements. Many of the ceramic media test stand design requirements are directly correlated to the size difference between the ceramic and metal media filters.

One of the primary differences between the metal media test stand and the ceramic media test stand is the flowrate requirements. The metal media test stand provided 130 to 160 CFM using the vortex blowers and claw compressor, while the ceramic media test stand only requires 5 to 20 CFM. Several iterations of test stand design are considered in the development of an apparatus that could house and test ceramic media filters. After several conference calls, the ceramic media filter Technical Working Group (TWG) decided on test performance requirements and a test matrix, which is found in Appendix D. Table 4.3 summarizes key differences between the initial and modified test stand performance characteristics.

Table 4.3 Comparison of metal media and ceramic media test stand requirements.

Metal Media Test Stand Design	Ceramic Media Test Stand Design
• House up to three 8-foot-long filter elements	• House single element and six-element ceramic media filters (0.75 – 0.92 feet long)

• Produce 50 – 160 ACFM of air flow at pressures up to 10 psi (68947.6 Pa) using a positive pressure system • Maintain conditions of 60 – 80 °F (15.556 – 26.667°C), 40 – 60% RH, up to 10 psig (68947.6 Pa) • Continuously measure and record static pressure, dP, temperature, RH, flow rate, particle concentration, and particle size	• Produce 5 – 25 ACFM of air flow (induced draft system); positive pressure system also included • Ambient conditions during testing; elevated temperature system to reach 752°F (400°C) and 932°F (500°C) at filter currently in development • Continuously measure and record static pressure, dP, temperature, RH, flow rate, and particle concentration, and particle size

Several modifications are made to the metal media test stand. First, the upstream piping section of the test stand is significantly shortened. The entire upstream section of the metal test stand, except for the section bolted to the housing, is removed. The reason for reducing the length is to minimize the heat loss in the upstream piping, so that the target temperatures of 752°F (400°C) and 932°F (500°C) at the filter can be achieved. The shortened upstream section is shown in Figure 4.4.

Figure 4.4 Upstream section of ceramic media test stand.

An updated image of the modified test stand is given in Figure 4.5.

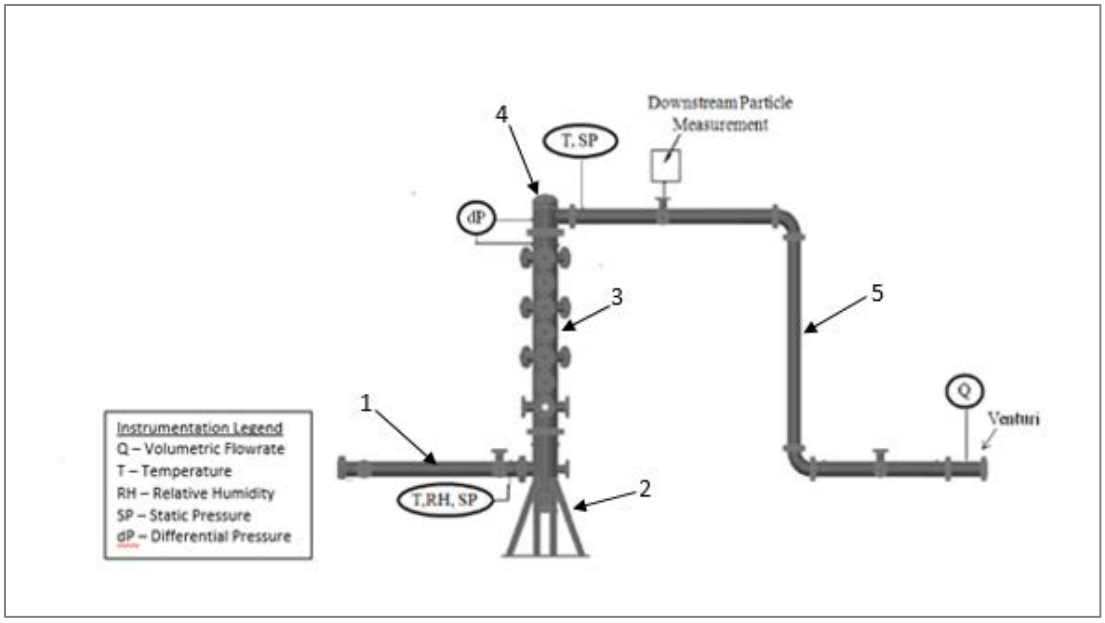


Figure 4.5 Ceramic media filter test stand sections.

In this figure, "1" represents the upstream section, "2" is the test stand base, "3" is the housing, "4" is the housing cap, and "5" is the downstream section.

Ceramic media test stand components

A major modification to the test stand is the air supply system. A positive pressure air flow system is generated first, which is shown in Figure 4.6.

Figure 4.6 Positive pressure air flow system for ceramic media test stand.

An air hose is connected to the system to supply compressed air from an Atlas Copco air compressor capable of providing 0 – 429.4 CFM at 132 psi (910108 Pa). After the air hose, a manual pressure regulator is added to control how much of the air can go into the system. A Spence Engineering Type J control valve is used to control how much air flow is traveling through the system. Connected to the flow control valve are two pressure gauges and a current to pressure transducer, which converts the analog signal (4 to 20 mA) to a proportional pneumatic output. The next item in the system is an Oripac Model 5300 orifice plate. This orifice plate is made of 304 stainless steel and is rated for 20 CFM air flow in a 0.5-inch diameter line. To appropriately select an orifice plate for the application of this project, *Process Measurement and Analysis* Chapter 2.14 is referenced [19]. Lambda Square, the company where the orifice plate was ordered from, provided a flow element calculation (using ORIFICE2) to more accurately select an orifice plate that fit the project requirements. Finally, the orifice plate is connected to a differential pressure sensor. This system operates based off how much air is going through the orifice plate. Both the orifice plate and the flow valve are connected to a programmable logic controller (PLC) in the test stand computer. A PID controller is used in the PLC to control the set points of the air flow.

An induced draft air flow system is later developed and utilized for filter testing. A Spencer vortex blower Model VB-037B-000 is used to create a negative pressure air flow system. This blower maintains specifications of 5 horsepower (hp) and 3450 revolutions per minute (RPM). It can produce low flow rates and a negative pressure environment inside the ductwork. The vortex blower is connected to the test stand by welding stainless steel piping from the test stand exit pipe to the inlet of the blower outside of the highbay. The vortex blower is shown in Figure 4.7.

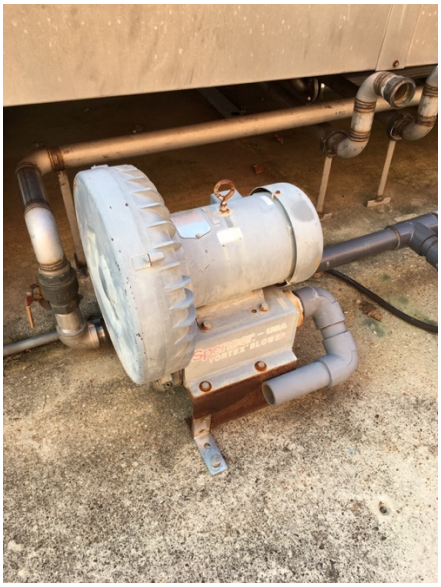


Figure 4.7 Spencer vortex blower used for induced-draft air supply system.

The induced draft air flow system is beneficial for ceramic media filter testing for various reasons. Ceramic media filter testing requires low flow rates and low pressure drops compared to metal media filter testing, so by using an induced draft system, ceramic media filters can be tested appropriately. Also, an induced draft system creates favorable conditions for the aerosol measurement instrumentation and helps increase the concentration of aerosol generation through negative pressure inside the ductwork. In the case of testing metal media filters in addition to ceramic media filters, the positive pressure flow system can be used.

To accommodate for elevated temperature testing, several components are purchased and installed on the test stand. A Tutco Farnam Heat Torch air heater is purchased and includes the following properties:

- 2-inch outer diameter
- 9 inch length
- 7 kW
- 208 volts
- Single phase
- 1-inch female NPT inlet and 1 ¼ inch female NPT outlet
- 1 type K thermocouple
- Maximum exhaust temperature of 1300°F (704.44°C)

The air heater is installed in-line between the orifice plate and the beginning of the upstream ductwork. A heater size of 7 kW is chosen based off prior calculations, which provides

temperatures well above 752°F (400°C) and 932°F (500°C). Higher temperatures were obtained using Cal Poly's HTTU unit, which included much less metal to be heated compared to ICET's large scale test stand. One single phase 7 kW heater is used at ICET, while 3 three phase 12.5 kW Tutco HT200 heaters were used in the HTTU unit. To select the right heater for the project application, the following equation is considered [20]:

$$\text{kW} = \frac{\text{CFM} \times \text{Temperature Rise (°F)}}{3000} \tag{4.1}$$

where an inlet air temperature of 70°F (21.11°C) and a pressure of 14.7 psia (101352.9 Pa) are assumed. Since airflow is given in CFM, a conversion to SCFM must be made in order to use equation 4.1. The conversion from CFM to SCFM is defined as:

$$\text{SCFM} = \text{CFM} \times \frac{\text{PSIG}+14.7}{\text{T}+460} \times 35.37 \tag{4.2}$$

A type K thermocouple is added to the heater outlet to ensure a failsafe against burning out the heater. Figure 4.8 displays the air heater installed in the test stand upstream section.

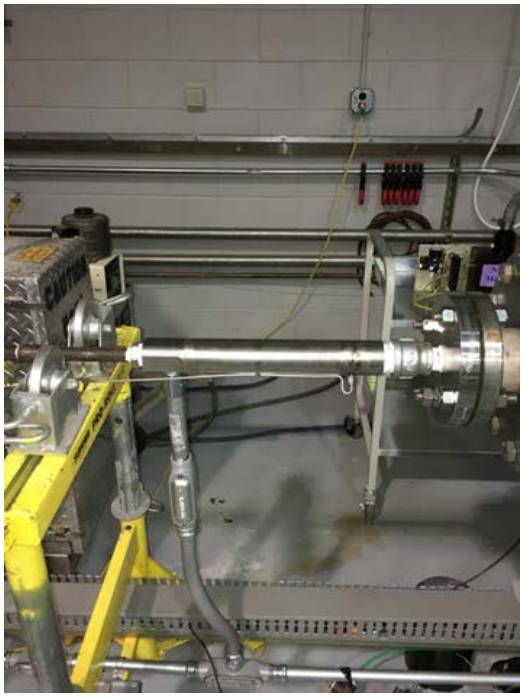


Figure 4.8 Air heater installed in test stand for high temperature testing.

Another component in the high temperature testing system is a low differential pressure switch purchased from Dwyer. The pressure switch is used to sense a difference in pressure between two pressure sources in the ductwork, and includes a range of 1.5 to 5.0 in. WC. The pressure switch is shown in Figure 4.9.

Figure 4.9 Low differential pressure switch.

Next, a Watlow Silicon Controlled Rectifier (SCR) Power Controller is placed into the elevated temperature system. This component controls the electric heat from the heater and is installed inside an electrical box as shown in Figure 4.10.

Figure 4.10 Watlow SCR power controller.

The power controller is rated for up to 55 amps and includes a 4-20 mA input and 100-240V line and load voltage. Additional components for elevated temperature testing includes thermocouples and thermocouple transmitters that can handle elevated temperatures. Like most of the other thermocouples found at ICET, the ones purchased for this project are Omega Type K thermocouples with ranges from -392°F (200°C) to 2282°F (1250°C). A total of four thermocouples were purchased. Two of them are 6 inches in length and ungrounded. One thermocouple is 12 inches in length and ungrounded, and the last thermocouple is 6 inches in length and grounded. The 6 inch thermocouples are placed in the upstream and housing sections of the test stand, while the 12 inch thermocouple is placed in the downstream section. A component that is included along with the thermocouples are the transmitters. Four Omega temperature transmitters are purchased and installed into the thermocouple cast iron housings. The cast iron heads are chosen for better resistance to high temperatures, which better protects the transmitters. The transmitters are programmable, galvanically isolated, include 56 preprogrammed ranges, and can provide measurements for types K, J, N, E, T, R, and S thermocouples and mV inputs. Figure 4.11 displays three thermocouples installed in the upstream section, housing, and downstream section of the test stand.

Figure 4.11 High temperature thermocouple and transmitter assembly.

The components in the elevated temperature system are arranged as illustrated in Figure 4.12.

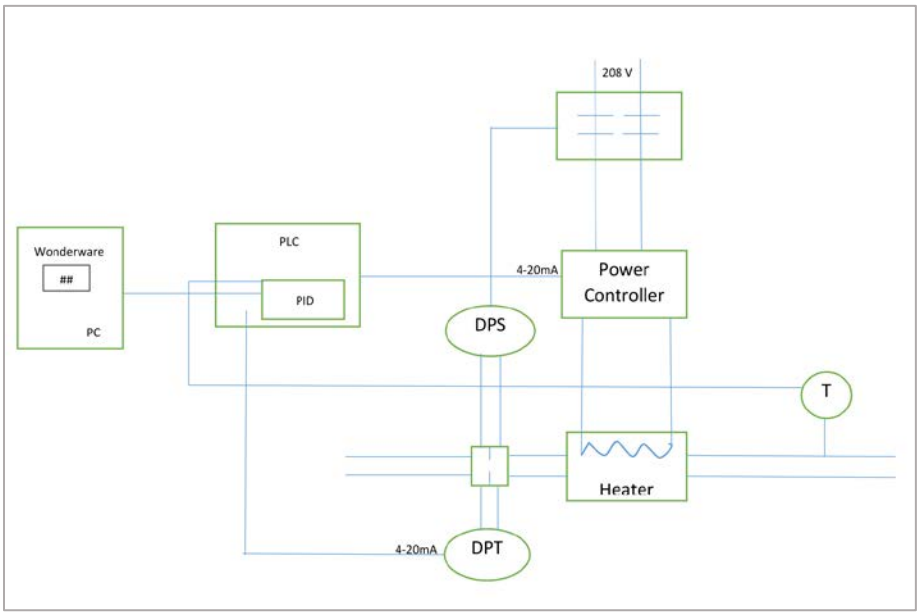


Figure 4.12 Schematic of the elevated temperature system operation.

In this figure, “PC” signifies the test stand computer with the software Wonderware installed. Through this interface, PID settings for the heater can be adjusted, and the PLC can be modified. “DPS” is the differential pressure switch, “DPT” is the differential pressure

transmitter, “T” is the heater thermocouple, and “208 V” is the voltage supply. The square box located between the differential pressure transmitter and differential pressure switch is the orifice plate installed in the upstream duct right before the in-duct air heater.

Characterization of ceramic media test stand

To verify that the induced draft airflow system operates correctly, traverse point measurements are taken with a TSI Alnor Model AVM440 air velocity meter. A total of six points are measured in the horizontal plane and six in the vertical plane of the test stand duct. The procedure on where to take the measurements and how many to take were based off the material found in the EPA Method 1 standard [21]. Figure 4.13 illustrates the desired traverse points to measure in circular stacks.

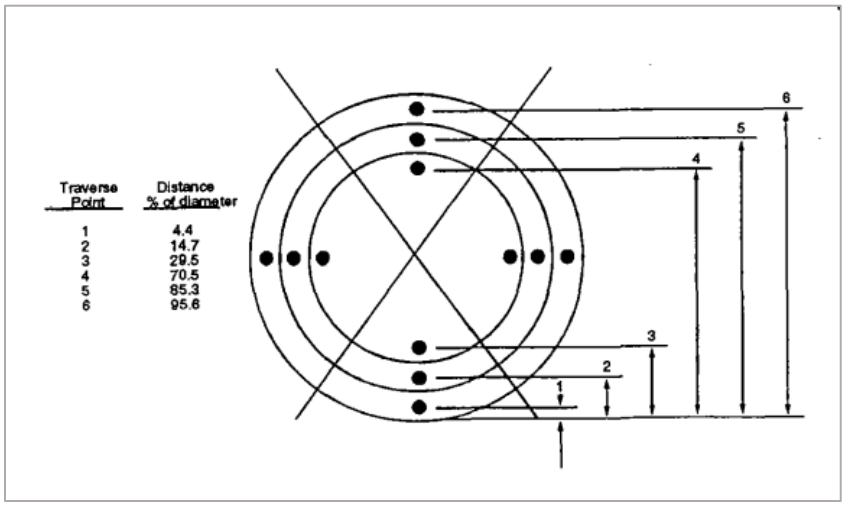


Figure 4.13 Cross-sectional view of traverse points on a circular stack.

Measurements are taken at approximately 4.4%, 14.7%, 29.5%, 70.5%, 85.3%, and 95.6% away from the duct wall for both the horizontal and vertical planes of the test stand duct. This procedure is followed when measuring the upstream section, housing, and downstream section of the test stand. At each location, the air velocity meter is fixed into a flange using the appropriate fittings. Once the first measurement is complete, the air velocity meter is taken out of the flange, extended to the next length, and re-installed back into the flange. A total of 720 measurements are taken to characterize the induced draft airflow system. Table 4.4 displays the averaged results for the induced draft airflow system characterization. Appendix B contains the traverse point measurement data collected.

Table 4.4 Summary for traverse point measurement of induced-draft airflow system.

Test Stand Location	Measurement Orientation	Setpoint (CFM)	Averaged Measured Flow (CFM)	Averaged Measured Velocity (ft/min)
Upstream	Horizontal	5	5.238	26.83
		20	21.16	108.5
	Vertical	5	5.265	27.00
		20	19.66	100.6
Downstream	Horizontal	5	5.920	30.16
		20	26.35	134.3
	Vertical	5	5.071	26.16
		20	21.73	110.6
Housing	Horizontal	10	31.92	40.50
		20	45.32	57.66
	Vertical	10	26.94	34.16
		20	58.99	75.16

The only outliers in this data include the measurements for the housing section. These values are greater than the airflow setpoint, which is due to the number of flanges located in the housing section. Also, the 5 CFM measurement is replaced with a 10 CFM measurement for the housing section since the velometer could not register readings at such a low velocity in the 12-inch diameter duct. To further characterize the induced draft air flow system, data for air flowrate, orifice plate dP, temperature, and relative humidity are collected during test stand operation and displayed in Figure 4.14.

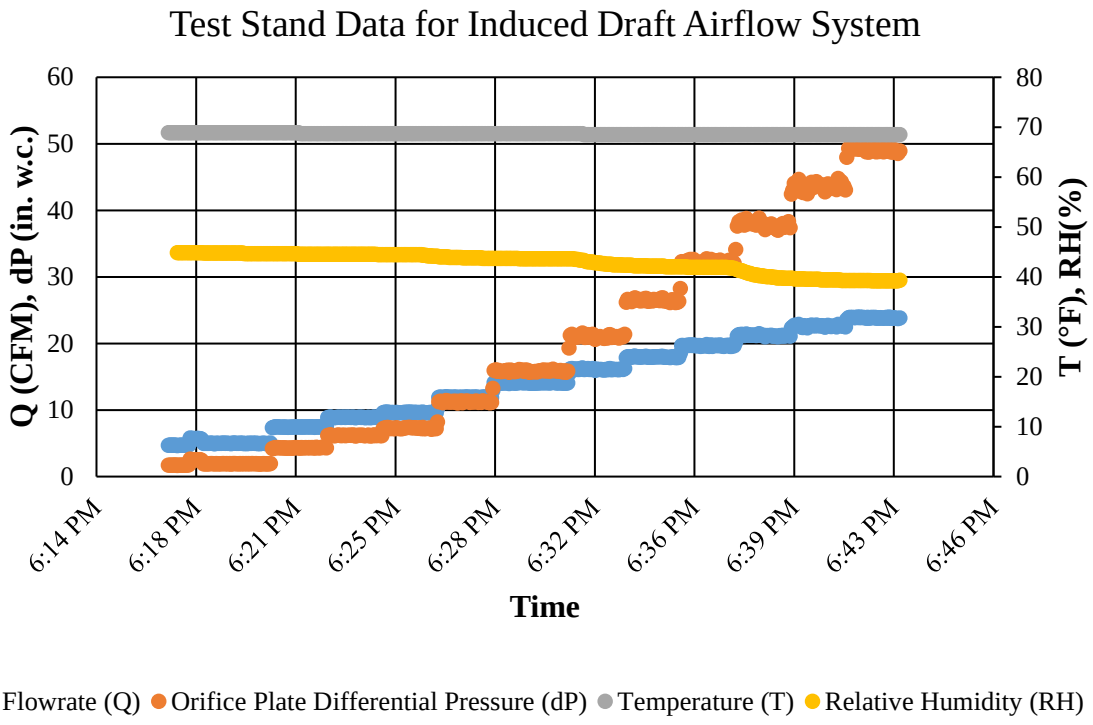


Figure 4.14 Test stand data for induced draft system characterization.

The data in this figure illustrates test stand characterization and does not include a filter element inside the housing. The air flowrate for the system, initially at 5 CFM, was increased incrementally up to 23 CFM without any aerosol added in the test stand.

Characterization of the test stand before filter testing includes leak checks. Details on this process are found in the procedures in Appendix E.

Tube sheets for ceramic media filters

Two tube sheets, used for filter element support, are fabricated in-house at ICET. One tube sheet is made for a six-element ceramic filter and another is fabricated for a single element ceramic filter. These tube sheets fit between the flanges of the test stand cap and housing section as illustrated in Figure 4.15.

Figure 4.15 Tube sheet installed between housing section and housing cap.

The tube sheets that hold the ceramic media filters are 0.5 inches in thickness and 12 inches in diameter. Designs for the six-element ceramic filter tube sheet required a 9-inch diameter circle to be cut out of the middle. This ensured that the six-element ceramic filters could fit inside the usable inside diameter of the tube sheet, and that the filters could be properly attached. An image of the tube sheet with a six-element filter attached is shown in Figure 4.16.

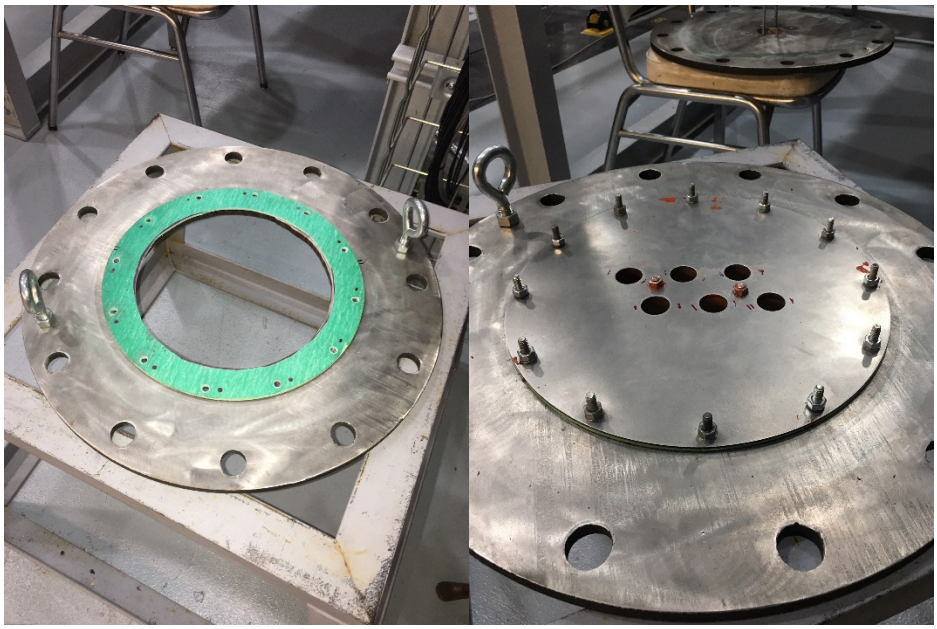


Figure 4.16 Six-element ceramic filter tube sheet with and without filter installed.

The single element tube sheet only has a 3-inch diameter hole cut in the middle so that the single element ceramic filters could fit. In addition, two rods and a metal plate were included so that the filters would have extra support and could be tightened securely in place. Figure 4.17 displays the tube sheet and the single element ceramic filter attached to it.

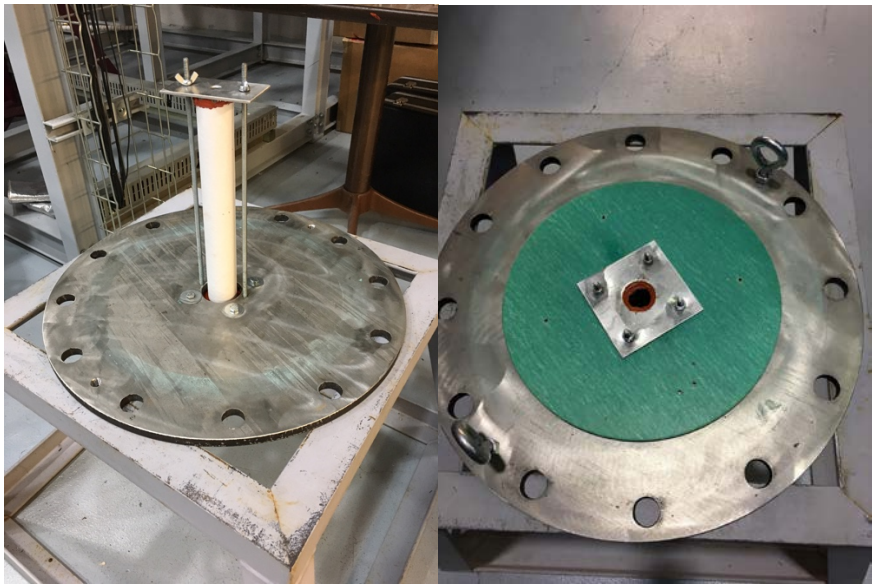


Figure 4.17 Single element ceramic filter tube sheet with filter installed.

Procedures on filter installation onto the tube sheets and tube sheet installation onto the test stand are found in Appendix E.7. Before testing, a gasket is placed onto the tube sheet. Then, the six-element ceramic filter is placed onto the gasket and bolted down to the tube sheet using a series of bolts, nuts, and washers. When a single element ceramic filter is installed onto the tube sheet, it is first attached to a metal plate (4-inch by 4-inch) using RTV 116 sealant. The sealant used was recommended by the Section FO technical working group, which is usable as a high temperature, versatile adhesive sealant. After curing, the plate (and filter attached to it) were bolted to the tube sheet using a series of bolts, nuts, and washers. Once all components had fully cured and dried, a metal plate was tightened to the filter end cap using two wingnuts.

Ceramic media test stand control system

The test stand induced air flow system is operated using a variable frequency drive (VFD) combined with a programmable logic controller (PLC) system. The initial VFD used was a Magnetek GPD 515 Model GPD515C-B014. This VFD was upgraded with a GS2 Series Micro Drive VFD from AutomationDirect. Air flow through the test stand is produced using an induced draft vortex blower, which is controlled by mass flow data generated as differential pressure values across an orifice plate. The VFD communicates with the PLC to adjust the blower speed based off the differential pressure readings. The PLC also communicates with Wonderware, a software used for parameter input, sensor data display, and data collection. Wonderware and the PLC are used in tandem with one another for data transfer from the test stand sensors to the computer system. Data is continuously logged into the computer system from all test stand sensors as long as the computer is turned on. The operator inputs the desired parameters, such as flowrate and heater setpoints, into the control system computer screen. Details on how to use the control system interface are found in the test procedures in Appendix E.2. Figure 4.18 shows the screen for test stand flow control.

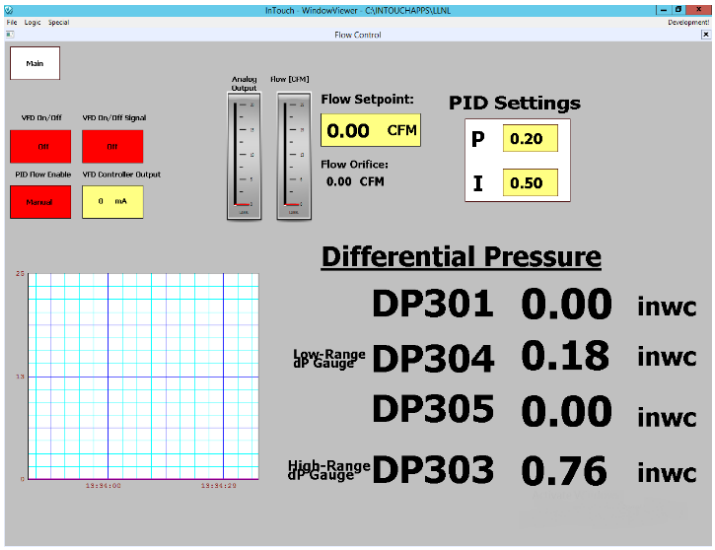


Figure 4.18 Test stand flow control screen.

In this screen, the desired test stand flowrate is input, and the differential pressures through the orifice are monitored as well as the differential pressures at the filter. Another screen in the test stand control system is shown in Figure 4.19.

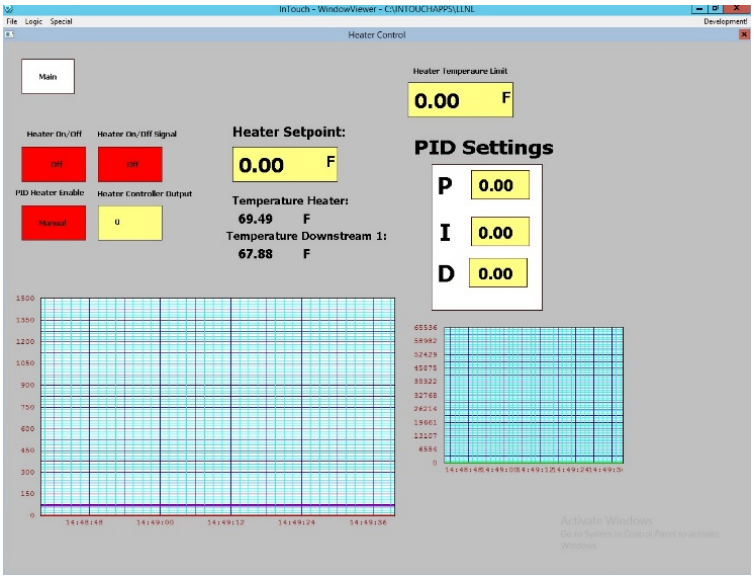


Figure 4.19 Test stand heater control screen.

This is the interface that controls the in-duct air heater in the upstream section of the test stand. Once all the parameters are input into the interface, the heater temperature and the temperature downstream of the heater are monitored on this screen.
The test stand data collection interface is controlled by using the screen displayed in Figure 4.20.

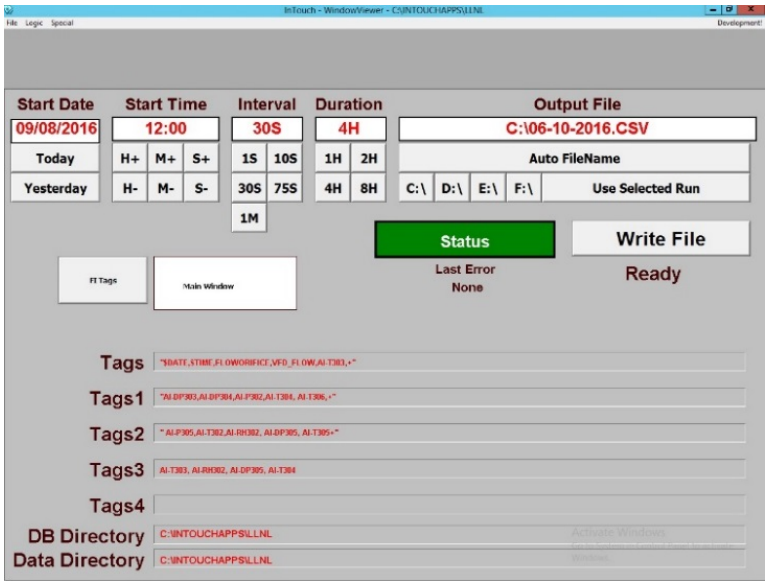


Figure 4.20 Test stand data screen.

The details associated with testing such as start time, start date, duration, interval for samples collected, and the output file name are found this screen. Data collected from any of the desired test stand sensors must be input into the "Tags" boxes, and the directories in "DB Directory" and "Data Directory" must be listed as well. Figure 4.21 displays the main screen of the test stand control system.

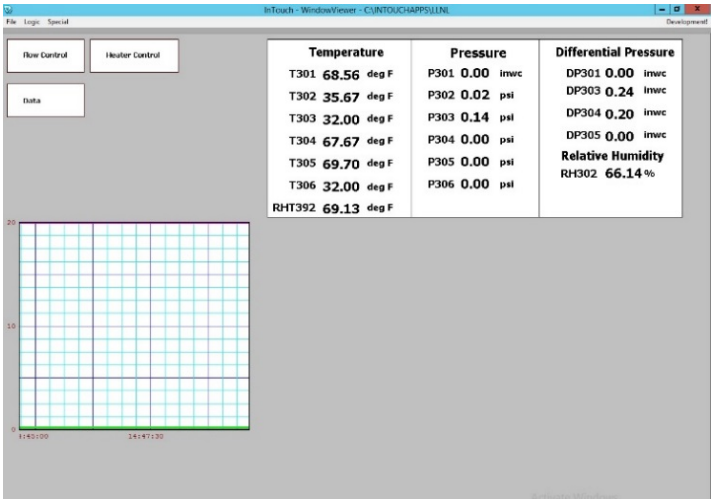


Figure 4.21 Test stand main screen.

From this screen the flow control, heater control, and data screens can all be accessed, and the test stand sensor data can be monitored.

Aerosol generation

Two different types of aerosols are used for testing activities in this study, which include DOP and KCl. Procedures for aerosol generation in this project are outlined in Appendix E.1. The DOP is produced using a TSI six-jet atomizer as illustrated in Figure 4.22.

Figure 4.22 TSI six-jet atomizer used for DOP generation.

The DOP generator arrangement on the test stand is shown in Figure 4.23.

Figure 4.23 DOP generator arrangement on test stand aerosol injection site.

The KCl challenge aerosol is produced using a large scale aerosol generator, which is depicted in Figure 4.24.

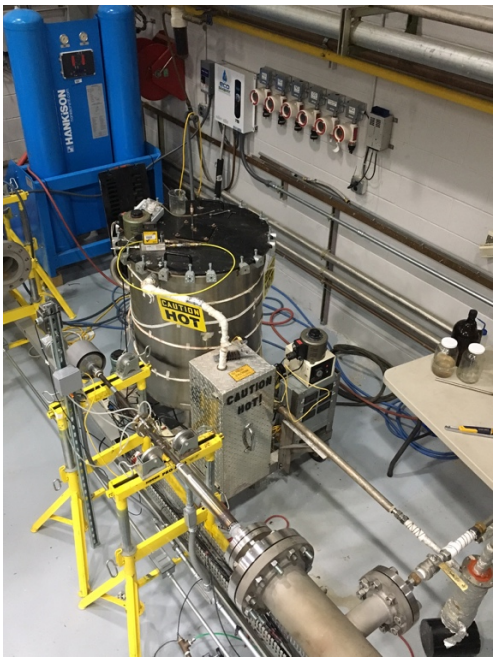


Figure 4.24 Large scale aerosol generator used for KCl aerosol production.

The details and design for a large scale aerosol generation system is described in [22]. From the testing completed in [22], optimum operation conditions include a flow rate of 28 liters per minute (LPM) of air through the atomizing nozzle, 10 milliliters per minute (mL/min) flow of liquid solution through the atomizing nozzle, and a flow rate of 130 LPM air sheath flow rate at a temperature of approximately 200°F (93.333°C). The wall temperature of the tank should reach approximately 200°F (93.333°C), and the tubing connecting the aerosol generator tank to the test stand also should reach 200°F (93.333°C).

An Atlas Copco air compressor is used to push dry air into the aerosol generation system. The dry air enters through a mass flow controller and then the air heating box, which are illustrated in Figures 4.25 and 4.26, respectively.

Figure 4.25 Mass flow controller which provides sheath air flow.

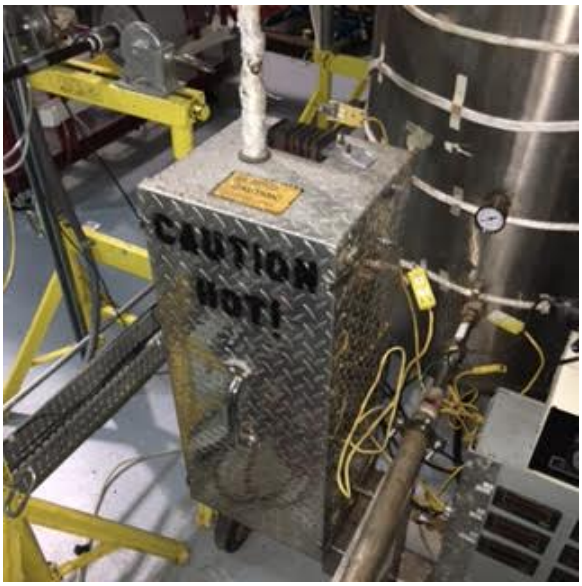


Figure 4.26 Air heating box on large-scale aerosol generator.

The air heating box contains three heating elements to heat the sheath air to an elevated temperature. Throughout numerous tests on the aerosol generator, the heating

elements burned out multiple times and were replaced to reach the required target temperatures.

Once the air is heated to an acceptable temperature, it travels through the stainless steel tank, which is shown in Figure 4.27.

Figure 4.27 Large scale aerosol generator tank.

The aerosol is generated in the atomizing nozzle by mixing dry air and liquid KCl solution. This apparatus operates based on the generation of a liquid aerosol by an atomizing nozzle, which is then heated when it travels into the stainless steel tank. The atomizing nozzle is shown in Figure 4.28 and is bolted to the top of the aerosol generator tank once the system is ready for operation.

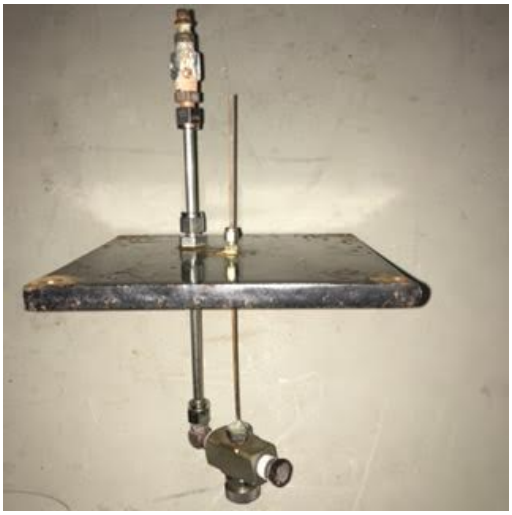


Figure 4.28 Large scale aerosol generator atomizing nozzle.

The aerosol is sprayed into the tank, dried, and then pushed into a heated transfer line. Once the aerosol passes through the transfer line, it travels through the cyclone. This component was designed to achieve a cut diameter (d_{50}) of 3 µm and is used to separate the large particles out of the aerosol stream. Figure 4.29 depicts both the heated transfer line and the cyclone, which are both in between the test stand aerosol injection site and the aerosol generator.

Figure 4.29 Heated transfer line and cyclone on aerosol generation system.

Finally, the aerosol is injected into the test stand after the aerosol generator exit valve is opened. Throughout operation of the large scale aerosol generator, it is imperative that the temperatures of each thermocouple are monitored to ensure that the aerosol is being generated properly. The thermocouple temperatures that indicate the aerosol generator is ready for operation are included in the Aerosol Generation procedure in Appendix E.1.

The KCl was purchased from Alpha Chemicals in five pound bags as a solid chemical powder. The KCl powder is mixed with deionized water to form a solution to be used as the challenge aerosol. The procedure for making the KCl solution is also found in Appendix E.1.

Aerosol measurement system for ceramic media test stand

An aerosol sampling system is incorporated into the test stand, which includes a TSI Scanning Mobility Particle Sizer (SMPS), TSI Laser Aerosol Spectrometer (LAS), and two TSI Model 3302 diluters. In addition to the sampling system, a Dekati Electrical Low Pressure Impactor (ELPI) is also utilized. The sampling system, shown in Figure 4.30, allows for both upstream and downstream sampling in the test stand.

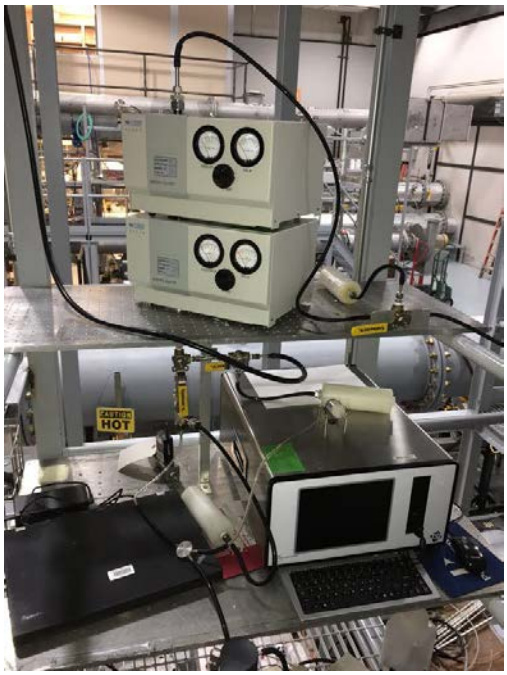


Figure 4.30 Test stand sampling train system.

The system is composed of two TSI Model 3302 diluters (100:1 and 20:1 diluters), the LAS particle sizer, the SMPS particle sizer, an Alicat Scientific Model MCP-50SLPM-D-30PSIA/CM flow controller, a second Alicat Scientific flow controller, three T-valves, an isokinetic coupler, two vacuum pumps, and four HEPA filter capsules. One Alicat flow controller, shown in Figure 4.31, controls the air being pulled through the diluters by the vacuum pump.

Figure 4.31 Isokinetic flow assembly for sampling system.

The diluters require at least 5 LPM of air to be pulled through to achieve isokinetic flow through the capillary tubes [23]. A HEPA filter capsule is placed before the flow controller so that clean air enters the flow controller and exits the vacuum pump. Conductive tubing is used to connect the isokinetic coupler to the HEPA filter capsule and the flow controller to the vacuum pump. The vacuum pump used to pull air through the sampling train is shown in Figure 4.32.

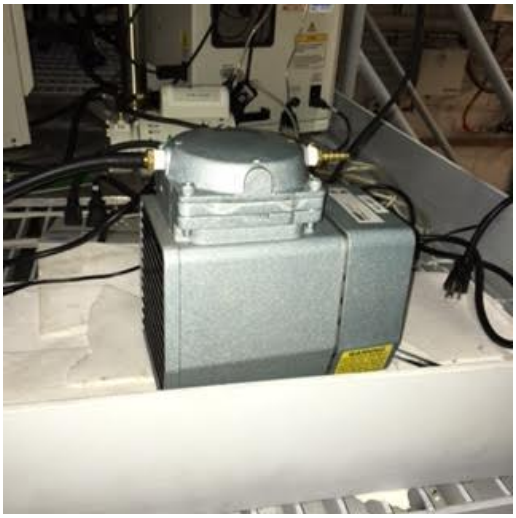


Figure 4.32 Vacuum pump used to pull air through sampling train.

Three T-valves are used in the sampling system so that upstream and downstream data can be conveniently collected. The valve system also enables the use of a quick purging system to clean the tubing and instruments with filtered air. Figure 4.33 displays the valves that are used on the sampling train.

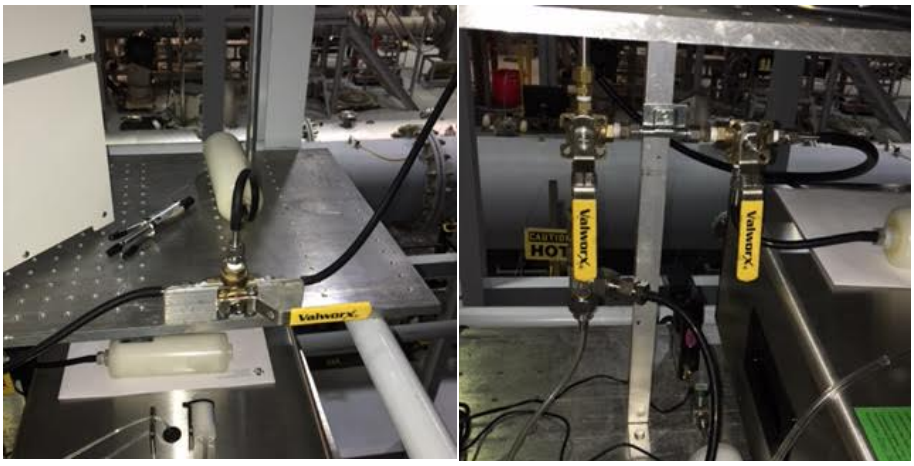


Figure 4.33 T-valves on sampling system for upstream and downstream measurement.

Two TSI Model 3302 diluters, shown in Figure 2.5, are utilized in this system. These decrease the aerosol concentrations from the test stand so that the LAS can operate in the correct concentration range. Diluter characterization is performed in this project by following the procedure listed as HEPA-M&TE-016. After characterization is completed, the dilution ratios are found to be 95.71 for the 100:1 diluter and 18.234 for the 20:1 diluter. Details on diluter characterization data reduction are found in the Mathcad sheet listed in Appendix F.2.

The LAS is illustrated in Figure 2.4. This instrument is important to include in this project because it offers advantages that other instruments could not. For example, it includes a wide size range for ceramic media filter testing (0.09 to 7.5 μm) and has a high sensitivity and resolution. In accordance with the ICET quality assurance program, the LAS instrument is received, a receipt inspection is performed, and a PSL (polystyrene latex) sphere verification test is completed. The referenced document for receipt inspection includes ICET-QA-009 Item Receipt and Control, and the document for PSL verification includes HEPA-M&TE-011 LAS Particle Sizing Verification.

Another instrument used in this study is the SMPS, which offers a view of particles in the size range of 10 nm to 1000 nm using a TSI Long DMA combined with the Electrostatic Classifier (EC) and Condensation Particle Counter (CPC). Figures 2.6 and 2.7 display the SMPS instrument used for testing activities in this study. The SMPS system separates the particles by size for high resolution measurements to produce reasonable particle size distributions (PSD). In this project, the CPC model required an external vacuum pump and flow controller to be used for sampling. The assembly is shown in Figure 4.34.

Figure 4.34 Condensation particle counter (CPC) external vacuum pump setup.

An Alicat Scientific flow controller is connected in between the CPC and the vacuum pump to control how much flow is being pulled out of the CPC. The target sample flowrate on the SMPS is 0.3 L/min, so the flow controller is adjusted when necessary. A HEPA filter capsule is connected between the CPC and flow controller so that only clean air travels into the flow controller and exits out of the vacuum pump. SMPS readiness and operation procedures for this project reference those found in HEPA-M&TE-002 Readiness and Operation of Scanning Mobility Particle Sizer (SMPS) Spectrometer. The SMPS and LAS both pull samples from the same line in the sampling train. This is possible by connecting the tubing from each instrument to a two-way splitter, which is shown in Figure 4.35.

Figure 4.35 Splitter used for simultaneous sampling of LAS and SMPS.

The top portion of the splitter leads to the sampling train assembly where air is pulled through the diluters so that aerosol samples can be collected. The conductive tubing on the bottom left of the splitter is the SMPS sampling line, and the bottom right conductive tubing is the LAS sampling line. Using the LAS in conjunction with the SMPS, meaningful data is collected and analyzed to characterize a range of ceramic media filters. Sampling nozzles for the aerosol measurement instrumentation are shown in Figure 4.36.

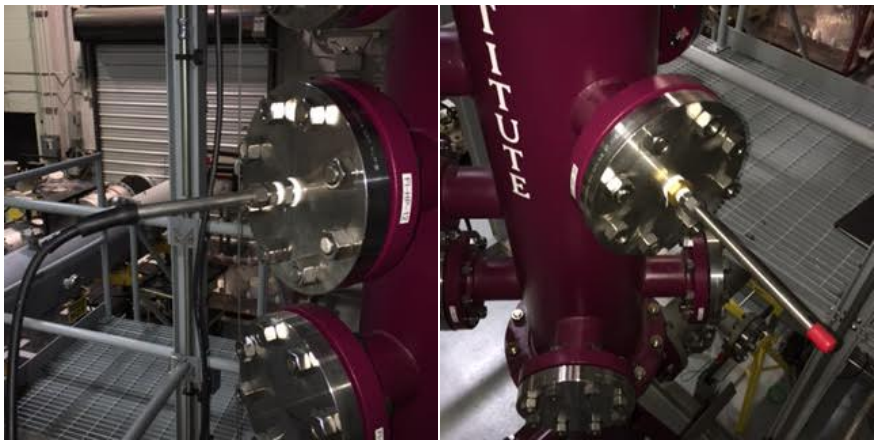


Figure 4.36 Sampling nozzles installed in test stand housing for aerosol sampling.

Both sampling nozzles are placed in the housing section of the test stand, upstream of the filter. These nozzles are installed facing the opposite direction (downward) of the airflow in the test stand and positioned in the center of the test stand duct. According to [21], aerosol sampling measurements should be performed at a location that is at least eight duct diameters downstream and two diameters upstream from any flow disturbance such as a bend, expansion, or contraction in the stack. This information is used as a guideline when placing the sampling nozzles into the middle portion of the housing section.

Data Reduction

Data reduction methods used for this project include the utilization of Microsoft Excel and PTC Mathcad. Raw data files are taken off the LAS, SMPS, and ELPI computers after testing is completed using a USB drive. The LAS and SMPS data files are imported into Mathcad to review the desired parameters. The Mathcad data reduction sheets for ceramic filter testing are listed in Appendix F.1. For the data reduction section, it is important to note that the same equations and procedures are applied to both the LAS and SMPS data. For simplicity, only the LAS data reduction methods are outlined since this is the primary instrument used in this project. It is also important to note that when performing an exponential curve fit analysis on the penetration curves within the data reduction sheet, the calculations are completed at 0.27µm. The reason for this has to do with the difference in refractive index values between DOP and PSL spheres, with which the LAS is calibrated. So, the penetration values and curve fits are generated at 0.27µm instead of 0.3µm. This procedure would need to be redone when using other test particles such as PAO.

CHAPTER V

CERAMIC MEDIA FILTER TESTING

Ceramic media filters used for testing activities

In this project, ceramic media filters are under evaluation to assist in the development of Section FO of the ASME AG-1 code on HEPA filters. Ceramic HEPA filters pose many potential benefits compared to fibrous glass HEPA filters such as [3]:

- Better resistance to higher temperatures, fires, and moisture
    - Capability of improving safety during fires
    - Capability of providing continuous ventilation system operation during a fire in facilities
- Potential for large life-cycle cost savings due to ability to clean and reuse filters
    - Significant cost savings in reducing radioactive waste volumes
    - Potential to be used in special applications (e.g., explosive applications)

The overall objective of ceramic filter R&D is to develop and deploy advances in HEPA filter technology related to ceramic HEPA filters to benefit DOE nuclear facilities by providing lower life-cycle costs and reducing or eliminating costs associated with safety class and safety significant systems in nuclear facilities. The design and operating conditions of ceramic media elements are listed in Table 5.1.

Table 5.1 Design and operating conditions of ceramic media filters.

	Ceramic Media
Filter Surface Area	• 0.343 ft^2 (Filter Media 1 single element) • 0.356 ft^2 (Filter Media 2 single element) • 2.150 ft^2 (Filter Media 1 six-element)

	• 2.039 ft^2 (Core six-element)
Testing Conditions	• Ambient temperature at 69.8°F (21°C) • Elevated temperatures at 752°F and 932°F (400°C and 500°C)
Rated Flows	• 5 CFM (single element) • 20 CFM (six-element)

The surface area values are calculated using the equation for the surface area of a cylinder. Filter dimensions including outer diameter, inner diameter, length, and wall thickness are measured using calipers five times each at several different locations on the filter elements. These values are used to calculate the surface area of both the six-element and single element filters using Equation 5.1:

$$Surface\ Area = D \times L \tag{5.1}$$

where "D" is the outer diameter and "L" is length. Only the exposed filter media on the outer surface of the filter element is used in this calculation. The length measurements are the entire length of the filter element excluding the end cap and the RTV 116 sealant. Initially, the rated flows of each filter type were calculated using the equation for the surface area of a hollow cylinder multiplied by a media velocity of 5 feet per minute (FPM). The equation for the surface area of a hollow cylinder is defined in Equation 5.2.

$$Surface\ Area_{HollowCylinder} = (2 \times \pi \times R \times h) + (2 \times \pi \times r \times h) \tag{5.2}$$

where "R" is the outer radius, "r" is the inner radius, and "h" is the length. After the surface area is calculated, the rated flow is determined for both the six-element and single element filters. Assuming a maximum media velocity of 5 FPM, the rated flow through the single element filter is determined to be 5 cubic feet per minute (CFM). The rated flow through the six-element filter is calculated to be 20 cubic feet per minute (CFM). A media velocity of 5 FPM is a surrogate for HEPA filter testing that dates back to 1970 [25] and is also discussed in [26]. The number of filters available for testing in this project includes seven Filter Media 2 single element filters, four Filter Media 1 single element filters, one Filter Media 1 six-element filter, and one core six-element filter. The six-element filters are previously shown in Figure 1.4. One is a series of six core filter elements wrapped with fibrous Filter Media 1. This filter media

is spiral wrapped with a bundle of fine ceramic fibers. The other six-element filter consists of a series of six different core filter elements with no filter media wrapped around them. The Filter Media 2 single element filters contain fabric wrapped around this same type of filter core. The other type of single element filter is the same as the six-element filter wrapped with Filter Media 1 except there is only one filter element as shown in Figure 5.1.

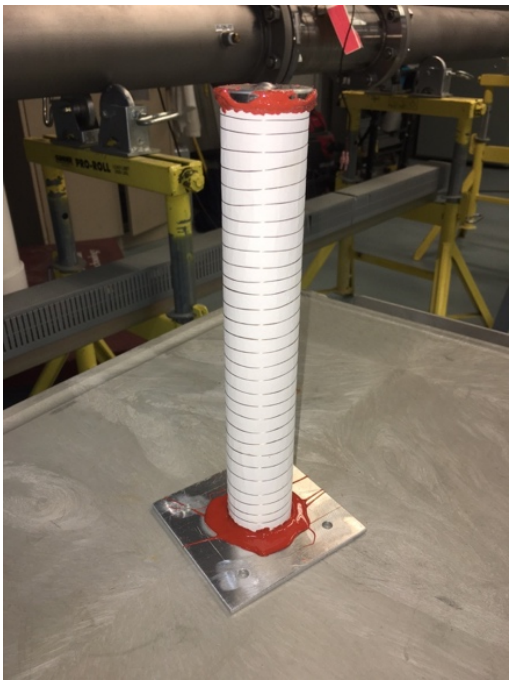


Figure 5.1 Filter Media 1 single element ceramic filter.

Filter Media 2, which is shown in Figure 5.2, is the other single element filter used for testing.

Figure 5.2 Filter Media 2 single element ceramic filter.

Ceramic media filter clean differential pressure test data

The following figures display clean differential pressure as a function of flowrate for the four ceramic filter types. Figure 5.3 illustrates the data for the six-element core filter. The filter is exposed to filtered, ambient air at 16 CFM and increased up to 21 CFM. Details on clean dP vs. flow test procedures are outlined in Appendix E.

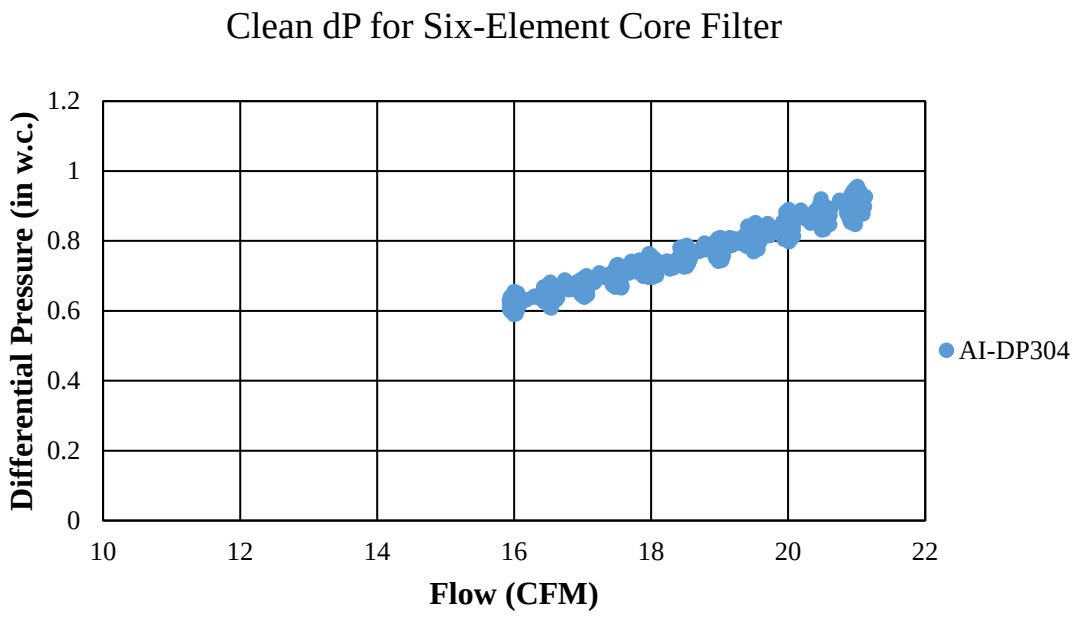


Figure 5.3 Clean differential pressure test data for six-element core filter.

Figure 5.4 displays the clean dP data for the Filter Media 1 six-element filter. Again, for the six-element filter, the flowrate is initially set to 16 CFM and increased to 21 CFM.

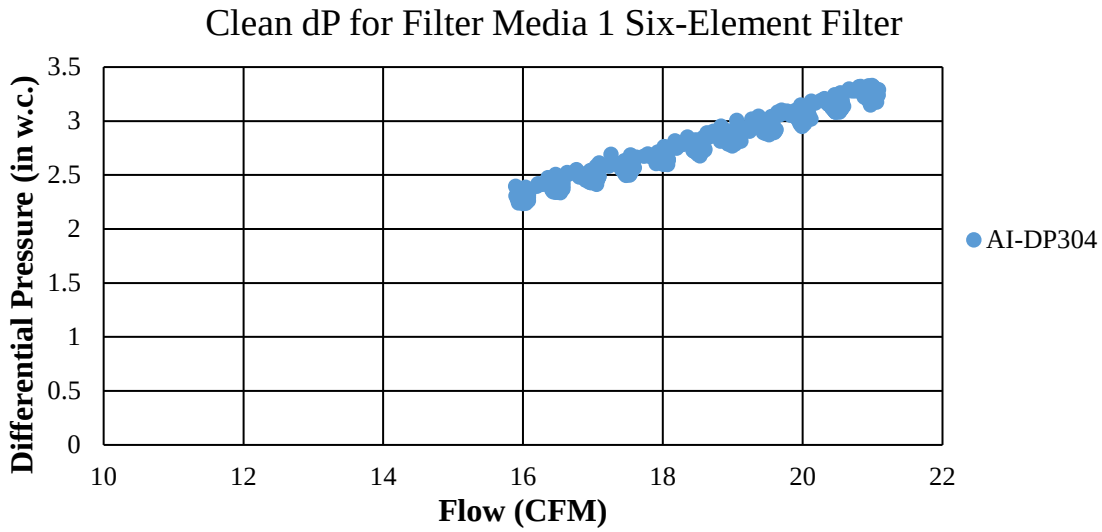


Figure 5.4 Clean differential pressure test data for Filter Media 1 six-element filter.

The next plot, shown in Figure 5.5, outlines the dP data for the Filter Media 2 single element filter. In this case, the initial flowrate is set at 0.5 CFM and increased up to 5 CFM.

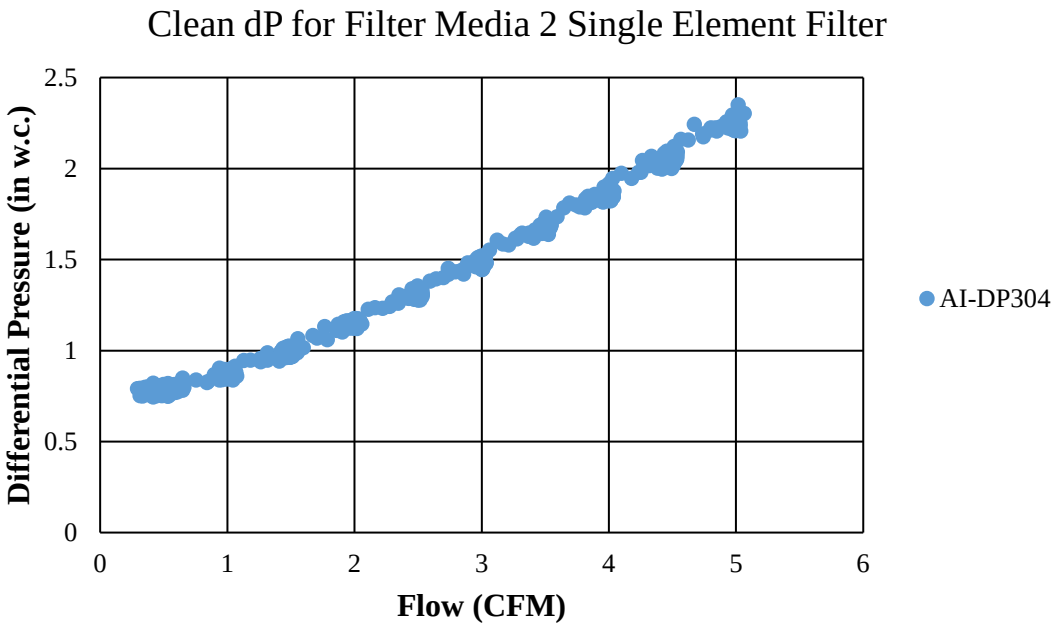


Figure 5.5 Clean differential pressure test data for Filter Media 2 single element filter.

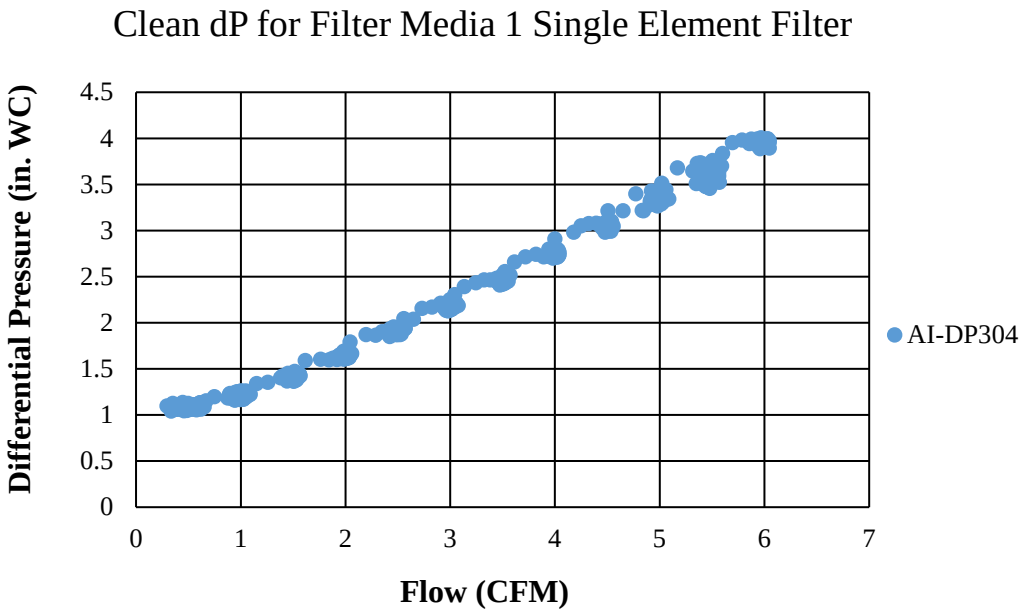


Figure 5.6 Clean differential pressure test data for Filter Media 1 single element filter.

CHAPTER VI

TEST RESULTS AND DISCUSSION

Table 6.1 includes details of all ceramic filters used in the project.

Table 6.1 Test matrix for ceramic filter project.

Test #	**Filter #**	**Media Type**	**Single Element or Six-Element**	**Aerosol used**	**Sealant used on Filter**	**Test Conditions**
	1	FM 1	Single	N/A	RTV 116	N/A
1	2	FM 1	Single	DOP	RTV 116	Ambient
2,3, and 4	3	FM 1	Single	DOP	RTV 116	Ambient
1	1	FM 2	Single	DOP	RTV 116	Ambient
2	2	FM 2	Single	DOP	RTV 116	Ambient
3	3	FM 2	Single	DOP	RTV 116	Ambient
4	4	FM 2	Single	DOP	RTV 116	Ambient
5	5	FM 2	Single	DOP and KCl	RTV 116	Ambient
6	6	FM 2	Single	DOP and KCl	RTV 116	Ambient
1	1	FM 2	Six	DOP	RTV 116	Ambient

Filter masses before and after testing are measured using a Mettler Toledo SB32001 DeltaRange balance. These values include the mass of the filter(s), sealant, and the plate or thin metal tubesheet that the filters are attached to. Masses are not available in some instances from the testing activities. One Filter Media 1 single element filter was not tested since it cracked during tubesheet installation. Another Filter Media 1 single element filter was challenged with DOP, but this test was during a period where testing procedures were primitive, so no reasonable data was generated. The first Filter Media 2 single element DOP test did not yield usable data. In this case, an oil/water substance was left inside an air hose, which ultimately traveled through the DOP generator and impacted the filter media.

Filter Media 1 single element ceramic filter DOP test 1

For the following test summaries, when FE measurements are reported, a dP value is noted for when downstream samples are recorded, and another value is noted for when upstream samples are recorded. For example, when an FE measurement is denoted as “2-4”, this means that the dP is 2 in. WC when the downstream sample collection starts and 4 in. WC when the upstream sample collection starts. Since DOP loaded on the filter so quickly in the initial stages of testing due to the small filter surface areas, there is limited time to collect downstream samples, allow the instruments to purge, and then collect the upstream samples. So, the reason for FE measurements having a dP range instead of a single dP value is a function of both the filter surface areas and the aerosol measurement instrumentation.

A Filter Media 1 single element filter is challenged with DOP at 5 CFM rated flow. Ambient conditions are used in this test, in which filtered, indoor air is drawn through the test stand inlet. The DOP generator is set to a pressure setting of 2 jets, 25 psi (172369 Pa) to produce a higher particle concentration. To effectively analyze particle behavior on the ceramic media filter, an SMPS is used. The test stand data collected during the DOP tests are shown in Figure 6.1.

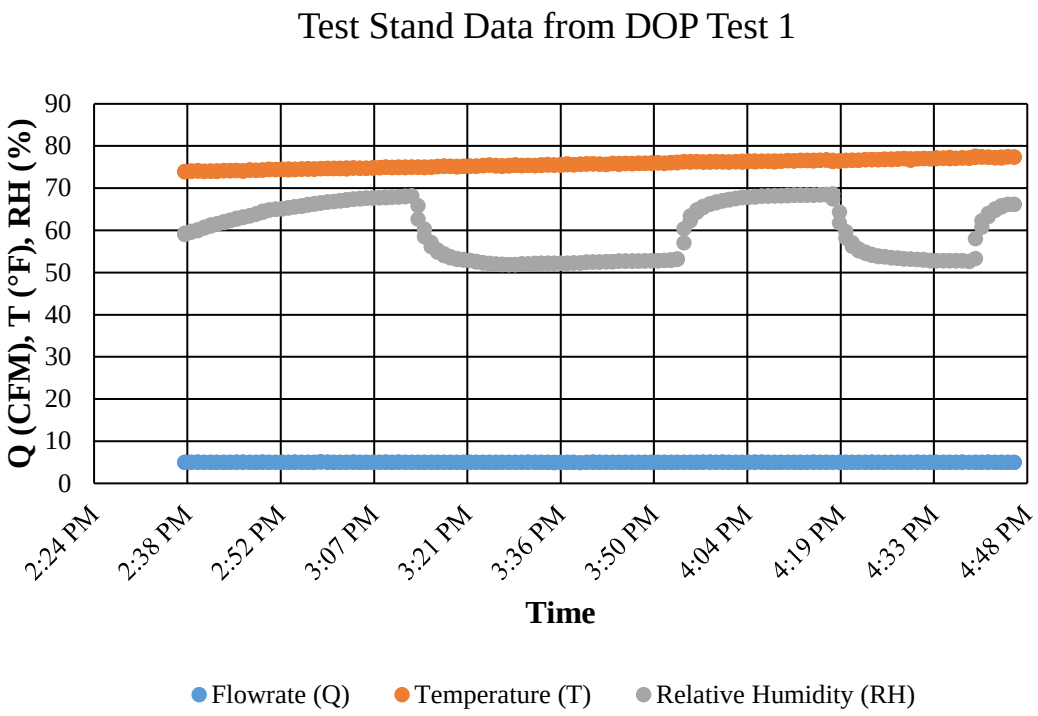


Figure 6.1 Test stand data from Filter Media 1 single element DOP test 1.

This figure displays the airflow, temperature, and relative humidity during testing. The relative humidity data fluctuates as a result of turning the DOP generator on and off without adjusting the test stand air flowrate setpoint first. When the DOP generator is turned on, the RH values decrease, and when it is turned off, the RH values increase. As for temperature and flowrate, these parameters remain relatively constant throughout testing. Also included is the loading curve for the single element filter for the entire duration of the test. In Figure 6.2, the ceramic filter displays an initial dP below 5 in. WC and increases all the way up to 45 in. WC at 5 CFM rated airflow.

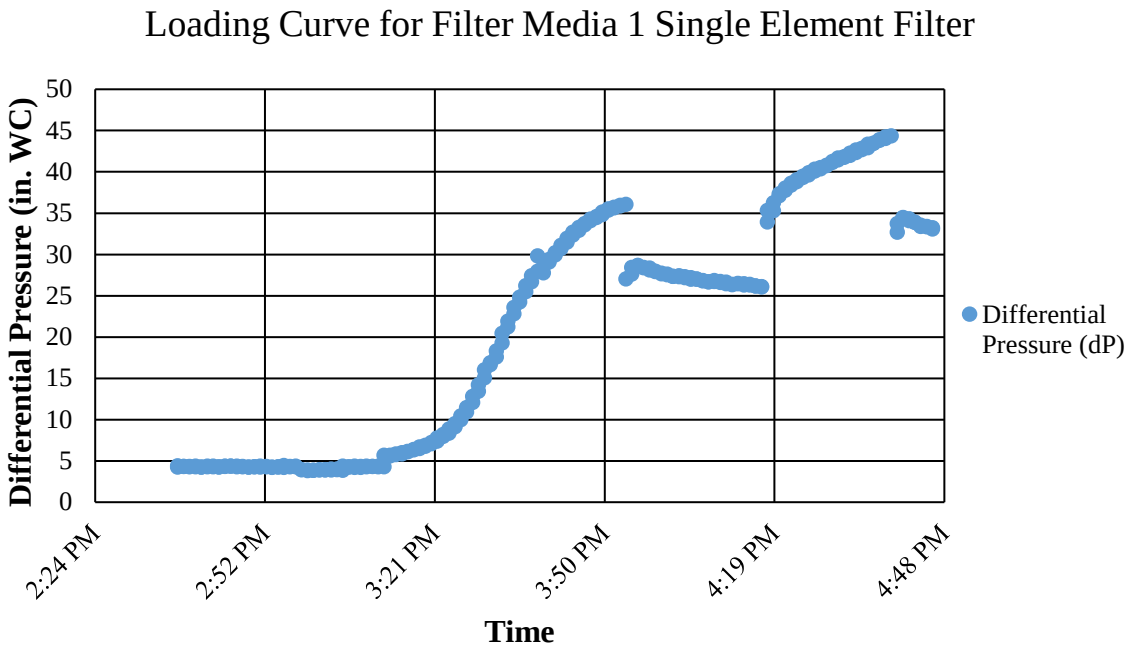


Figure 6.2 Loading curve Filter Media 1 single element DOP test 1.

The fluctuations, again, are due to the DOP generator being turned on and off without adjustment of the air flowrate in the test stand. The large pressure drop was anticipated for this combination of filter media and core material with improvements expected with Filter Media 2. Filter Media 1 and 2 were selected for initial testing as diverse samples to test the performance range of the ceramic test stand. The test results indicate that the ceramic filter components are capable of performing at pressure drops well in excess of the nominal expected pressure drop. Figure 6.2 shows a pressure drop of nearly 10 times the pressure drop expected under nominal flow conditions for the single ceramic tube filter element.

Figure 6.3 displays the particle size distribution (PSD) of both upstream and downstream (with background data included) at an FE measurement at 6.5-16.65 in. WC.

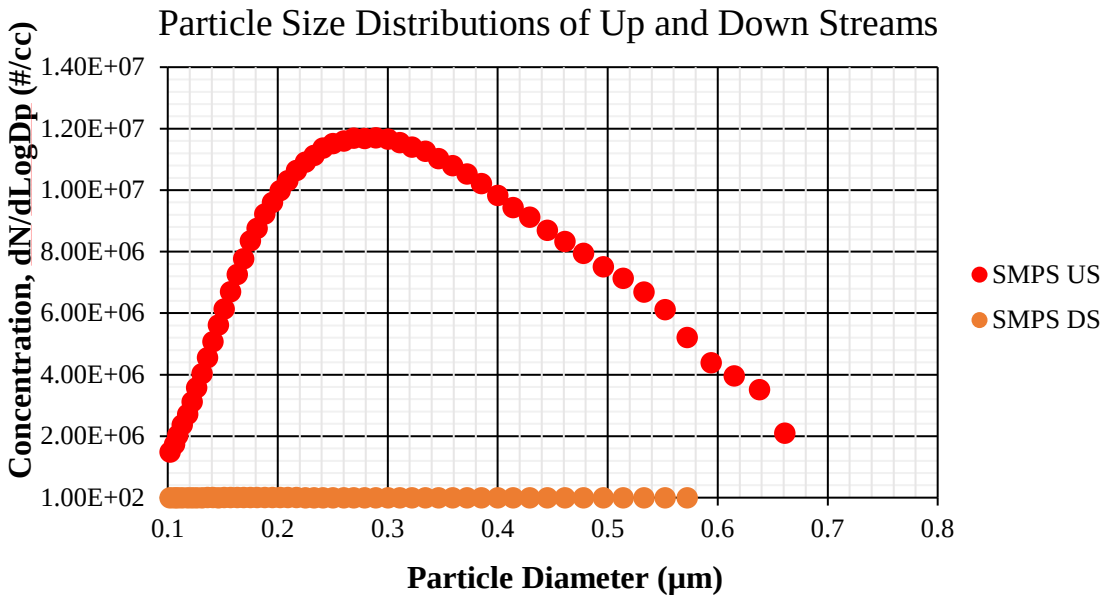


Figure 6.3 PSD curves for upstream and downstream with background data.

The data in Figure 6.3 include an average of two samples taken during testing, which summarize the particle concentration vs. diameter of both upstream and downstream of the filter media. Particle penetration is outlined in Figure 6.4.

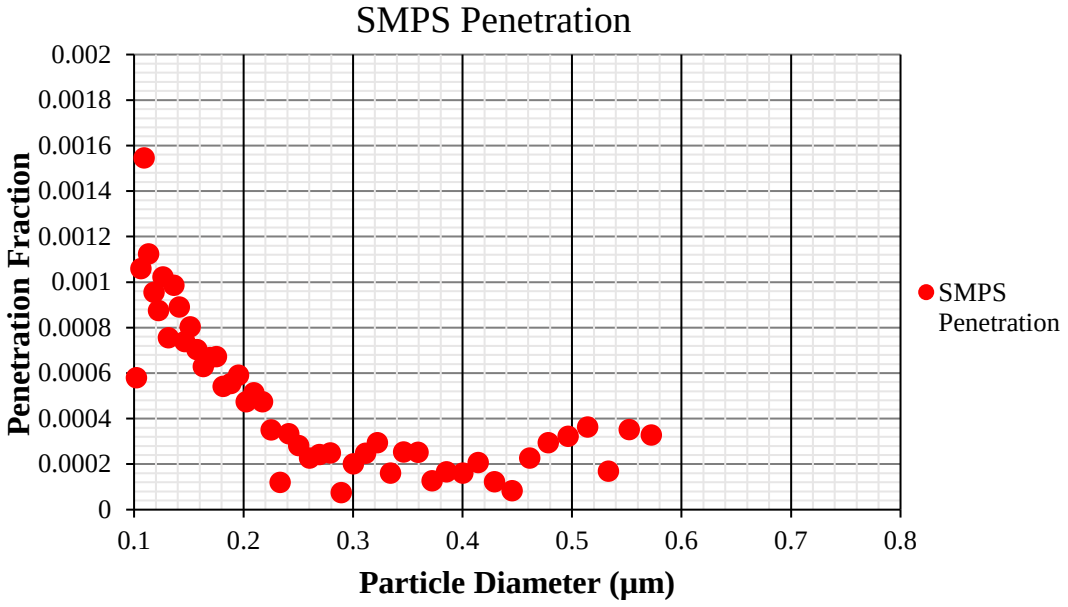


Figure 6.4 SMPS penetration curve from Filter Media 1 single element DOP test 1.

This data shows the penetration (in units of number/number) of the particles from the DOP test, which is found by dividing the downstream concentration by the upstream concentration. Further analysis of Figure 6.4 leads to the production of Figure 6.5.

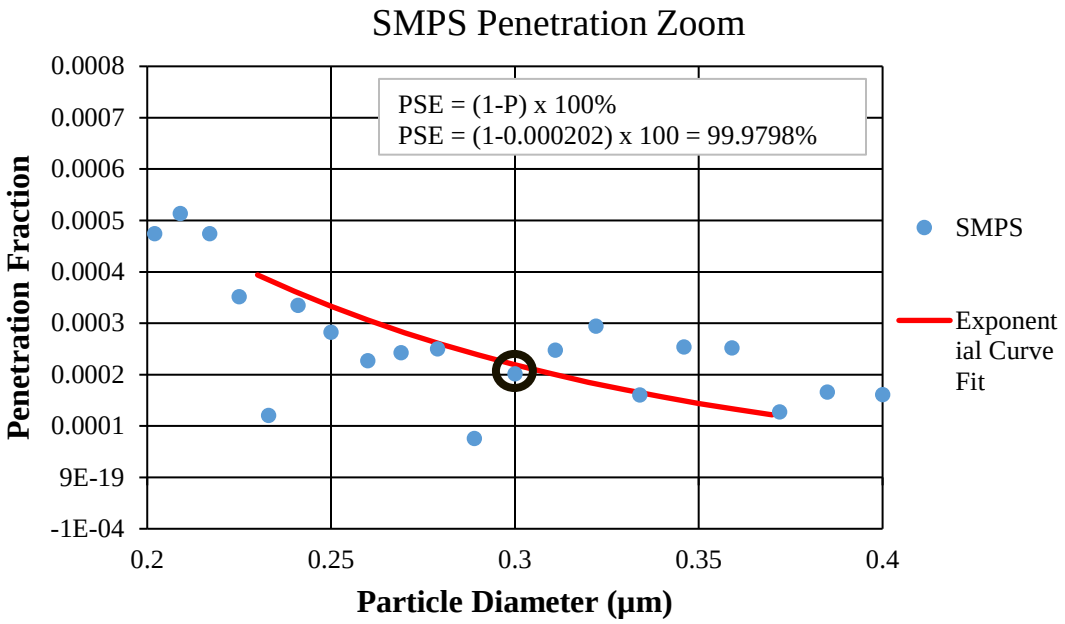


Figure 6.5 Zoomed-in view of penetration curve with exponential curve fit.

This figure displays a zoomed-in view of the penetration curve (from 0.2 µm to 0.4 µm) and includes an exponential curve fit. Examination of the circled data point at 0.3 µm shows a penetration fraction value of 0.000202. Using the equation for particle size removal efficiency (PSE), a value of 99.9798% is calculated. The equation used in this case is found in Chapter 7 of [27].

Filter Media 2 single element ceramic filter Test Results

Filter media 2 single element DOP test 1

Filter Media 2 DOP test 1 is completed in three different parts. For this test, the test stand air flow is set to 4 CFM so that a rated flow of approximately 5 CFM would be seen at the filter. DOP is used during this test, in which FE measurements could be determined at multiple intervals. The DOP generator settings for each FE measurement includes the following:

- 2 in. WC- 3 jets, 30 psi (206843 Pa)
- 5-7 in. WC- 3 jets, 30 psi (206843 Pa)

- 14 in. WC- 1 jet, 7 psi (48263.3 Pa)
- 50 in. WC- 2 jets, 25 psi (172369 Pa)

These settings all equated to approximately 5 CFM rated flow at the filter. An LAS and SMPS are used for data collection, but only the LAS data is reported. Both 100:1 and 20:1 diluters are used for upstream (US) measurements, and no diluters are used for downstream (DS) measurements. For the final FE measurement at 50 in. WC, a 100:1 diluter is used for DS measurements. Figure 6.6 displays the PSD curves at the 2 in WC (initial) FE measurement interval. The data in the PSD plots for the entire results section include averages of four samples each.

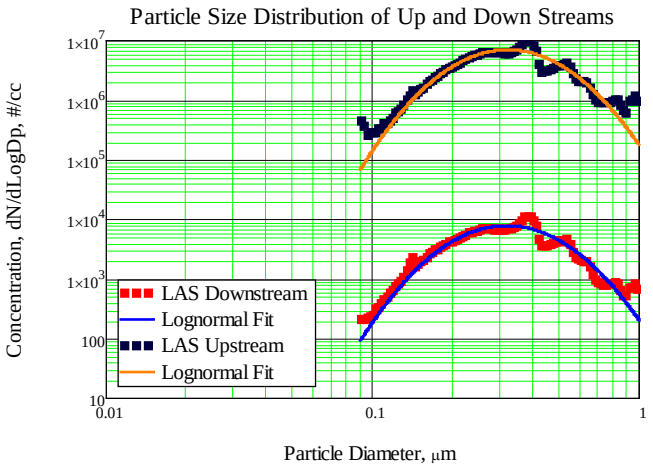


Figure 6.6 PSD curves with lognormal curve fit for 2 in. WC (Initial) FE measurement.

Figure 6.7 displays the penetration curve at the 2 in. WC FE measurement along with an exponential curve fit, lognormal curve fit, and zoomed-in views of each curve fit.

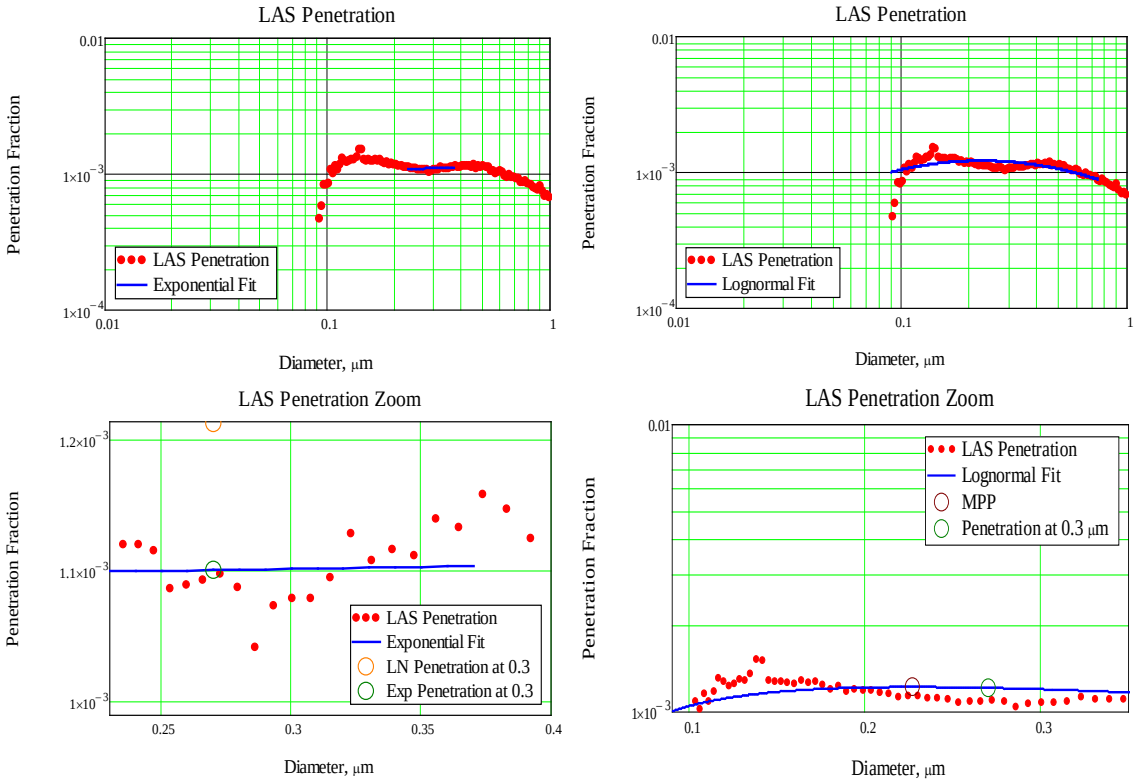


Figure 6.7 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 2 in. WC (initial) FE measurement.

The next FE measurement is taken at 5-7 in. WC, and the results are outlined in the following figures. Figure 6.8 shows the PSD curves for this FE interval.

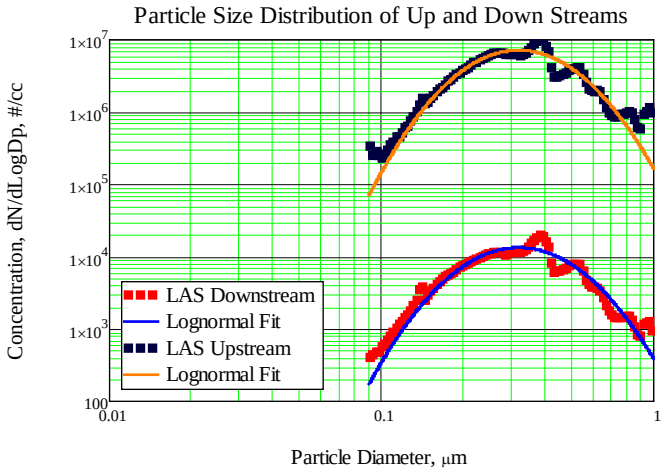


Figure 6.8 PSD curves with lognormal curve fit for 5-7 in. WC FE measurement.

The penetration curves are listed in Figure 6.9.

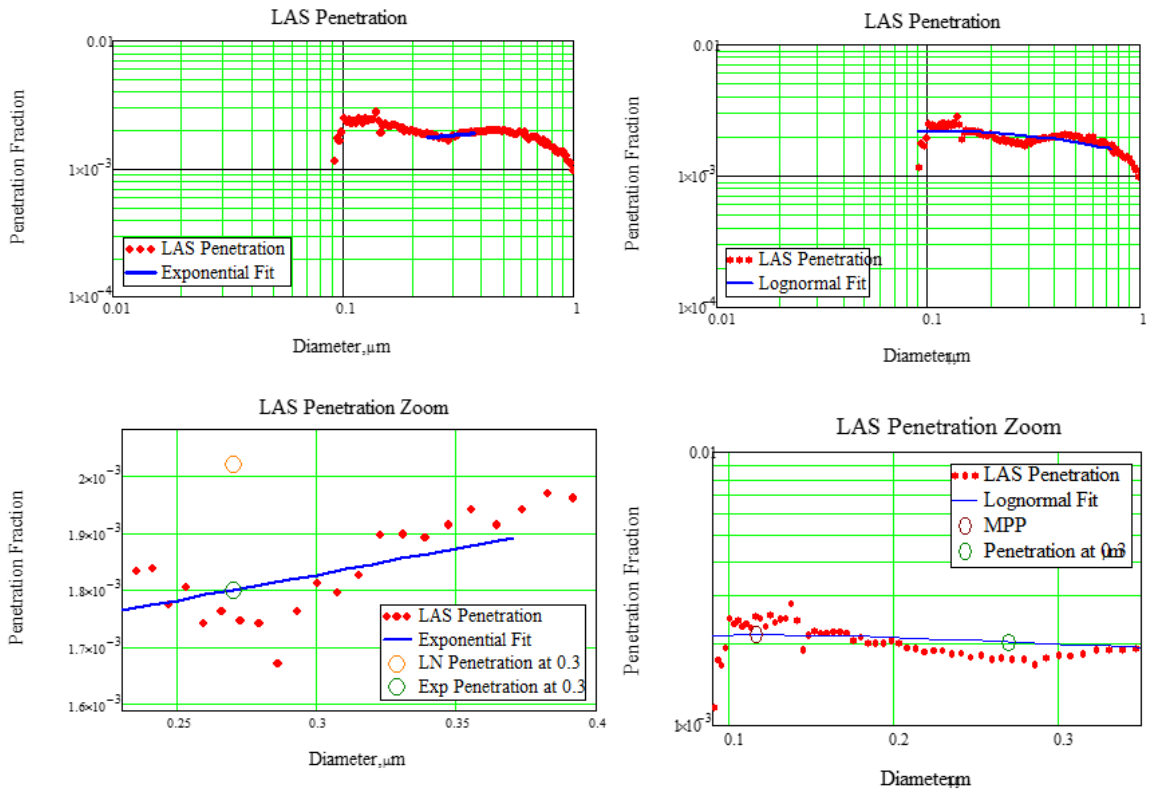


Figure 6.9 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 5-7 in. WC FE measurement.

The third FE measurement is taken at 14 in WC. The PSD curves are illustrated in Figure 6.10.

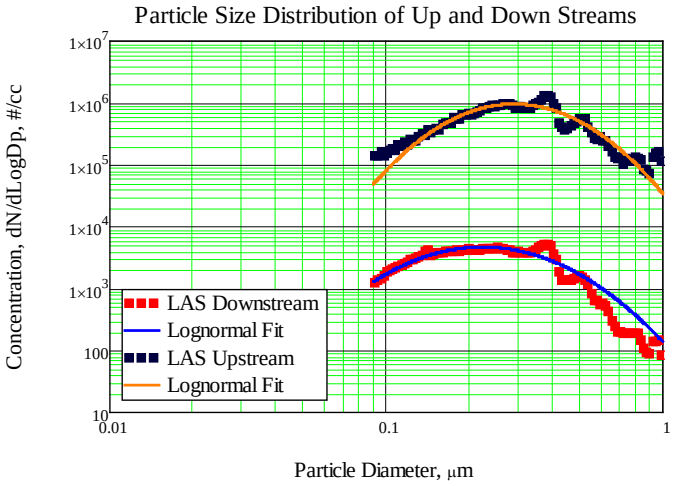


Figure 6.10 PSD curves with lognormal curve fit for 14 in. WC FE measurement.

Penetration curves with the appropriate curve fits are outlined in Figure 6.11.

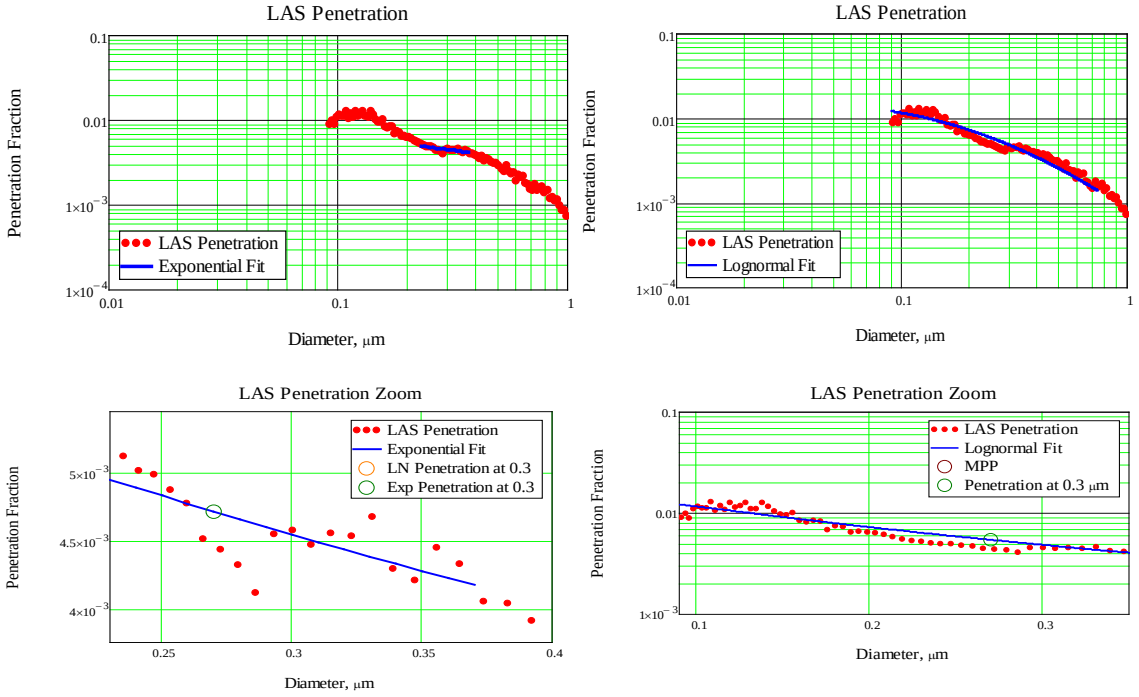


Figure 6.11 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 14 in. WC FE measurement.

A final FE is taken at 50 in. WC, and the PSD curves are shown in Figure 6.12.

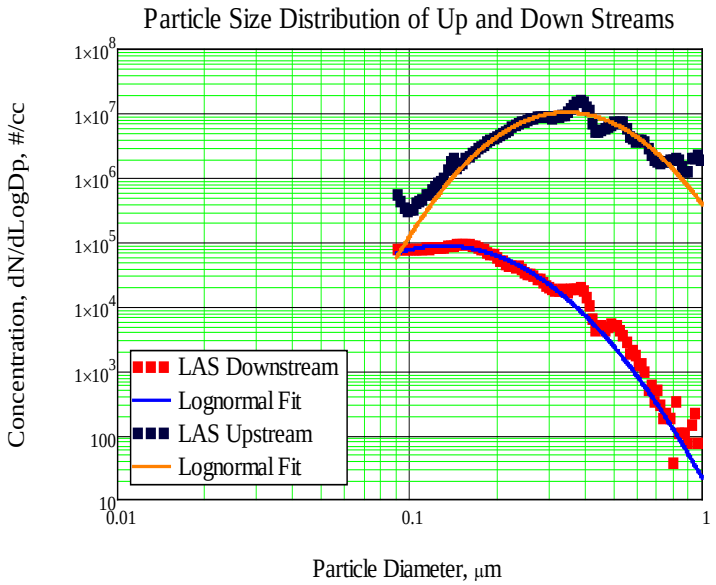


Figure 6.12 PSD curves with lognormal curve fit for 50 in. WC FE measurement.

The penetration curves for the final FE measurement are illustrated in Figure 6.13.

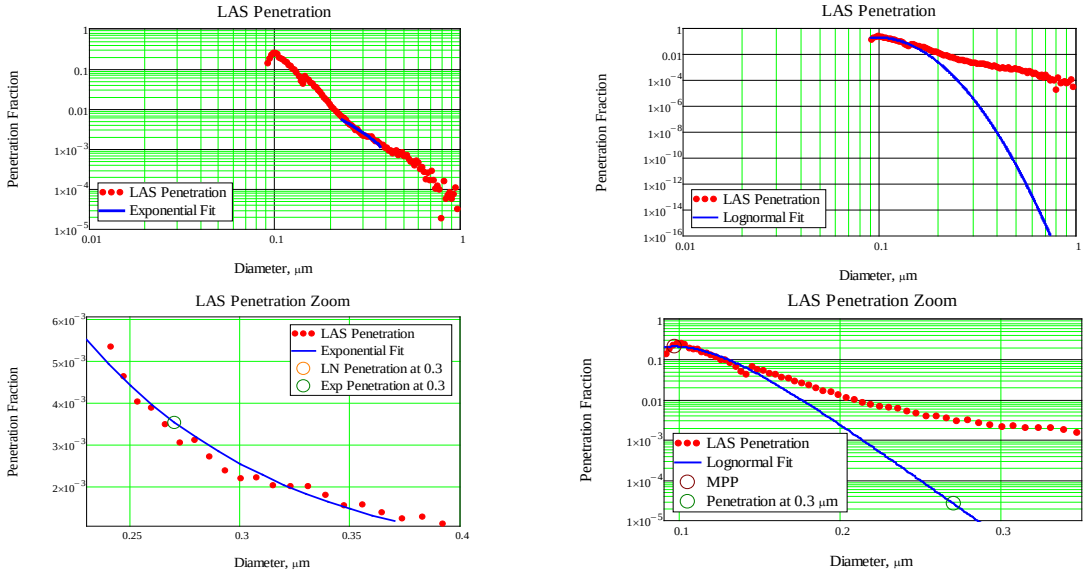


Figure 6.13 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential

zoom (bottom left), and lognormal zoom (bottom right) for 50 in. WC FE measurement.

Since this test is completed in three different parts, the loading curve is separated into three different segments as shown in Figure 6.14.

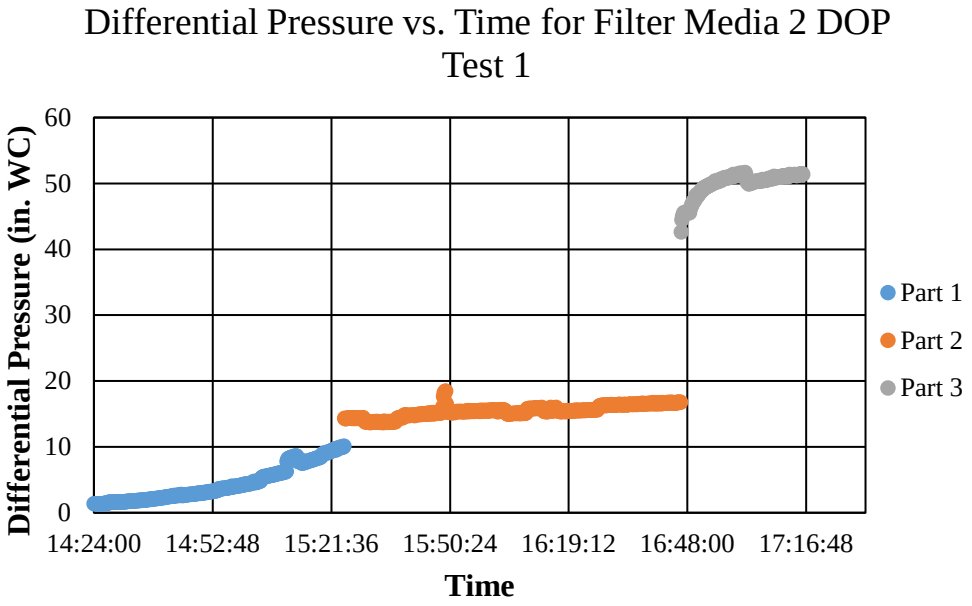


Figure 6.14 Loading curve for Filter Media 2 DOP test 1.

The filter loads up to about 10 in. WC after part 1, then slowly loads from 15 in. WC to approximately 19 in. WC in part 2. For part 3, the dP starts at approximately 40 in. WC since the filter had become saturated with DOP and increased to 52 in. WC. The discrepancy seen at 40 in. WC is due to the fact that the DOP saturated the filter media, causing a much higher starting dP on the third day of testing.

To summarize the data collected, Table 6.2 is generated to display important parameters such as geometric mean (GM), geometric standard deviation (GSD), penetration fraction, FE, and MPPS for each measurement.

Table 6.2 Summary of parameters from testing.

FE Measurement	**2 in. WC**	**5 in. WC**	**14 in. WC**	**50 in. WC**
GM Upstream	0.3208	0.319	0.2859	0.3415
GSD Upstream	1.5492	1.5437	1.6197	1.5536
GM Downstream	0.3133	0.3124	0.23	0.1613
GSD Downstream	1.5345	1.5415	1.601	1.4834
GM Penetration	0.2841	0.2768	0.1954	0.1182
GSD Penetration	1.939	1.9707	1.8006	1.2808
Penetration Fraction at 0.3 μm	1.1006×10^{-3}	1.8×10^{-3}	4.7163×10^{-3}	3.5411×10^{-3}
Filtering Efficiency at 0.3 μm (Exponential)	99.89%	99.82%	99.53%	99.65%
Most Penetrating Particle at MPPS	0.2267 μm	0.1169 μm	0.0441 μm	0.0964 μm
Penetration Fraction at MPPS	1.2214×10^{-3}	2.1545×10^{-3}	0.0142	0.2072

Post-test images of the filter are shown in Figure 6.15.

Figure 6.15 Filter media 2 single element filter after DOP test 1.

From observation of the images, a conclusion is made that the DOP saturated the media, which potentially caused DOP to bleed into the downstream.

Filter media 2 single element DOP test 2

Test 2 was completed using another Filter Media 2 single element filter with DOP as the challenge aerosol. For this test, the test stand airflow setpoint is 4.5 CFM so that a rated airflow of 5 CFM is seen at the filter. The other 0.5 CFM accounted for the output of the DOP generator. The DOP generator was set to 2 jets, 25 psi (172369 Pa) for the entire duration of the test. Again, this test utilizes an LAS to collect the necessary data. Included with the LAS are the 100:1 and 20:1 diluters for US measurements, and a 100:1 diluter for DS measurements. The PSD curves at the 2-4 in. WC (initial) FE interval are shown in Figure 6.16. This figure and the remaining figures from this test include averages of four samples taken by the LAS.

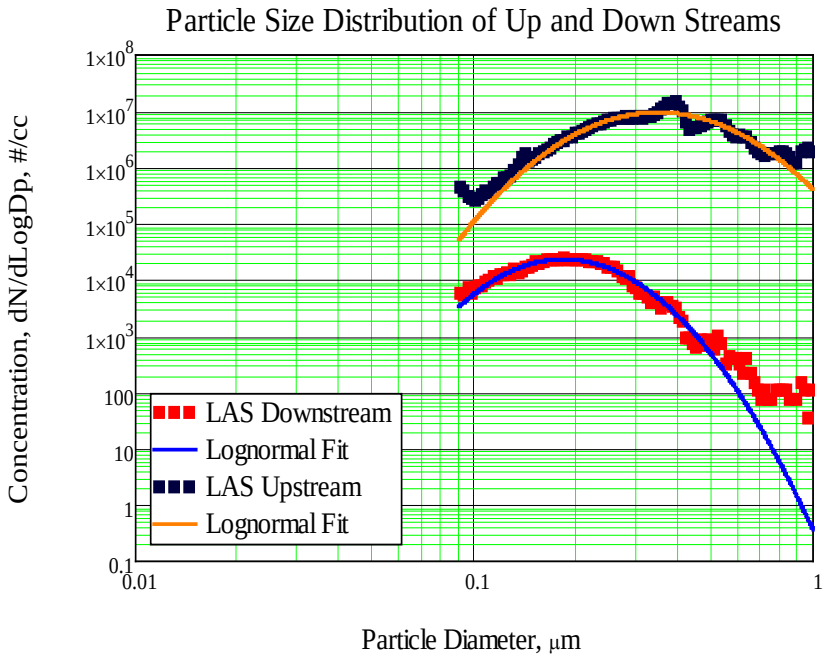


Figure 6.16 PSD Curves with lognormal curve fit for 2-4 in. WC (Initial) FE measurement.

The following plots display the penetration curve for the 2-4 in. WC FE measurement.

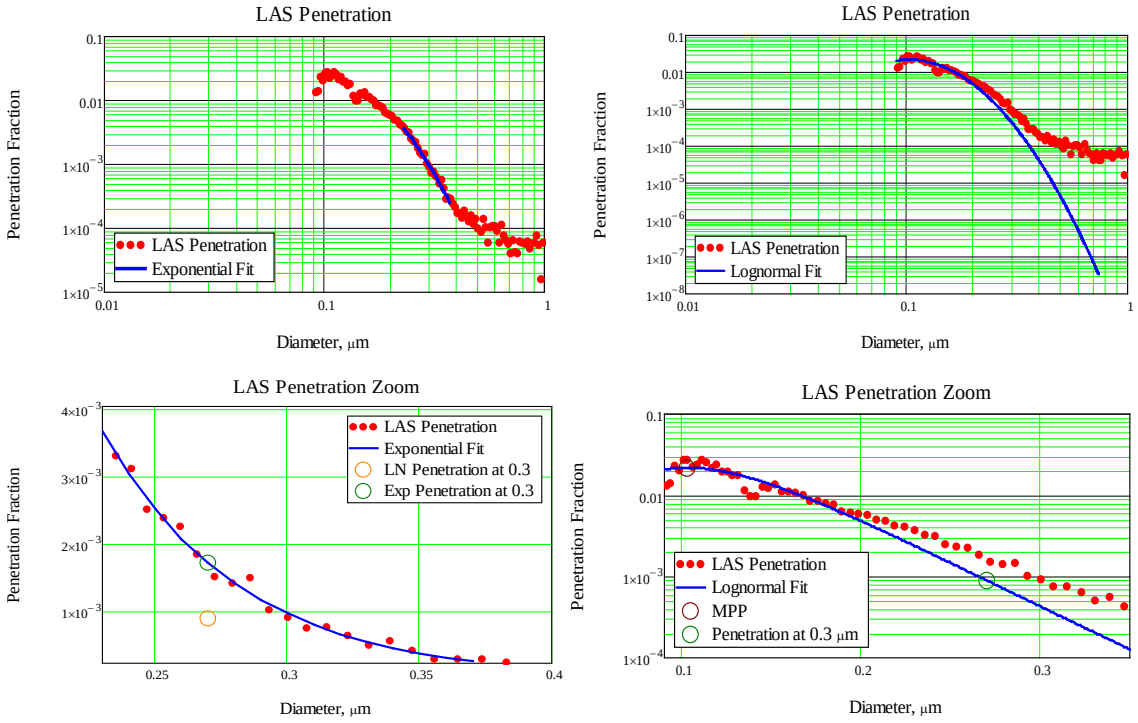


Figure 6.17 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 2-4 in. WC (Initial) FE measurement.

Results from the next FE measurement, 9-13 in. WC, are illustrated in the following figures. Figure 6.18 displays the PSD curves.

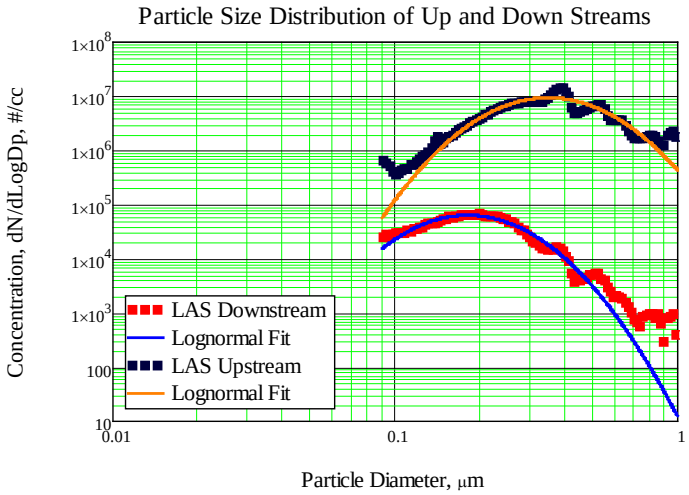


Figure 6.18 PSD curves with lognormal curve fit for 9-13 in. WC FE measurement.

Figure 6.19 contains the penetration curve from the 9-13 in. WC FE measurement.

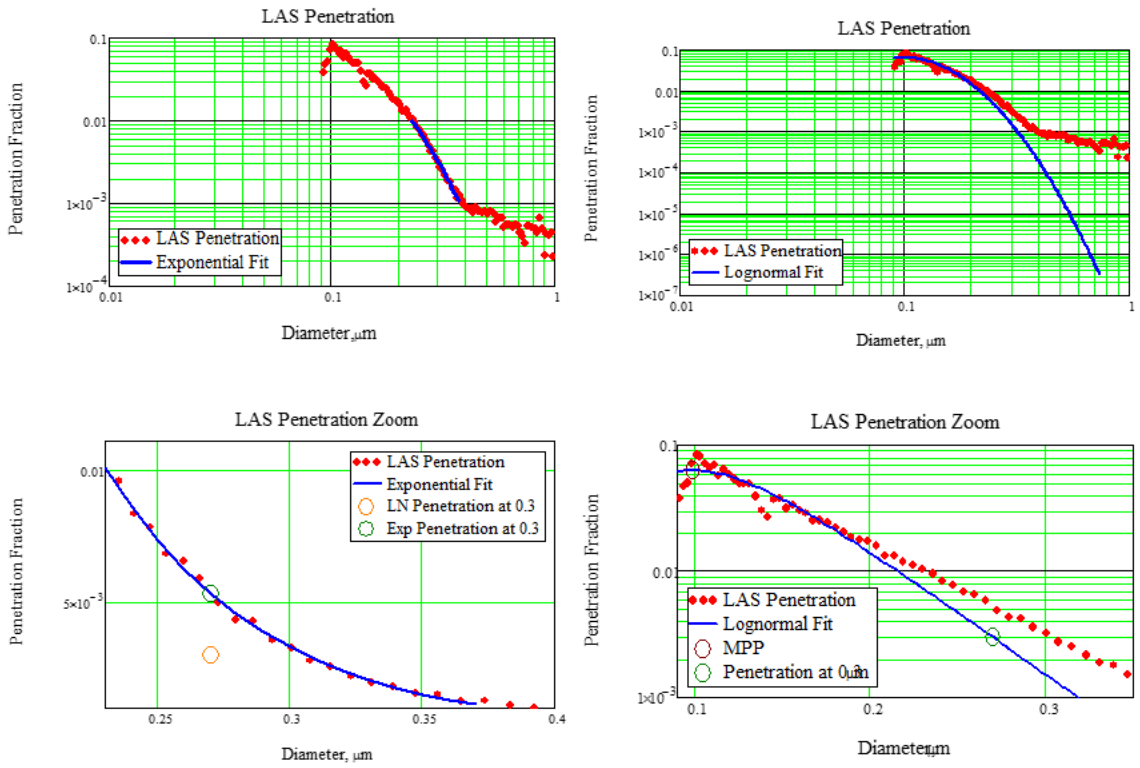


Figure 6.19 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 9-13 in. WC FE measurement.

The next FE measurement is taken at 20-22 in. WC, and the PSD curves are displayed in Figure 6.20.

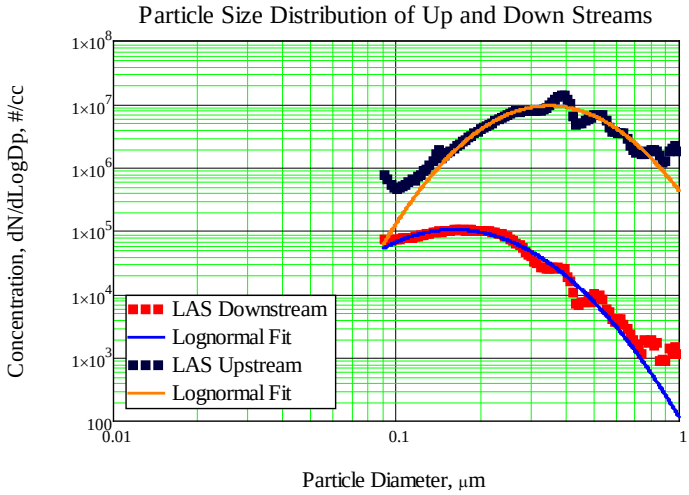


Figure 6.20 PSD curves with lognormal curve fit for 20-22 in. WC FE measurement.

Figure 6.21 displays the penetration curve generated for the 20-22 in. WC FE measurement.

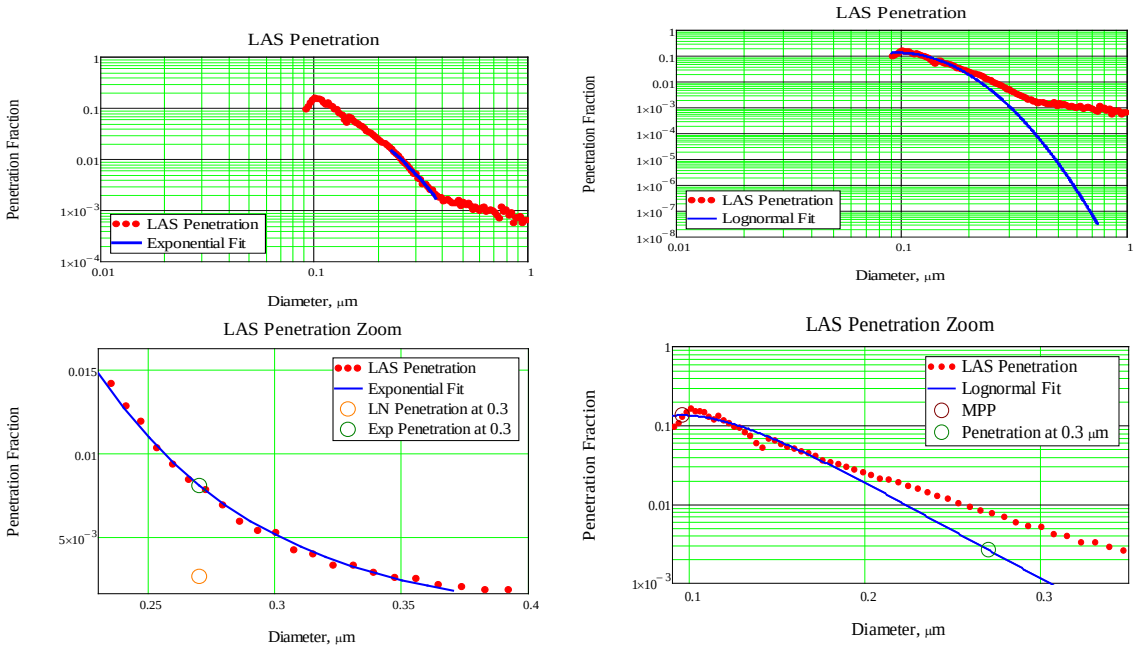


Figure 6.21 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 20-22 in. WC FE measurement.

For the next measurement, an FE is taken at 27 in. WC. The PSD curves are shown in Figure 6.22.

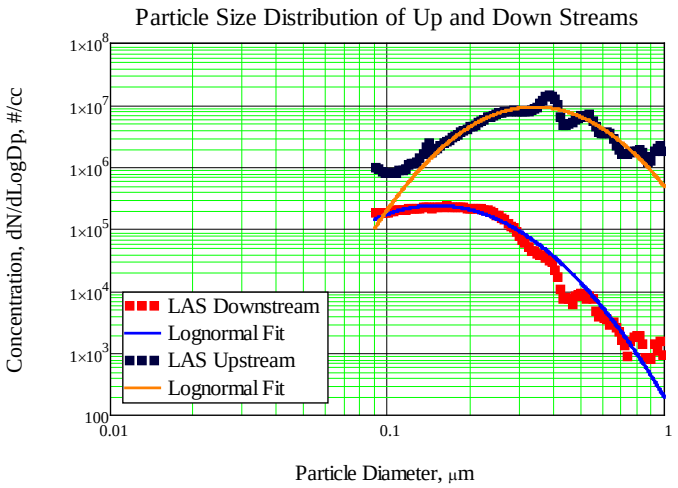


Figure 6.22 PSD curves with lognormal curve fit for 27 in. WC FE measurement.

The penetration curve plots are outlined in Figure 6.23.

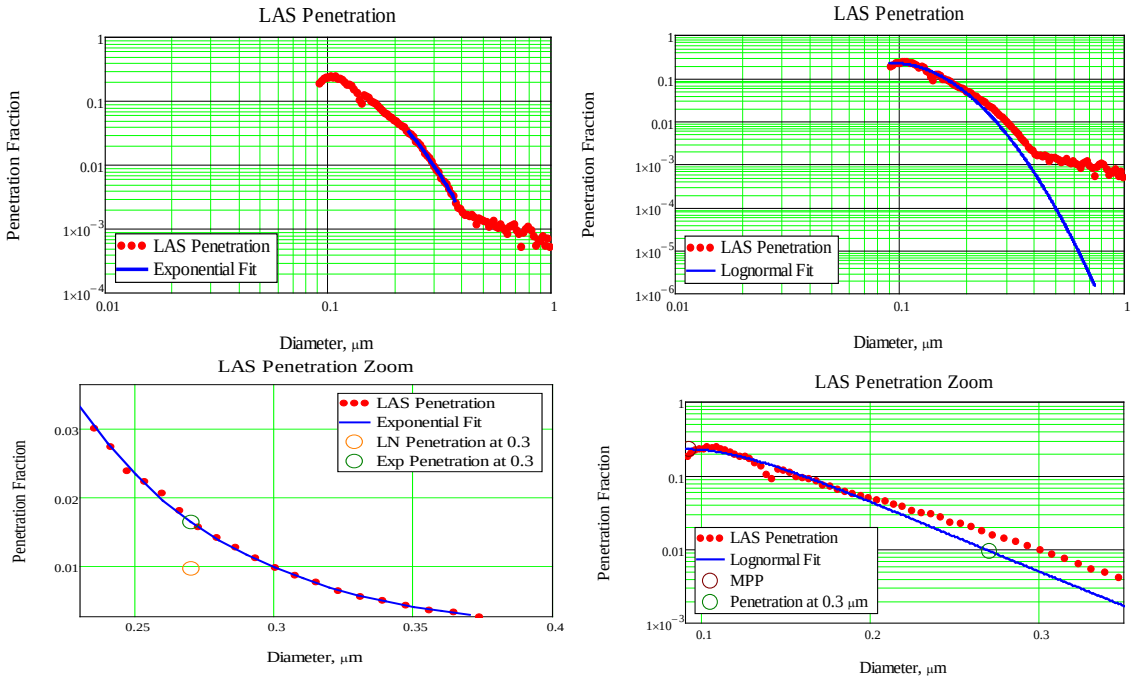


Figure 6.23 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 27 in. WC FE measurement.

Data for the differential pressure across the filter is collected, and a loading curve is generated, which is shown in Figure 6.24. The fluctuations at approximately 23 in. WC and 26 in. WC are due to the adjustment of valves on the sampling train before modifying the flowrate setpoint in the test stand computer.

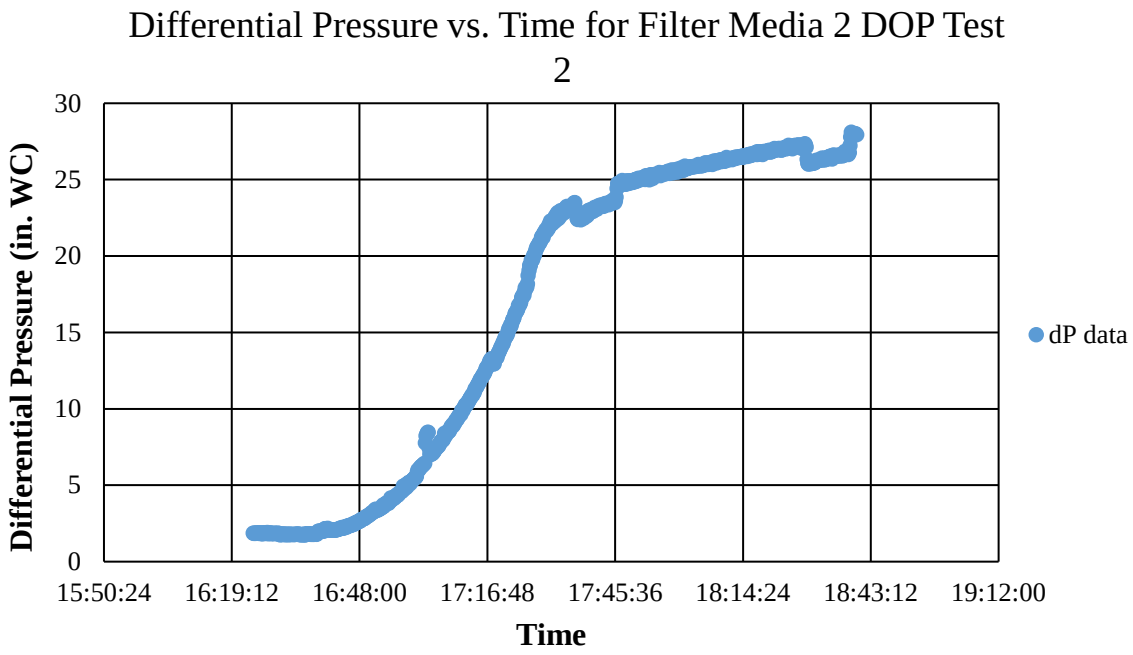


Figure 6.24 Loading curve for US Media filter DOP test 2.

Table 6.3 contains important parameters from DOP Test 2.

Table 6.3 Summary of parameters from testing.

FE Measurement	**2-4 in. WC**	**9-13 in. WC**	**20-22 in. WC**	**27 in. WC**
GM Upstream	0.346	0.3442	0.3413	0.3318
GSD Upstream	1.555	1.567	1.574	1.6011
GM Downstream	0.186	0.1889	0.1792	0.169
GSD Downstream	1.4209	1.4895	1.5169	1.467
GM Penetration	0.133	0.1349	0.1389	0.1314
GSD Penetration	1.3535	1.4023	1.389	1.3666
Penetration Fraction at 0.3 μm	1.714×10^{-3}	5.292×10^{-3}	8.0679×10^{-3}	0.0164
Filtering Efficiency at 0.3 μm (Exponential)	99.83%	99.47%	99.19%	98.36%
Most Penetrating Particle at MPPS	0.1029 μm	0.0985 μm	0.0955 μm	0.0921 μm
Penetration Fraction at MPPS	0.022	0.0627	0.1349	0.2286

Figure 6.25 displays images of the filter after completion of DOP Test 2.

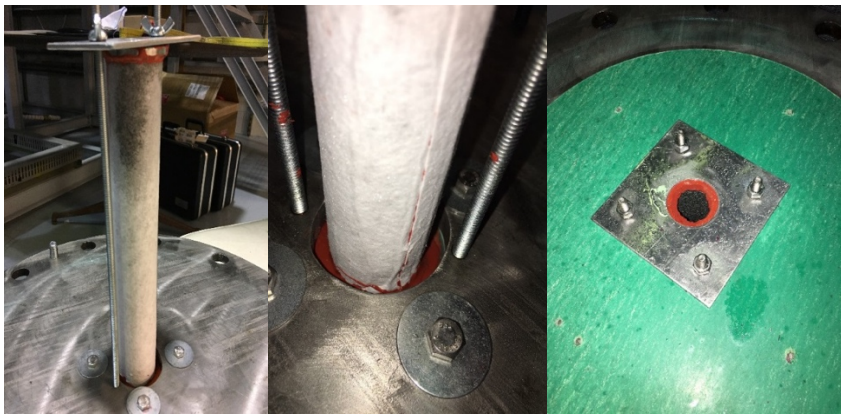


Figure 6.25 Post-test images from DOP test 2.

The photo on the left illustrates that the filter media was saturated with DOP at the end of testing, thus causing a higher downstream concentration of DOP than expected. The image on the very right shows leakage of DOP on the downstream side of the filter. This explains why the downstream concentrations were higher than usual as there is evidence that DOP leaked onto the filter plate and gasket.

Filter media 2 single element DOP test 3

The next test completed was on a third Filter Media 2 single element filter challenged with DOP. The test stand airflow setpoints are manually adjusted in the test stand computer based on the following conditions:

- sampling train configuration (upstream sampling, downstream sampling, or purging)
- instrument being used (LAS, SMPS, and/or ELPI)
- opening or closing the DOP generator exit valve

Settings for the DOP generator remain constant throughout testing at 2 jets, 25 psi (172369 Pa). Both 100:1 and 20:1 diluters are used for US measurements, while only the 100:1 diluter is used for DS measurements. The PSD curves for the 2.8-6.1 in. WC (Initial) FE measurement are illustrated in Figure 6.26.

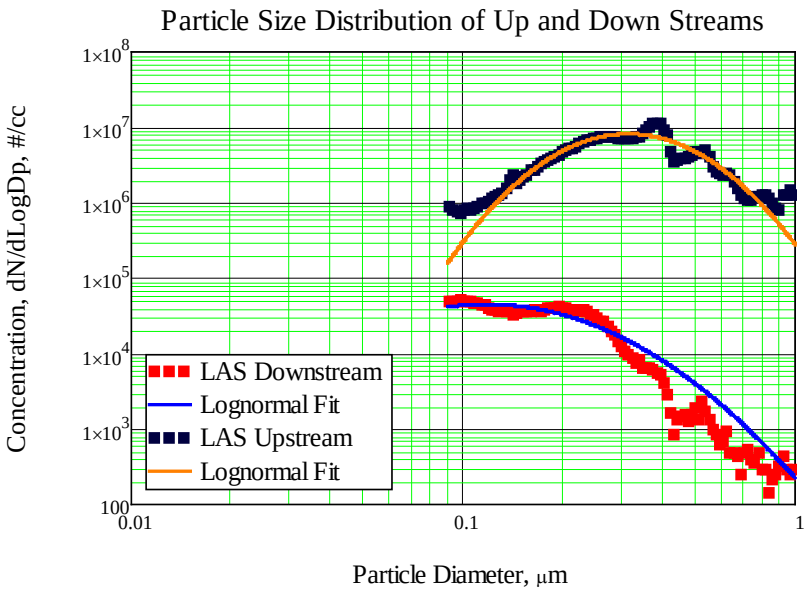


Figure 6.26 PSD curves with lognormal curve fit for 2.8-6.1 in. WC (Initial) FE measurement.

Figure 6.27 illustrates the penetration curve for the 2.8-6.1 in. WC (Initial) FE measurement.

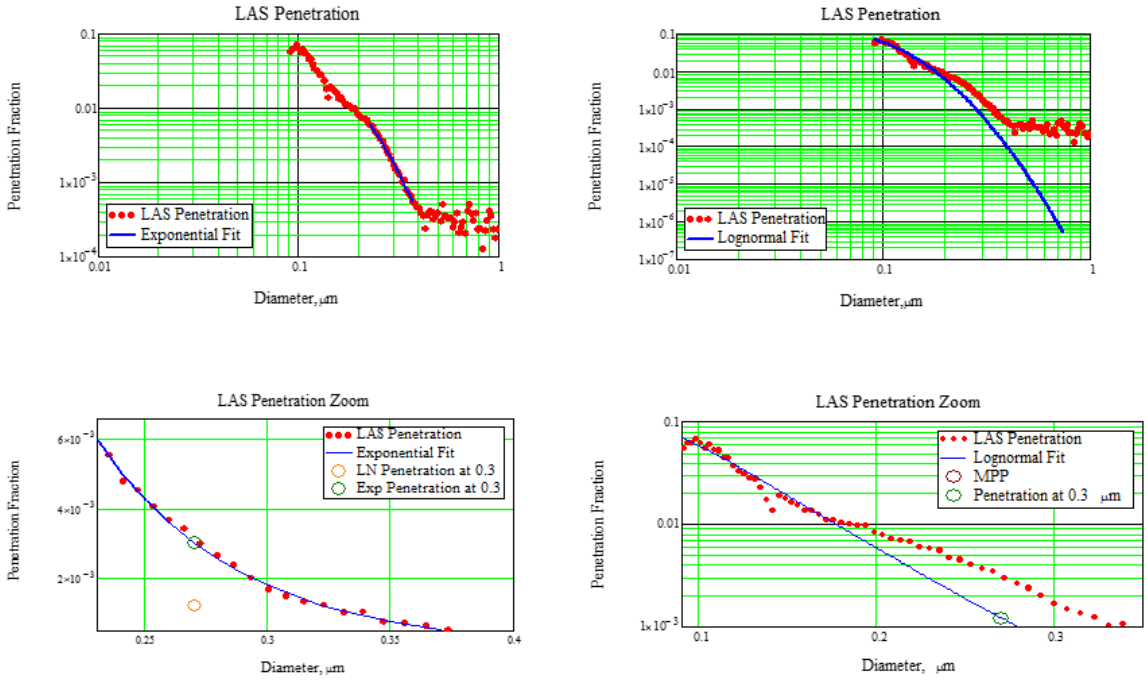


Figure 6.27 Penetration curve with exponential curve fit (top left), lognormal curve fit(top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 2.8-6.1 in. WC (Initial) FE measurement

The next FE measurement is taken at 15.2-22.4 in. WC. The PSD curves are given in

Figure 6.28.

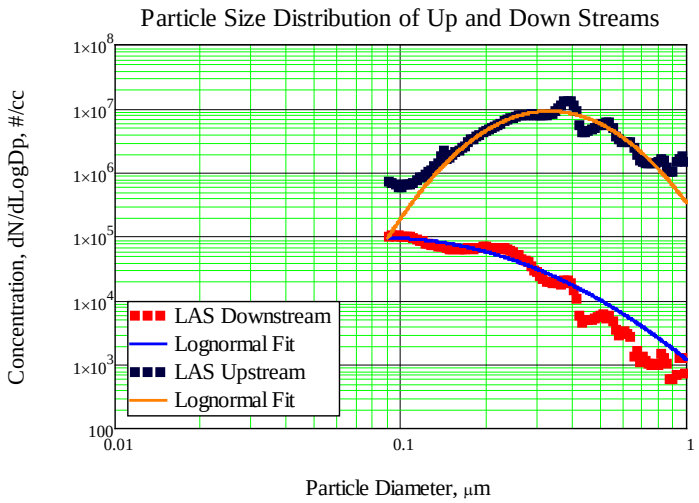


Figure 6.28 PSD curves with lognormal curve fit for 15.2-22.4 in. WC FE measurement.

For the 15.2-22.4 in. WC FE measurement, penetration curves are generated and are given in Figure 6.29.

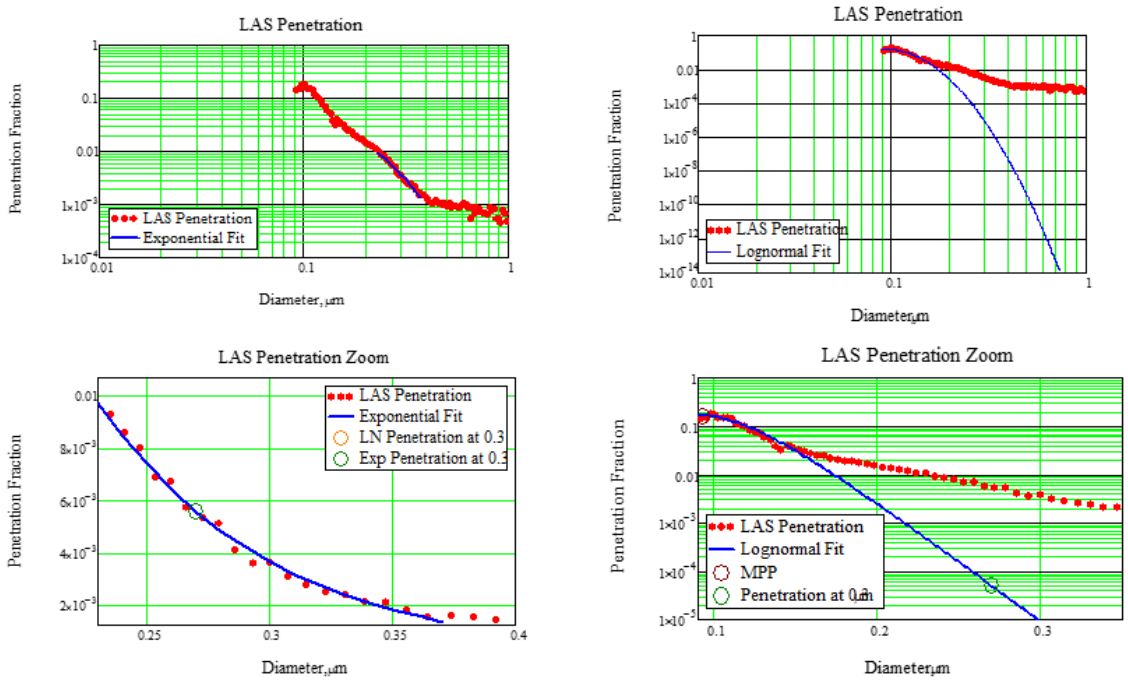


Figure 6.29 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 15.2-22.4 in. WC FE measurement.

The next FE measurement is taken at 29.9-31.3 in. WC. The PSD curve for this interval is illustrated in Figure 6.30.

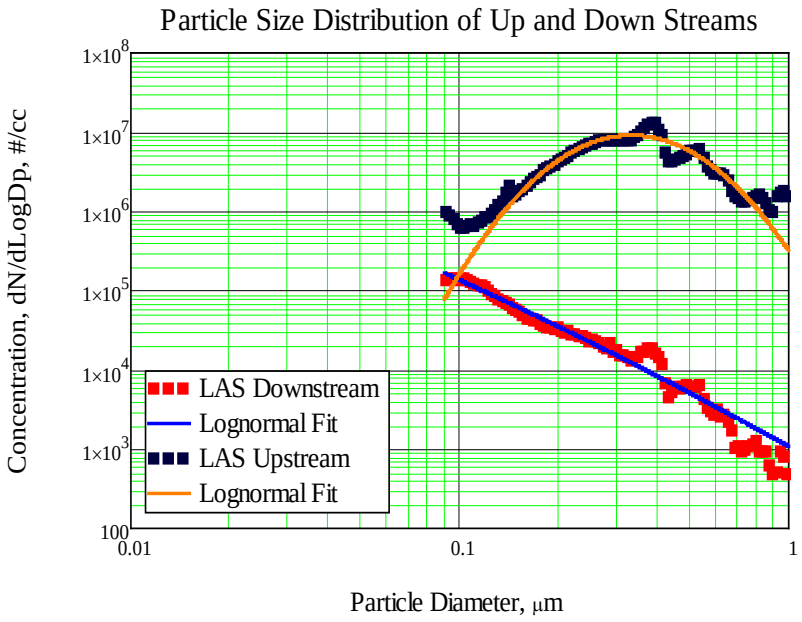


Figure 6.30 PSD curves with lognormal curve fit for 29.9-31.3 in. WC FE measurement.

The penetration curve for the 29.9-31.3 in. WC FE measurement is given in Figure 6.31.

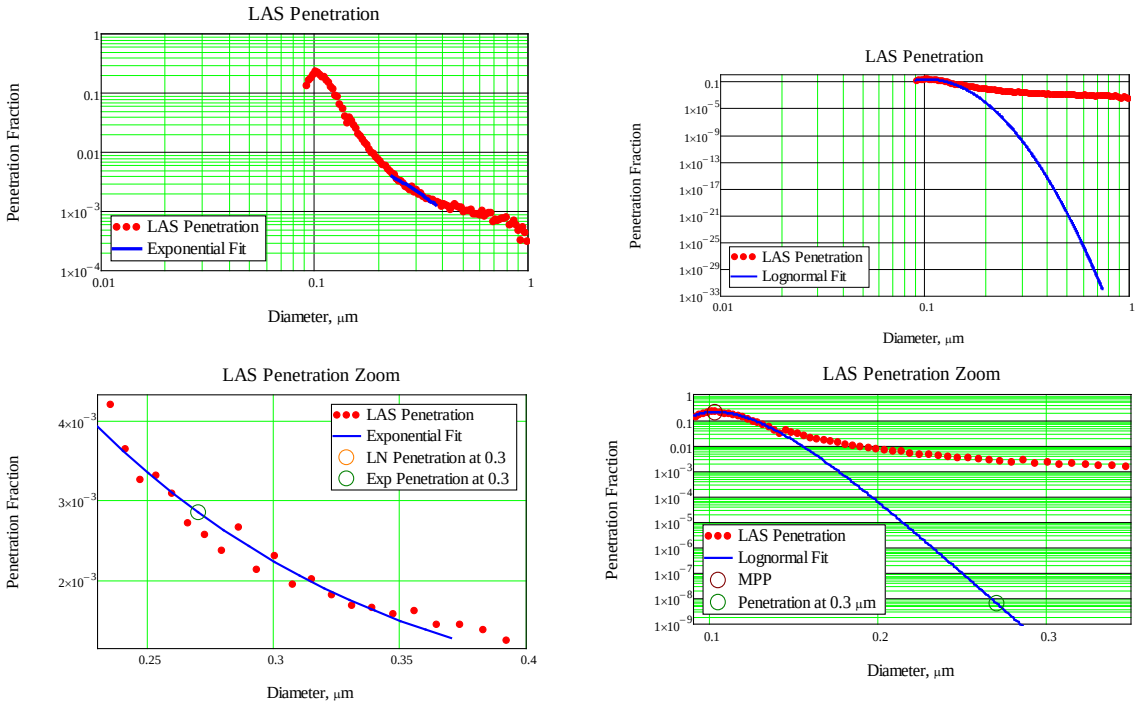


Figure 6.31 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 29.9-31.3 in. WC FE measurement.

Next, an FE measurement is taken at 35.5-36.9 in. WC. The PSD curves for this measurement is outlined in Figure 6.32.

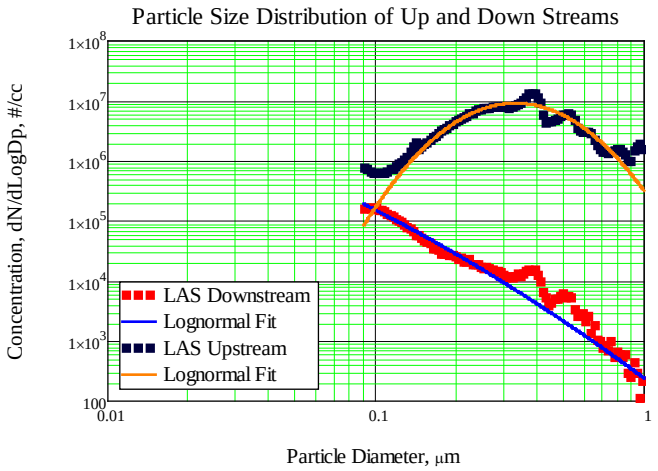


Figure 6.32 PSD curves with lognormal curve fit for 35.5-36.9 in. WC FE measurement.

A penetration curve is given in Figure 6.33 for this FE measurement.

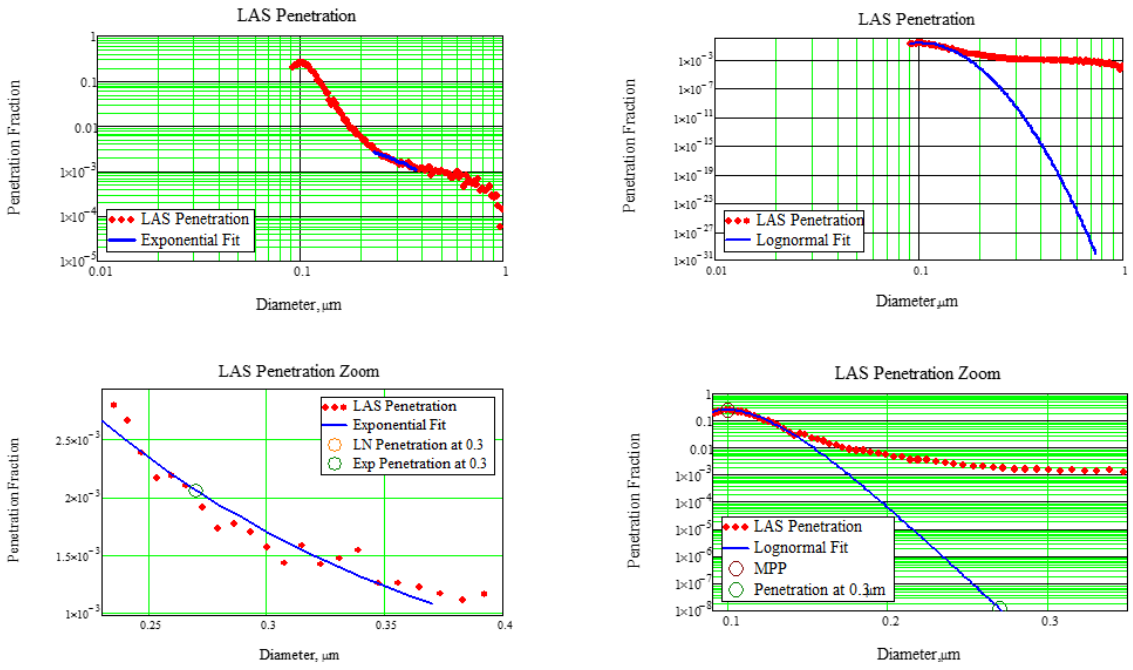


Figure 6.33 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 35.5-36.9 in. WC FE measurement.

The final FE measurement is taken at 39.9-40.6 in. WC, and the PSD curves are given in Figure 6.34.

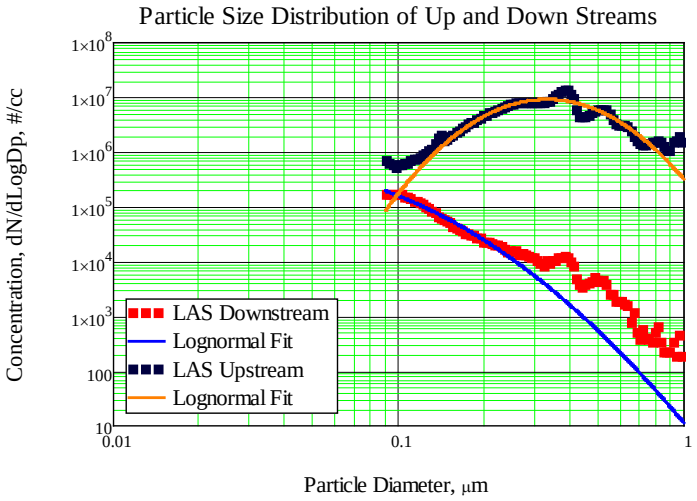


Figure 6.34 PSD curves with lognormal curve fit for 39.9-40.6 in. WC FE measurement.

The penetration curve at the FE measurement is illustrated in Figure 6.35.

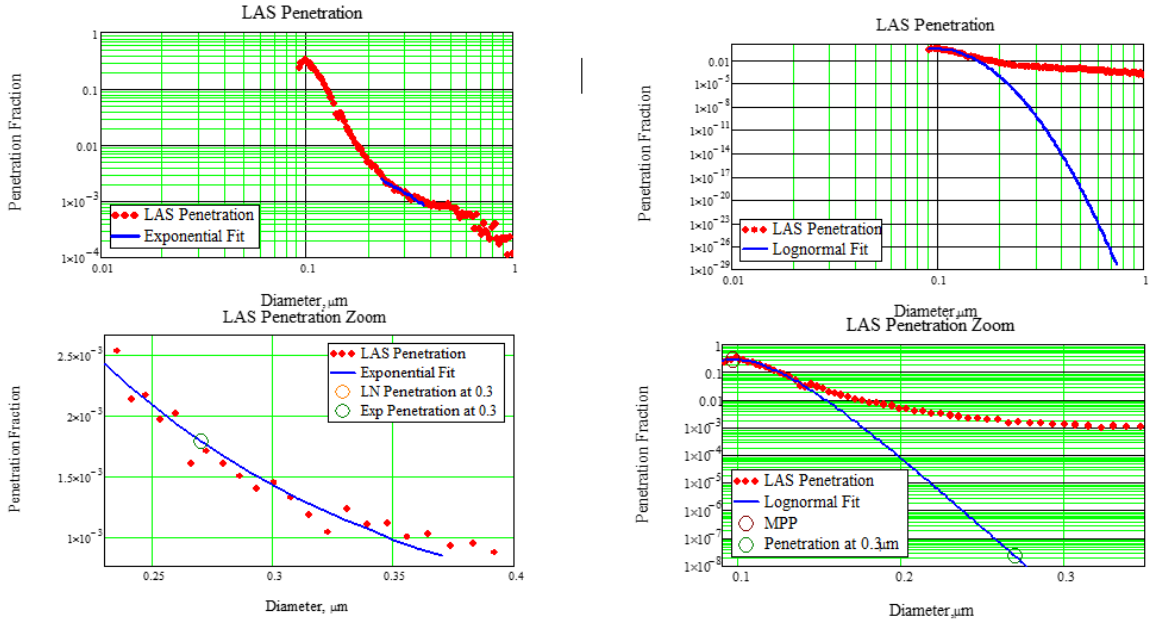


Figure 6.35 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 39.9-40.6 in. WC FE measurement.

A loading curve is generated and can be found in Figure 6.36. The dP quickly increases from 2.5 in. WC up to 24 in. WC. After it reaches 25 in. WC, the dP gradually increases all the way up to approximately 40 in. WC.

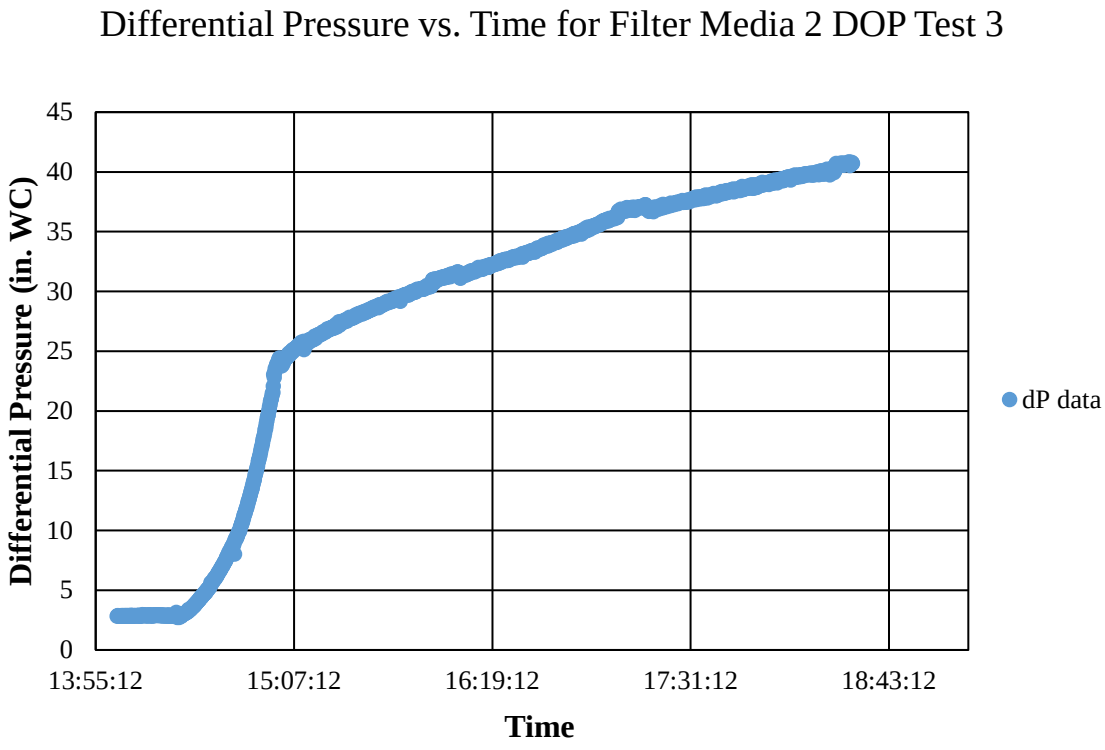


Figure 6.36 Loading curve for Filter Media 2 DOP test 3.

A summary of the parameters generated from this test is given in Table 6.4.

Table 6.4 Summary of parameters from testing.

FE Measurement	**2.8-6.1 in. WC**	**15.2-22.4 in. WC**	**29.9-31.3 in. WC**	**35.5-36.9 in. WC**	**39.9-40.6 in. WC**
GM Upstream	0.3102	0.3262	0.3276	0.327	0.3273
GSD Upstream	1.5917	1.577	1.5784	1.5739	1.5713
GM Downstream	0.1633	0.1654	0.1459	0.1379	0.1339
GSD Downstream	1.4903	1.5463	1.5576	1.5225	1.4809
GM Penetration	0.1257	0.1224	0.1166	0.1128	0.1109
GSD Penetration	1.3849	1.374	1.3094	1.267	1.2393
Penetration Fraction at 0.3 μm	3.0222×10^{-3}	5.5656×10^{-3}	2.8476×10^{-3}	2.0608×10^{-3}	1.7899×10^{-3}
Filtering Efficiency at 0.3 μm (Exponential)	99.70%	99.44%	99.72%	99.79%	99.82%
Most Penetrating Particle at MPPS	0.0595 μm	0.0923 μm	0.1029 μm	0.0992 μm	0.0964 μm
Penetration Fraction at MPPS	0.0975	0.1619	0.2068	0.2474	0.2925

Figure 6.37 displays pre-test filter images from DOP Test 3, and Figure 6.38 illustrates the filter post-test images.

Figure 6.37 Pre-test images of filter from DOP test 3.

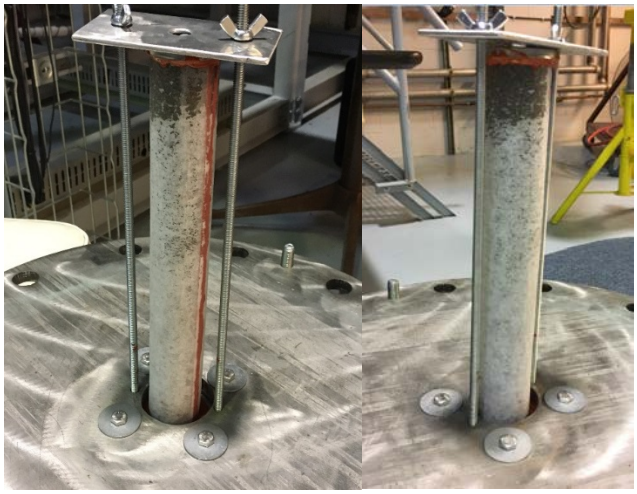


Figure 6.38 Post-test images of filter from DOP test 3.

Filter media 2 single element loading test 1

This test was completed on a fifth Filter Media 2 single element filter using both DOP and KCl as challenge aerosols. A solid particle aerosol (KCl) is used to load the filter throughout the entire test. At certain intervals during the test, DOP is used to record an FE measurement. After this FE measurement, testing resumes with KCl to load the filter. This process is repeated until a certain number of FE measurements are collected and until the filter loads to a certain dP value. Again, like DOP Test 3, the test stand airflow setpoints are adjusted based on sampling

configuration, instruments used, and aerosol generator used, so that the filter receives a rated flow of 5 CFM. The 100:1 and 20:1 diluters are both used for US measurements, while a 100:1 diluter is used for DS measurements. In this test, the DOP generator settings remain constant throughout testing at 2 jets, 25 psi (172369 Pa). The KCl generator is set to use optimized settings, which are outlined in the aerosol generation section within this text.

The PSD curve at the 9.2-19 in. WC FE interval is shown in Figure 6.39.

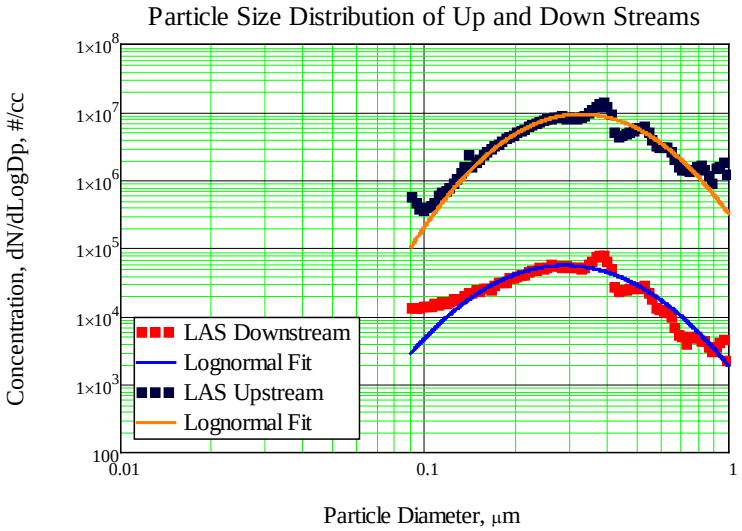


Figure 6.39 PSD curves with lognormal curve fit for 9.2-19 in. WC FE measurement.

The penetration curve is given in Figure 6.40.

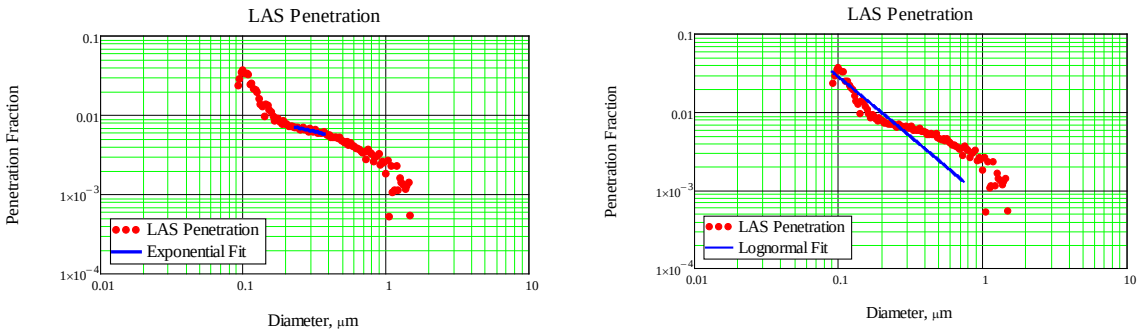


Figure 6.40 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 9.2-19 in. WC FE measurement.

The filter loaded very quickly from 2 in. WC to 20 in. WC using DOP. Again, the small surface area of the filter and the instrument purging cycles between DS and US sample collection made it particularly difficult to get FE measurements at lower dP ranges. Only one FE measurement is recorded from Loading Test 1. A summary of parameters from the test is listed in Table 6.5. For the data analysis in this test, a lognormal curve fit was not a good representation of the loading curve. The loading curve is relatively linear, in which a lognormal analysis is not able to produce a good fit within Mathcad. Therefore, instead of the curve fit generating values for MPPS and penetration fraction at MPPS, the values are extracted manually from Mathcad. For Loading Test 1, the maximum point in the loading curve is 0.037 with a corresponding diameter of 0.099.

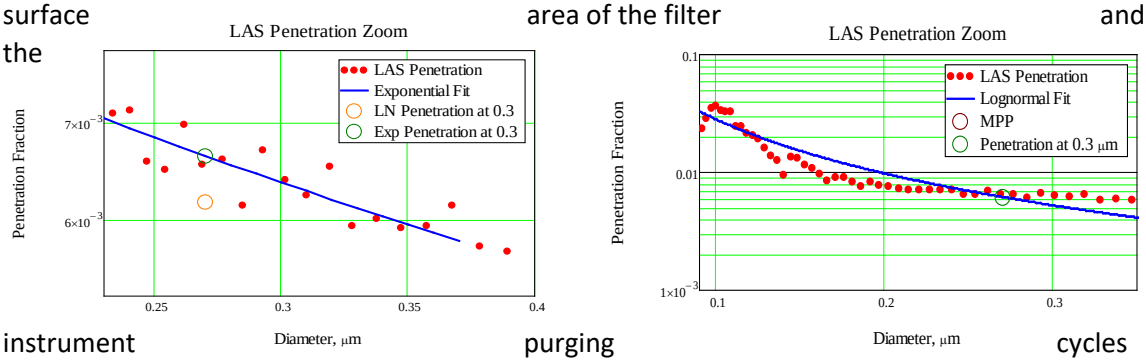


Table 6.5 Summary of parameters from testing.

FE Measurement	**9.2-19 in. WC**
GM Upstream	0.3314
GSD Upstream	1.5972
GM Downstream	0.2758
GSD Downstream	1.6245
GM Penetration	0.1917
GSD Penetration	2.0158
Penetration Fraction at 0.3 μm	6.6601×10^{-3}
Filtering Efficiency at 0.3 μm (Exponential)	99.33399%
Most Penetrating Particle at MPPS	0.099 μm
Penetration Fraction at MPPS	0.037

A dataset that was associated with this test is the upstream PSD for the KCl loading interval, which is shown in Figure 6.41. The PSD curve in this figure includes an average of five samples.

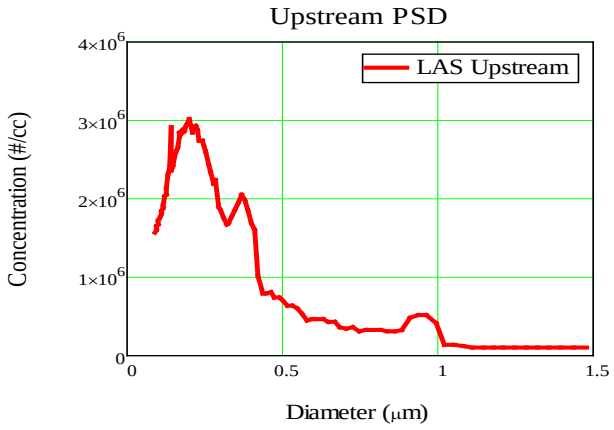


Figure 6.41 Particle size distribution at KCl loading interval during loading test 1.

In addition to the plots previously outlined, the loading curve for Loading Test 1 is given in Figure 6.42.

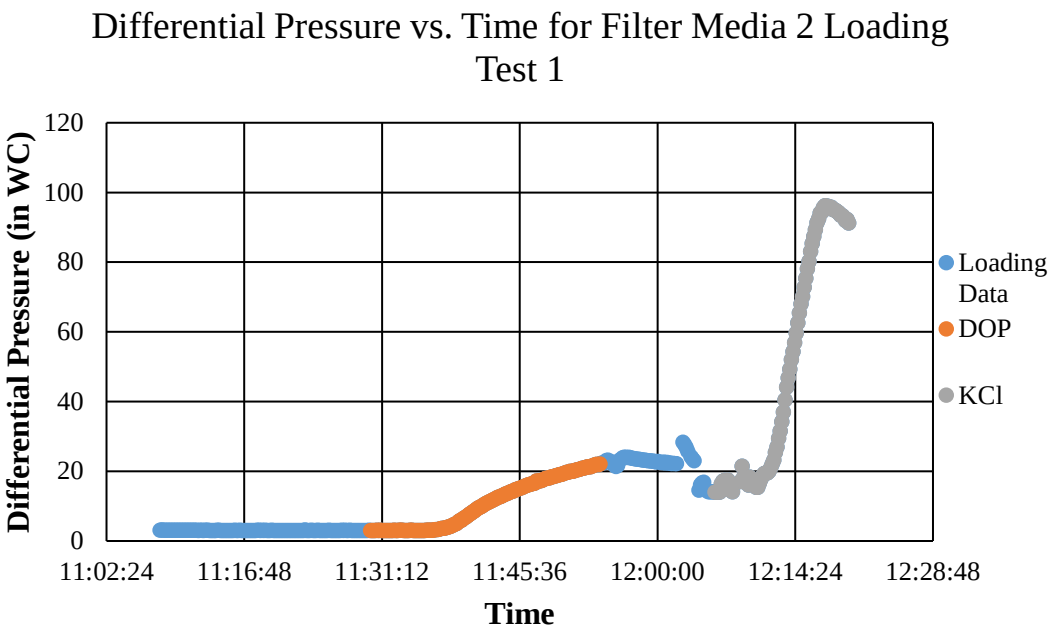


Figure 6.42 Loading curve for loading test 1.

The blue markers in the plot denote the dP data collected for the entire test. To clarify further, the orange data points represent the interval where DOP loads onto the filter, and the grey data points represent KCl loading onto the filter. When KCl is loaded onto the filter, the dP quickly increases since KCl is a solid particle aerosol and cakes onto the filter media. The fluctuations at approximately 30 in. WC are due to sampling valve adjustments, adding the ELPI sampling line to the housing section, or opening the KCl generator exit valve without adjusting the test stand air flowrate in the CPU first. Images of the filter after Loading Test 1 are found in Figure 6.43.

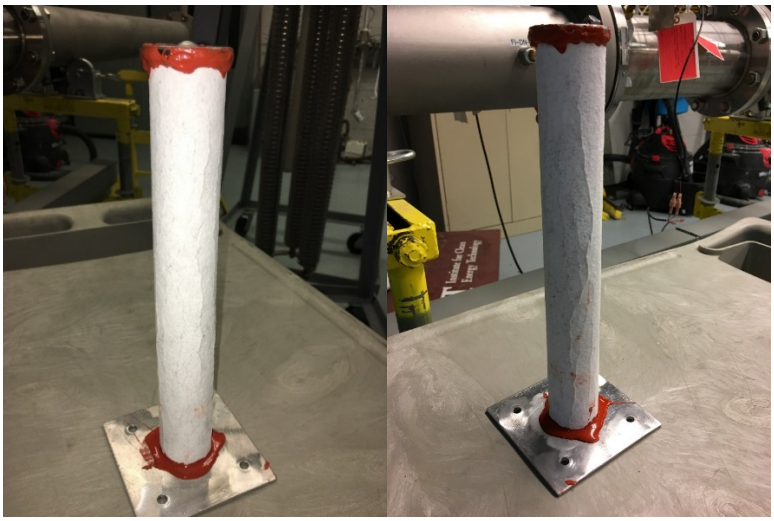


Figure 6.43 Post-test images from loading test 1.

As opposed to the previous tests, the filter was not overly saturated with DOP. This test used both DOP and KCl, but the filter was not exposed to DOP for an extended amount of time like the other filters had been.

Filter media 2 single element loading test 2

The second loading test was very similar to Loading Test 1 in regard to testing methodologies. Both 100:1 and 20:1 diluters are used for US measurements, and a 100:1 diluter is used for DS measurements. The test stand airflow setpoints are adjusted based on sampling configuration, instruments used, and aerosol generator used. The DOP generator is set to 1 jet, 25 psi (172369 Pa) for this test, and the KCl generator optimized settings are also used. The first set of PSD curves, generated for the 2.9-4.8 in. WC (Initial) FE interval, are shown in Figure 6.44.

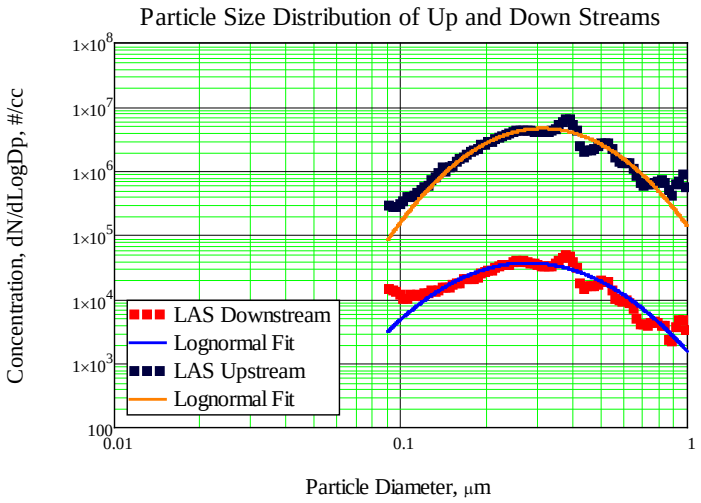


Figure 6.44 PSD curves with lognormal curve fit for 2.9-4.8 in. WC (Initial) FE measurement.

In addition to the PSD curves, the penetration curve is generated for this FE measurement and is shown in Figure 6.45.

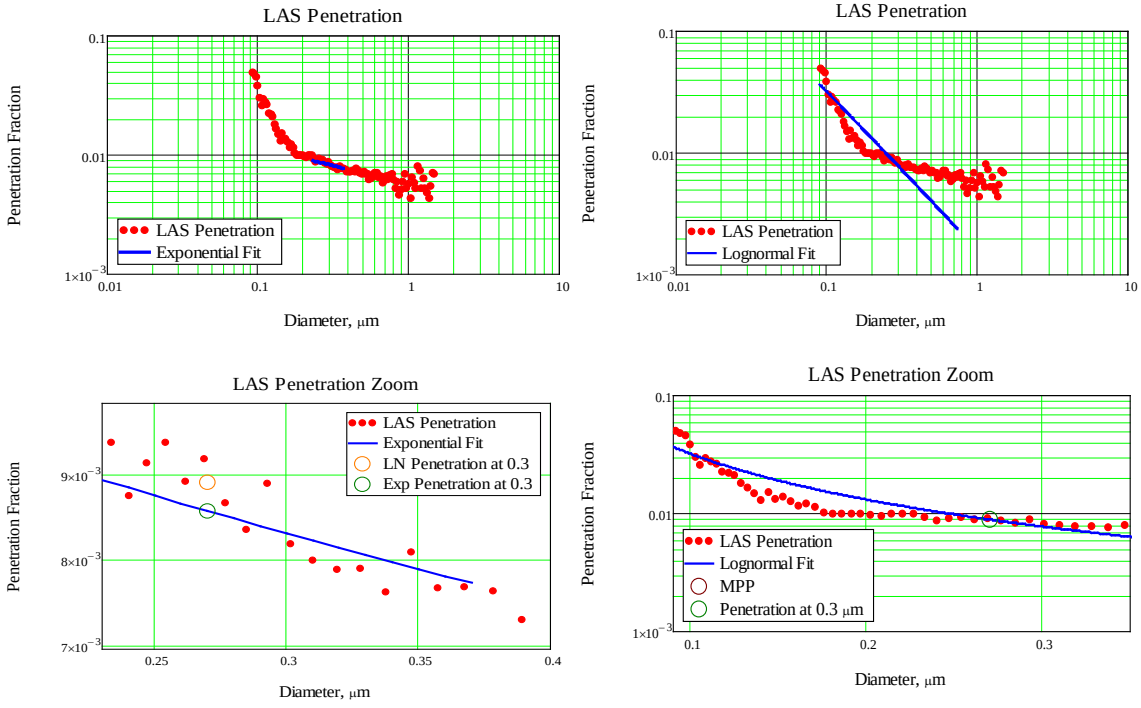


Figure 6.45 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 2.9-4.8 in. WC FE (Initial) measurement.

The PSD curves for the next FE measurement at 18.5-26.5 in. WC is given in Figure 6.46.

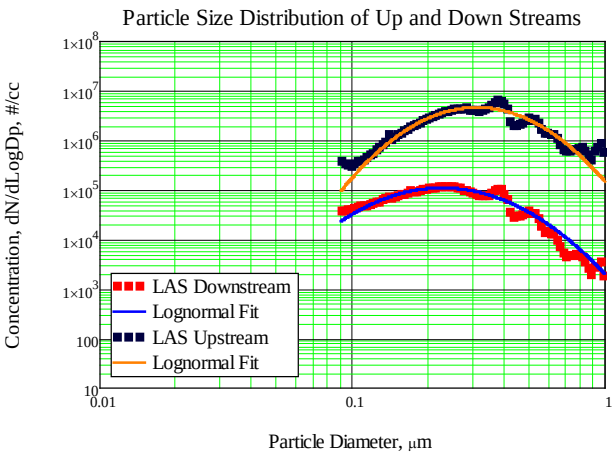


Figure 6.46 PSD curves with lognormal curve fit for 18.5-26.5 in. WC FE measurement.

The penetration curve is given in Figure 6.47.

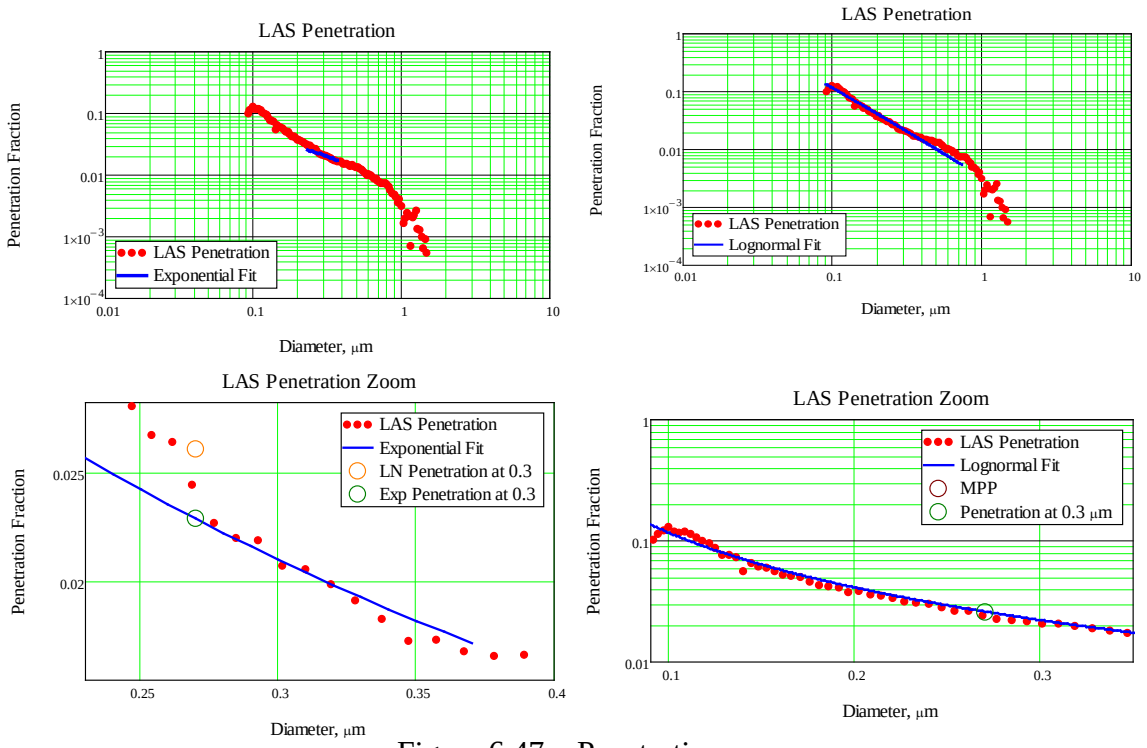


Figure 6.47 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 18.5-26.5 in. WC FE measurement.

The next set of data illustrates the 29-30.6 in. WC FE measurement. The PSD curves are given in Figure 6.48.

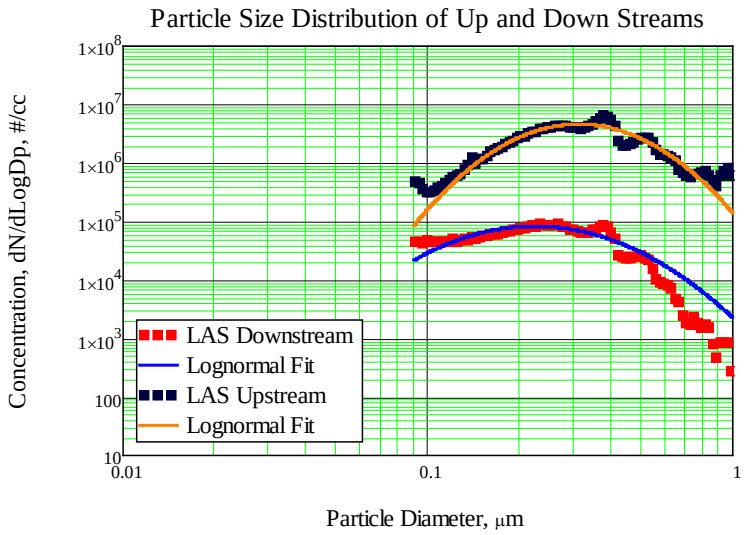


Figure 6.48 PSD curves with lognormal curve fit for 29-30.6 in. WC FE measurement.

Also included is the penetration curve for this FE measurement, which is illustrated in Figure 6.49.

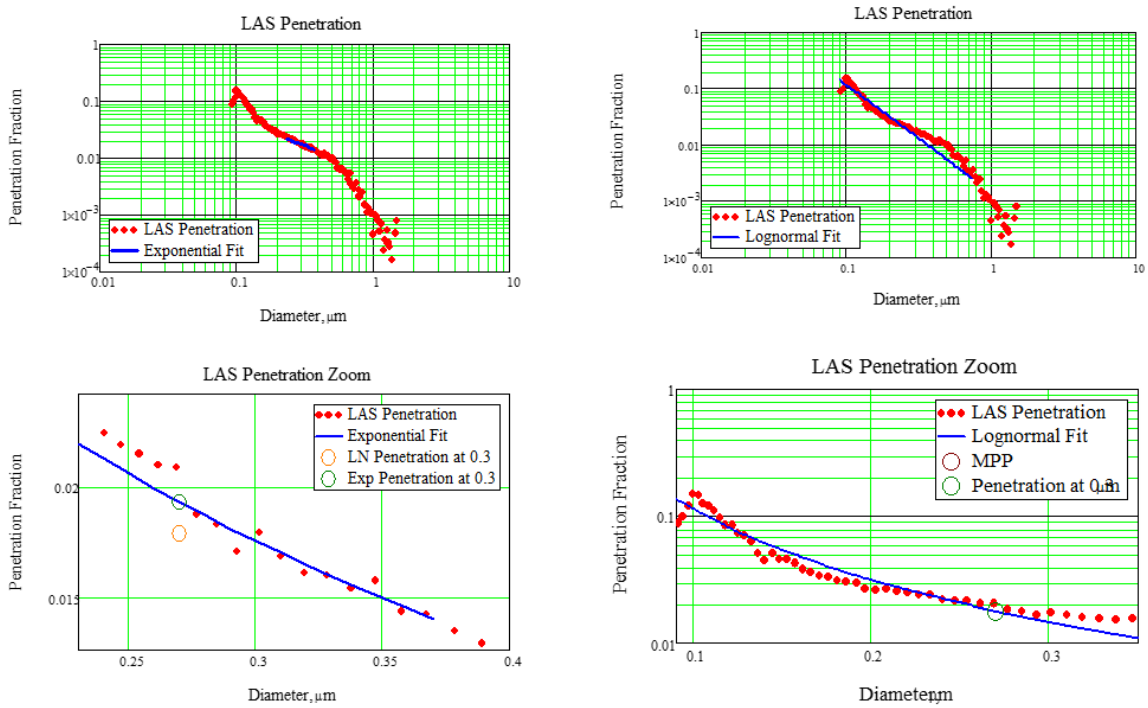


Figure 6.49 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 29-30.6 in. WC FE measurement.

Table 6.6 displays some of the notable parameters generated from this test. Similar to Loading Test 1, a lognormal curve fit was not a good representation of the loading curve. The loading curve is relatively linear, in which a lognormal analysis is not able to produce a good fit within Mathcad. Therefore, instead of the curve fit generating values for MPPS and penetration fraction at MPPS, the values are extracted manually from Mathcad.

Table 6.6 Summary of parameters from testing.

FE Measurement	**2.9-4.8 in. WC**	**18.5-26.5 in. WC**	**29-30.6 in. WC**
GM Upstream	0.3165	0.3151	0.3159
GSD Upstream	1.6088	1.6136	1.6146
GM Downstream	0.2729	0.2319	0.2252
GSD Downstream	1.6764	1.5979	1.6011
GM Penetration	0.2302	0.1688	0.155
GSD Penetration	2.2969	1.7742	1.6736
Penetration Fraction at 0.3 μm	8.5723×10^{-3}	0.0229	0.0193
Filtering Efficiency at 0.3 μm (Exponential)	99.14%	97.71%	98.07%
Most Penetrating Particle at MPPS	0.091 μm	0.099 μm	0.099 μm
Penetration Fraction at MPPS	0.05	0.13	0.153

Another important set of plots included is the upstream PSD curves for KCl loading intervals. The plots include an average of 10 samples taken using the LAS and are found in Figure 6.50.

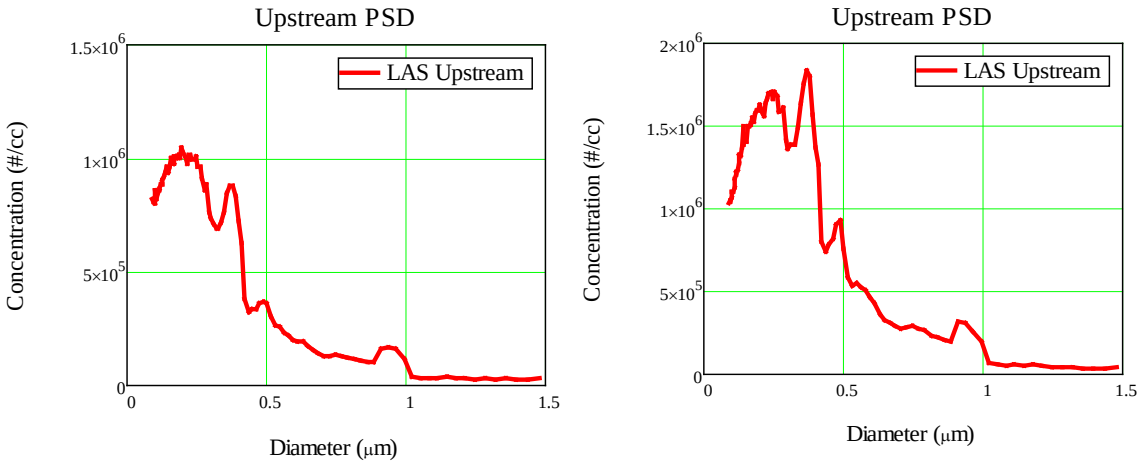
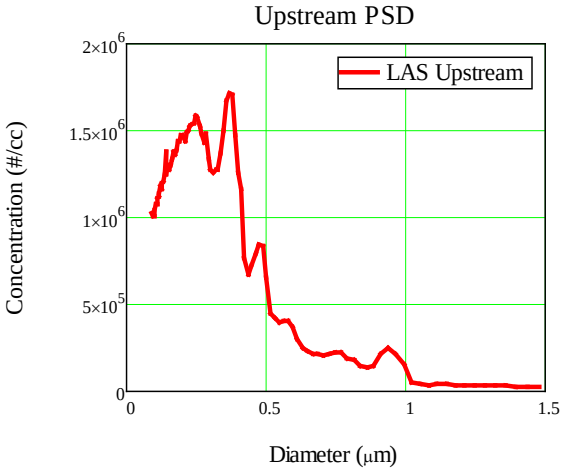


Figure 6.50 PSD curves at three KCl loading intervals during loading test 2.



The loading curve for Loading Test 2 is found in Figure 6.51 below.

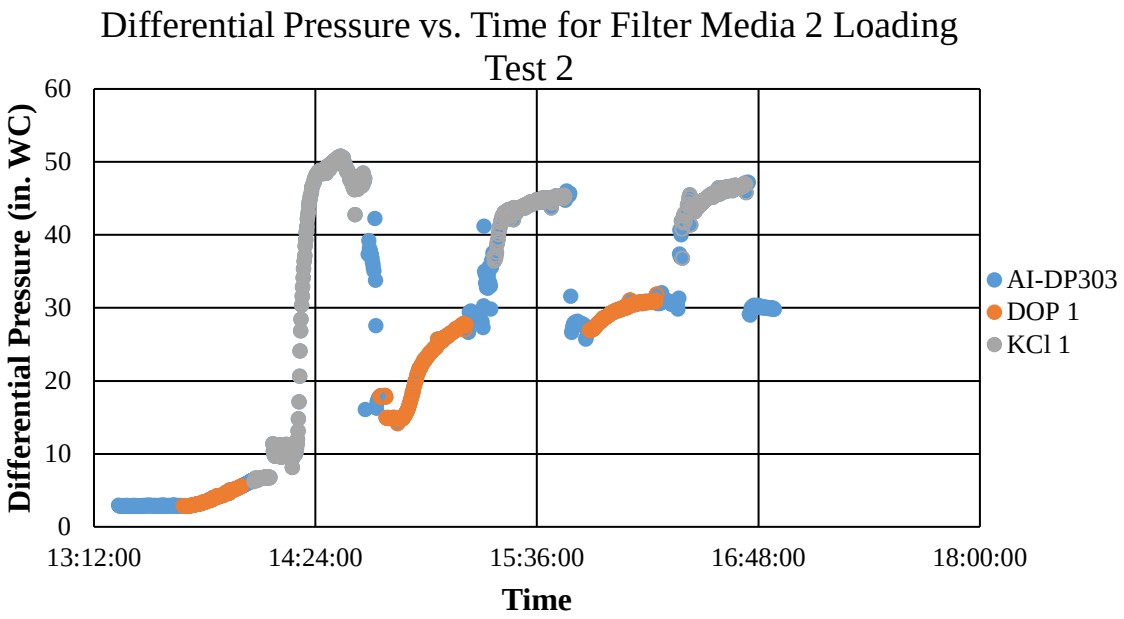


Figure 6.51 Loading curve for loading test 2.

Similar to Figure 6.42, the blue data points include all the dP data collected during the test. The orange data points are the dP values when the filter is loaded with DOP, and the grey data points are the dP values when the filter is loaded with KCl. Again, the introduction of KCl into the test stand and onto the filter causes a quick rise in dP across the filter. Images of the filter before and after Loading Test 2 are given in Figures 6.52 and 6.53, respectively.

Figure 6.52 Pre-test image of filter for loading test 2.

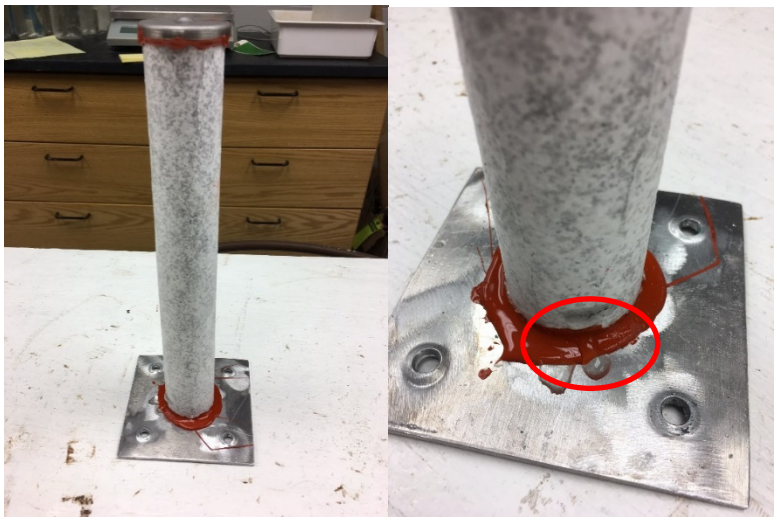


Figure 6.53 Post-test images of filter for loading test 2.

As shown in Figure 6.53, there appears to be a DOP leak at the base of the filter onto the metal plate. The area circled in red is the source of this leak, which may indicate a fracture in the filter core or tear in the filter paper. To provide further information from the testing activities on the Filter Media 2 single element filters, Table 6.7 summarizes the final dP values seen for each filter.

Table 6.7 Initial and final differential pressures for filter 4 and 5 KCl loading intervals.

Filter 4		**Filter 5**	
KCl Load 1 initial dP	16.44748	KCl Load 1 initial dP	34.13439
KCl Load 1 final dP	91.23012	KCl Load 1 final dP	47.60358
Max dP	96.20966	KCl Load 2 initial dP	42.90419
		KCl Load 2 final dP	45.21955
		KCl Load 3 initial dP	44.27473
*all values in units of in. WC		KCl Load 3 final dP	47.13941

Filter media 1 six-element filter DOP test

For this test, a six-element ceramic filter wrapped with Filter Media 1 is challenged with DOP. DOP generator settings include 1 jet, 25 psi (172369 Pa) used throughout the entire test. A rated airflow of approximately 20 CFM at the filter is used for this test. A 20:1 diluter is used for downstream measurements instead of a 100:1 diluter as seen in the previous test summaries. Again, both diluters are used for the upstream measurements. The PSD curves for the 3.1-3.4 in. WC (Initial) FE measurement are given in Figure 6.54, and the penetration curves are summarized in Figure 6.55.

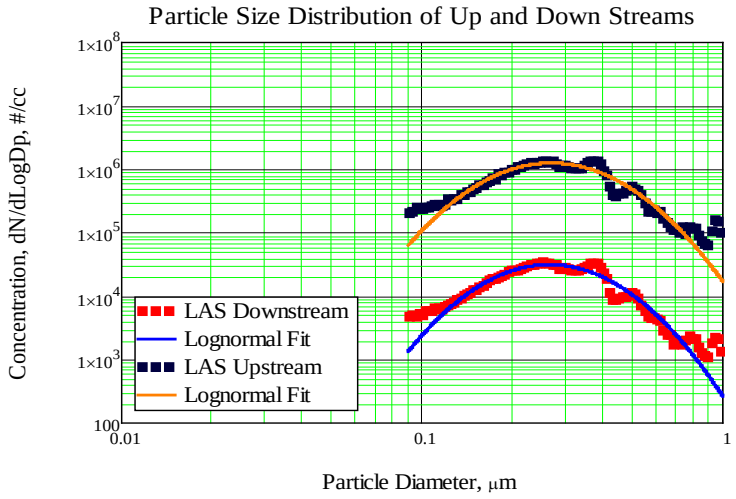


Figure 6.54 PSD curves with lognormal curve fit for 3.1-3.4 in. WC (Initial) FE measurement.

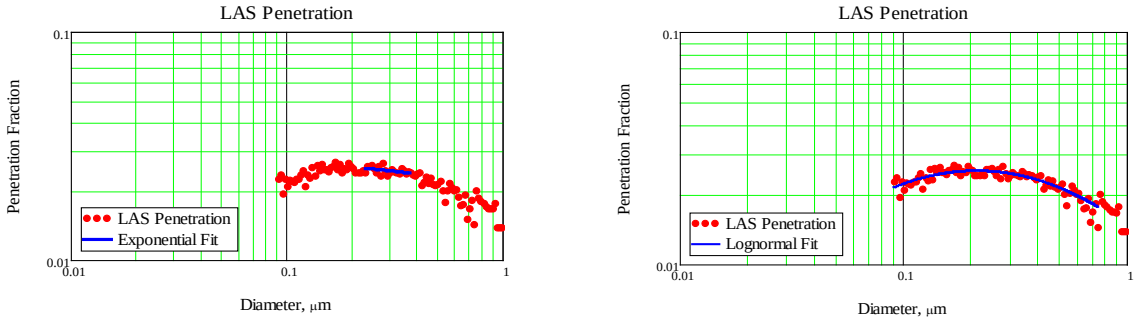
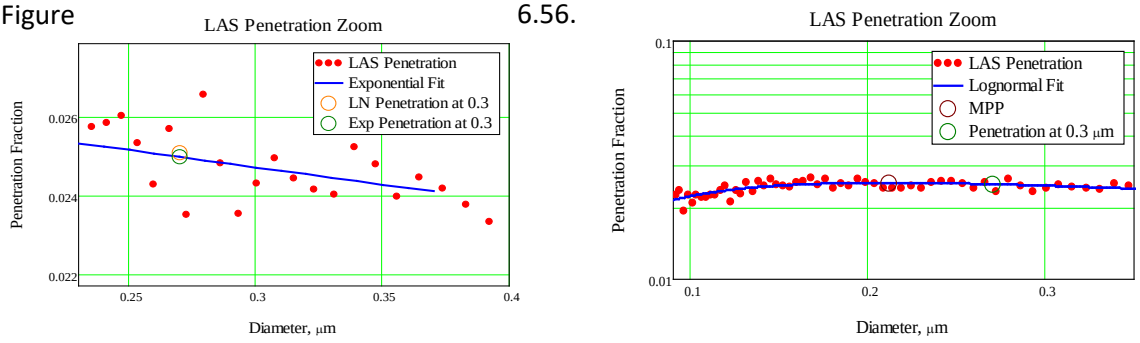


Figure 6.55 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 3.1-3.4 in. WC FE (Initial) measurement.

The next FE measurement is taken at 6.4-12.8 in. WC, and the PSD curves are shown in Figure 6.56.



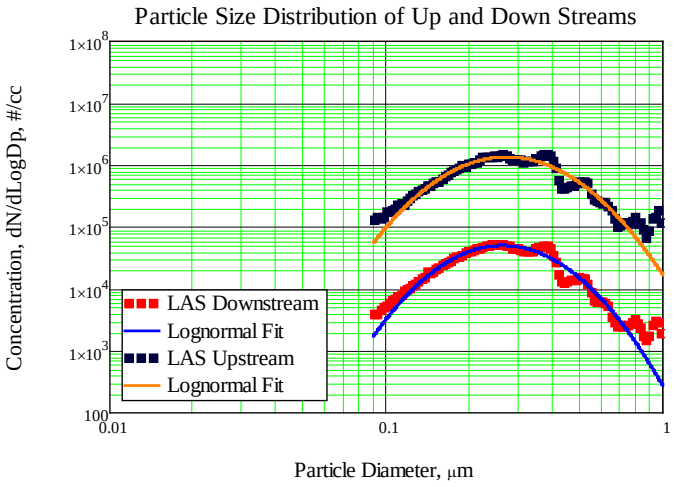


Figure 6.56 PSD curves with lognormal curve fit for 6.4-12.8 in. WC FE measurement.

The penetration curve and the lognormal and exponential fits are displayed in Figure 6.57.

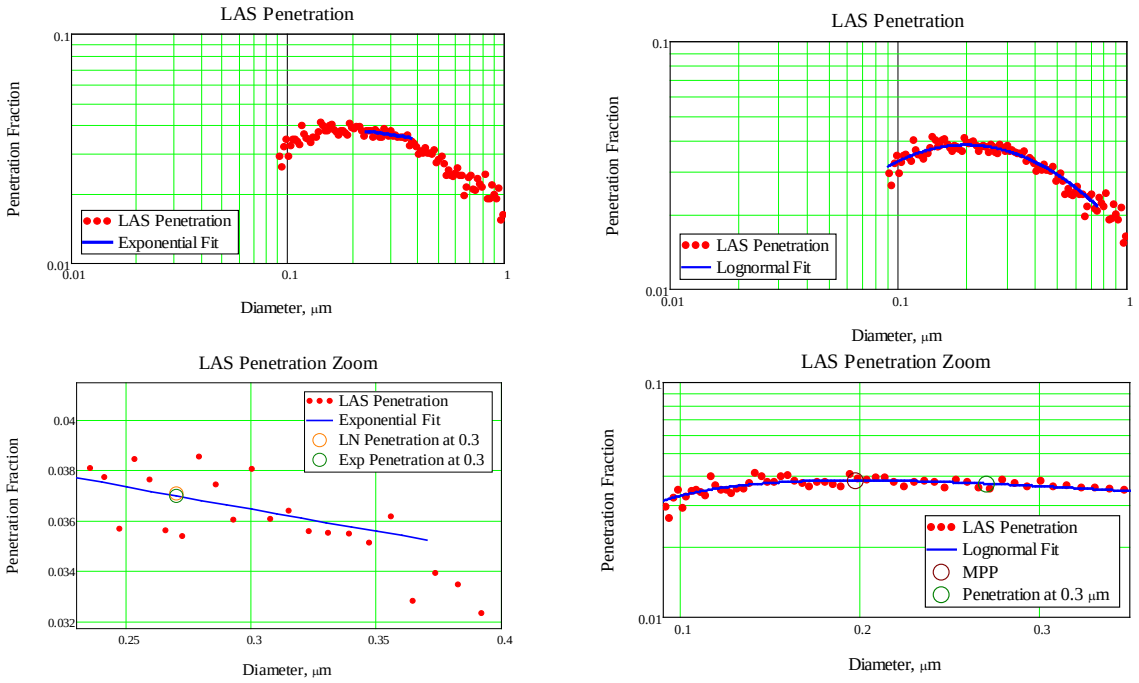


Figure 6.57 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 6.4-12.8 in. WC FE measurement.

Another set of PSD curves is given in Figure 6.58. These are from the 23.3-28.6 in. WC FE measurement.

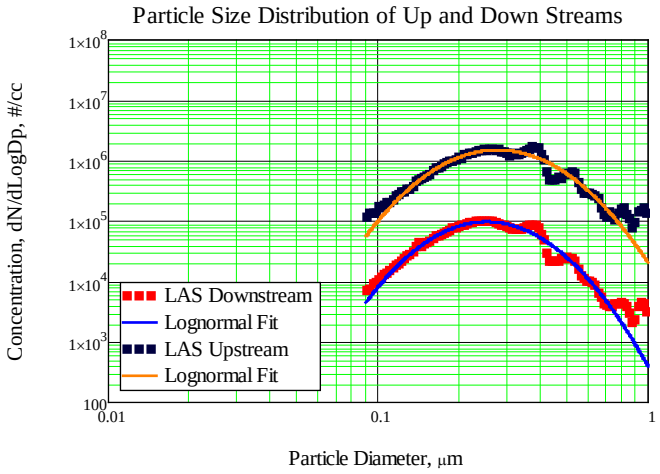


Figure 6.58 PSD curves with lognormal curve fit for 23.3-28.6 in. WC FE measurement.

The penetration curve is given in Figure 6.59.

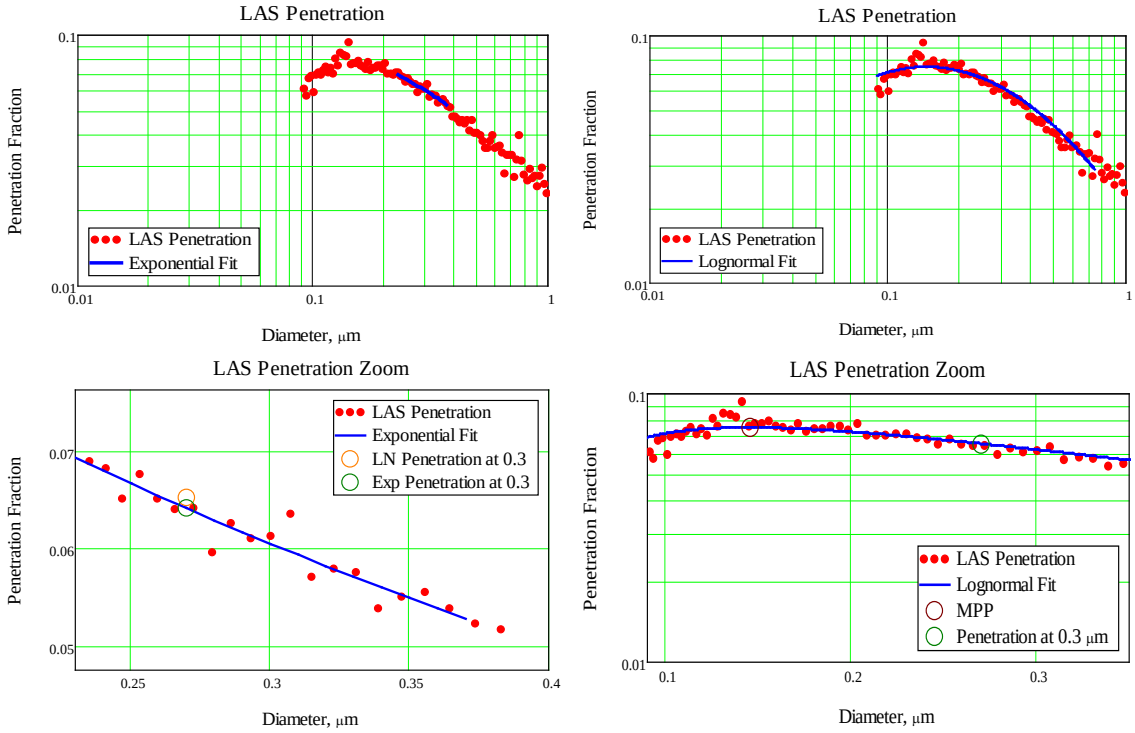


Figure 6.59 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 23.3-28.6 in. WC FE measurement.

A third FE measurement is taken at 35.6-36.1 in. WC, and the PSD curves are illustrated in Figure 6.60.

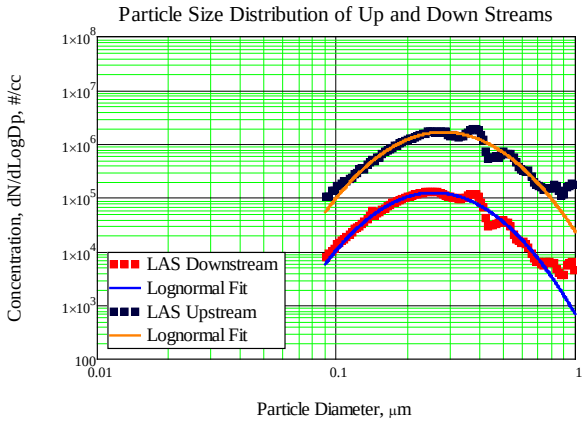


Figure 6.60 PSD curves with lognormal curve fit for 35.6-36.1 in. WC FE measurement.

The corresponding penetration curve for the 35.6-36.1 in. WC FE measurement is displayed in Figure 6.61.

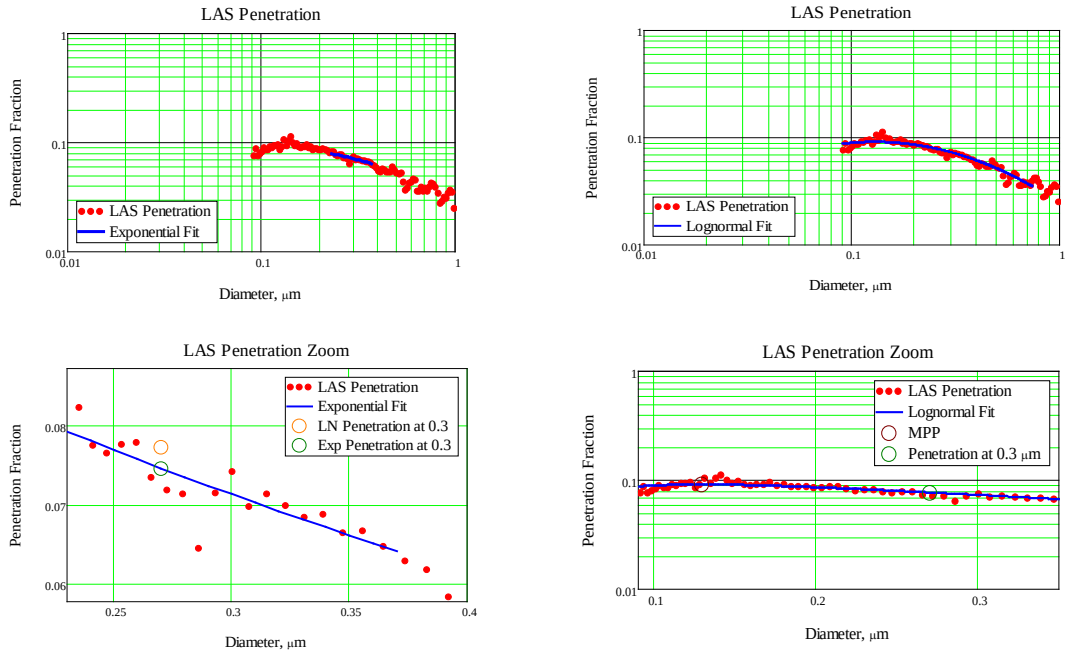


Figure 6.61 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 35.6-36.1 in. WC FE measurement.

The final FE measurement is taken at 41 in. WC, and the PSD curves at this interval is shown in Figure 6.62.

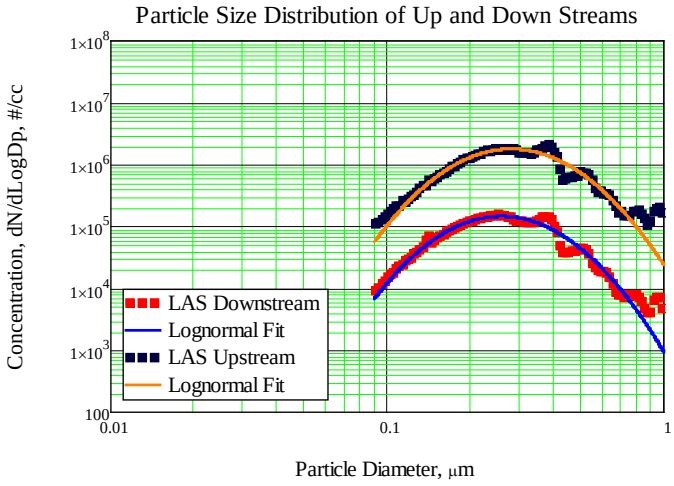


Figure 6.62 PSD curves with lognormal curve fit for 41 in. WC FE measurement.

The penetration curve at this FE interval is given in Figure 6.63.

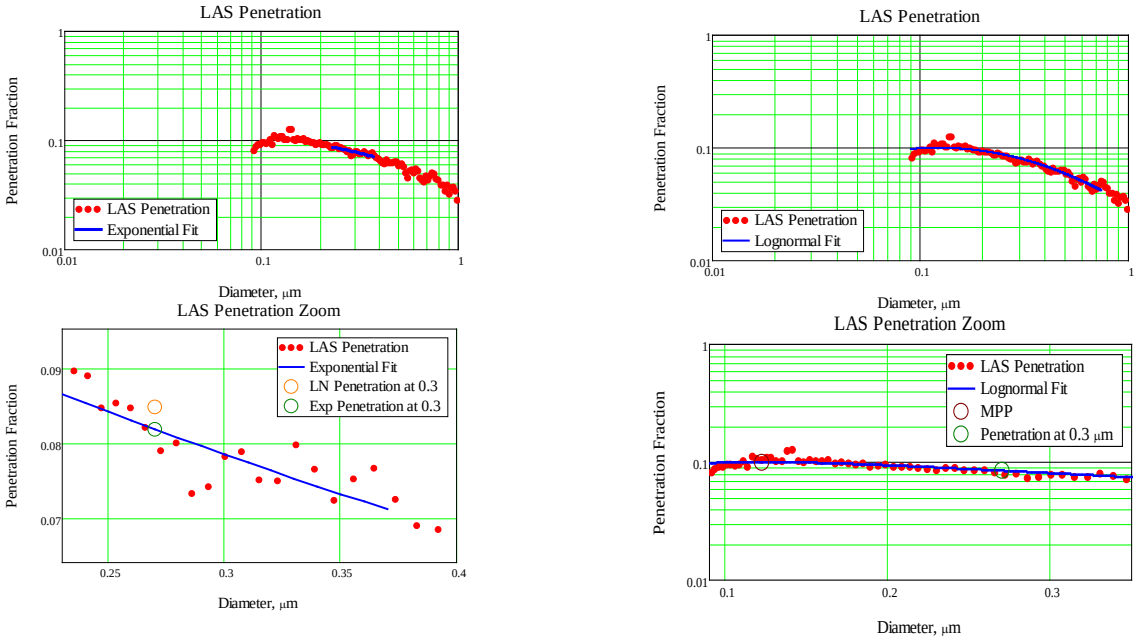


Figure 6.63 Penetration curve with exponential curve fit (top left), lognormal curve fit (top right), exponential zoom (bottom left), and lognormal zoom (bottom right) for 41 in. WC FE measurement.

The loading curve for this test is given in Figure 6.64, and a summary table from the ceramic filter tests is listed in Table 6.8.

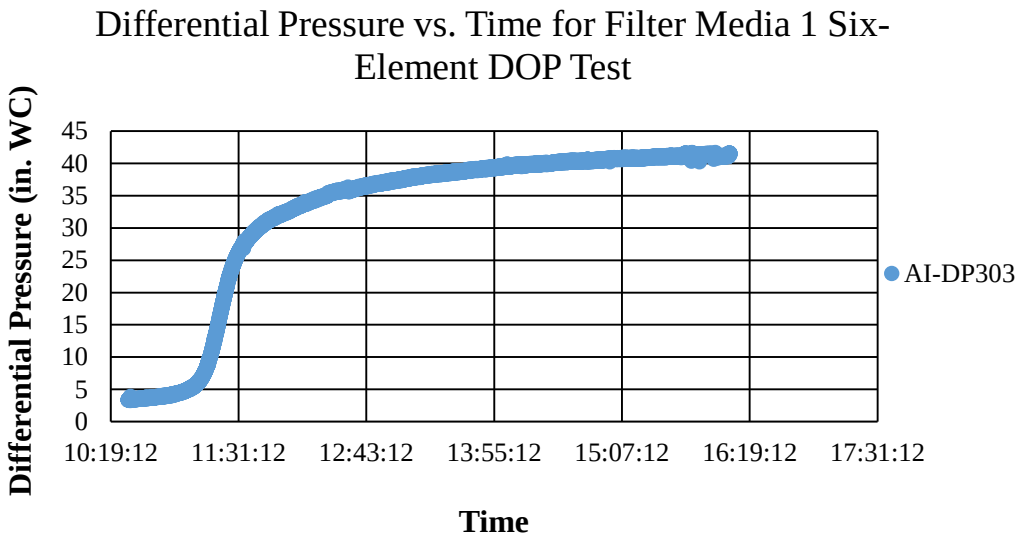


Figure 6.64 Loading curve for Filter Media 1 six-element DOP test.

Table 6.8 Summary of parameters from testing.

FE Measurement	**3.1-3.4 in. WC**	**6.4-12.8 in. WC**	**23.3-28.6 in. WC**	**35.6-36.1 in. WC**	**41 in. WC**
GM Upstream	0.2677	0.2743	0.2786	0.2834	0.2831
GSD Upstream	1.5886	1.5712	1.5661	1.5645	1.5608
GM Downstream	0.2619	0.2627	0.2538	0.2576	0.2595
GSD Downstream	1.5542	1.5246	1.5179	1.5236	1.5267
GM Penetration	0.2796	0.2679	0.2435	0.2419	0.2447
GSD Penetration	1.94	1.9122	1.8875	1.8943	1.9047
Penetration Fraction at 0.3 μm	0.025	0.037	0.0641	0.0746	0.0819
Filtering Efficiency at 0.3 μm (Exponential)	97.50%	96.30%	93.59%	92.54%	91.81%
Most Penetrating Particle at MPPS	0.2115 μm	0.1972 μm	0.1451 μm	0.1293 μm	0.1219 μm
Penetration Fraction at MPPS	0.0254	0.0383	0.0749	0.0915	0.1006

The filtering efficiency in this test starts at a value of 97.50% and decreases to 91.81% at the end of testing. This decrease in FE is largely due to potential leaks in the filter. When RTV 116 was applied to seal the filter end caps, several areas could not be properly sealed as a result of the arrangement of the six elements. Another cause of the decrease in FE is a potential assembly and shipping issue. Pre-test and post-test images of the Filter Media 1 six-element filter are given in Figures 6.65 and 6.66, respectively.

Figure 6.65 Pre-test image of Filter Media 1 six-element filter.

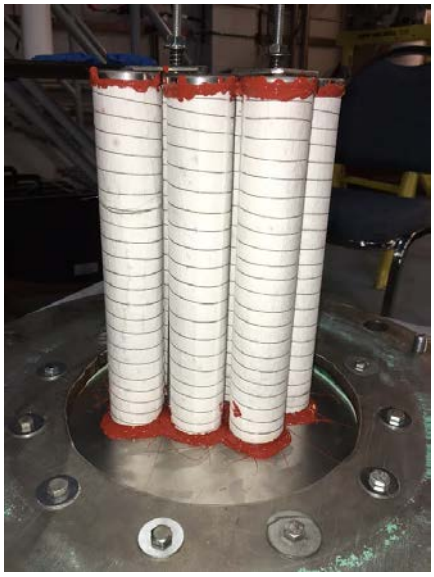


Figure 6.66 Post-test image of Filter Media 1 six-element filter.

Post-test analysis of the filters indicate that there was a small amount of DOP on the downstream side of the filter. Compared to previous tests, the amount of DOP that leaked to

the downstream side of the filter was minimal. Table 6.9 is inserted to summarize the initial and final FE values and dP values from testing.

Table 6.9 Filter FE and differential pressure values from testing.

Filter Tested	**Test Type**	**Initial FE (%)**	**Final FE (%)**	**Initial dP (in. WC)**	**Final dP (in. WC)**
FM 1 Single Element	DOP	99.98	N/A	4.252	44.352
FM 2 Single Element	DOP	99.89	99.65	1.396	51.48
FM 2 Single Element	DOP	99.83	98.36	1.859	27.95
FM 2 Single Element	DOP	99.70	99.82	2.842	40.79
FM 2 Single Element	Loading	99.33	N/A	3.106	91.23
FM 2 Single Element	Loading	99.14	98.07	2.865	46.85
FM 1 Six-Element	DOP	97.50	91.81	3.309	41.48

Elevated Temperature Test Stand Characterization

To develop procedures for elevated temperature testing of ceramic filters, an initial step is to ensure the in-duct air heater works properly. The heater used in this study, as discussed in the test stand development section, can provide elevated temperatures up to 1300°F (704.444°C). Figure 4.2 displays the elevated temperature sensor locations on the test stand. The tag AI-T304 is the designation for the thermocouple approximately four feet downstream of the heater (test stand upstream), AI-T302 is the thermocouple two feet downstream of the housing cap (test stand downstream), AI-T305 is the thermocouple inside the heater, and AI-

T303 is the thermocouple located at the filter (test stand housing). For these characterization tests, a filter is not installed in the test stand housing and no aerosol is injected. A total of 5 heater tests are performed, but only two are outlined in this text. Test 1 is conducted using four thermocouples to fully characterize the test stand at elevated temperatures. The airflow setpoint in these tests is 10 CFM. The heater setpoint is increased from 100°F (37.778°C) to 1000°F (537.778°C). Figure 6.67 displays the results of the heater test.

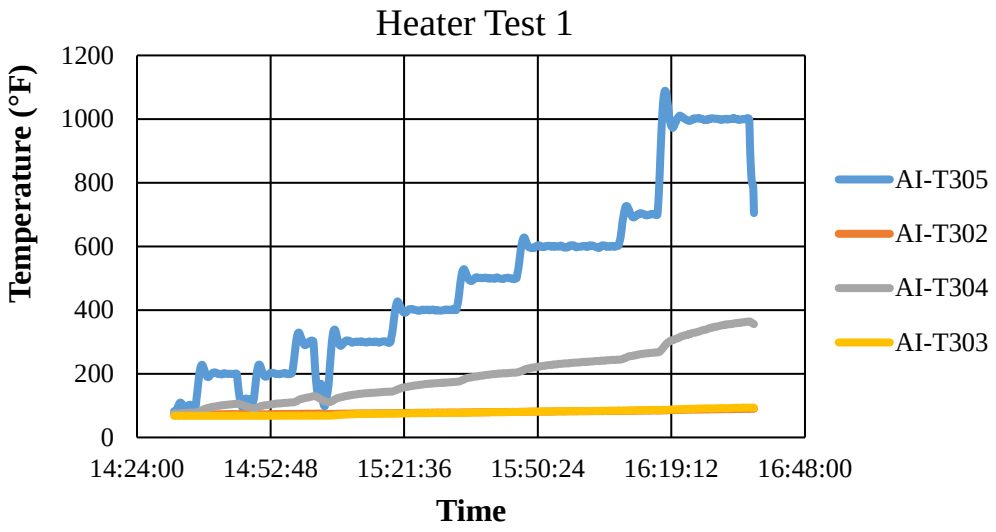


Figure 6.67 Heater test 1 results at 10 CFM airflow.

The next heater test is shown in Figure 6.68. The initial heater setpoint is 200°F (93.333°C) and is increased to 1200°F (648.889°C) with a test stand airflow of 20 CFM. The setpoint is left at 1200°F (648.889°C) for approximately 30 minutes to see what temperatures would be produced in the housing section. A maximum temperature of 1200°F was seen at the heater exit. Temperatures in the test stand upstream section reached approximately 600°F measured by the thermocouple located four feet downstream of the heater. The temperatures in the housing cap and downstream section both reached a maximum of approximately 190°F.

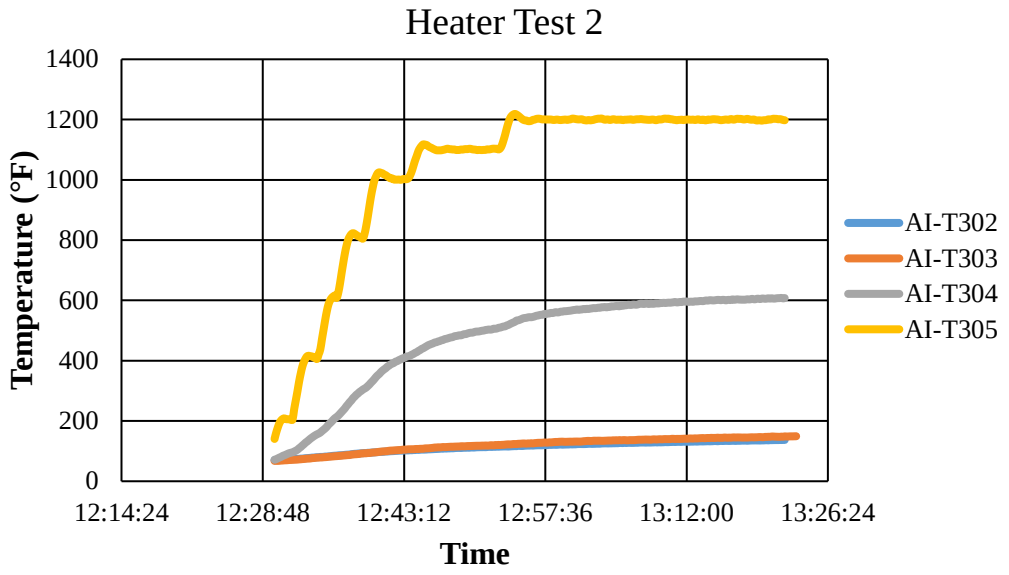


Figure 6.68 Heater test 2 results at 20 CFM airflow.

Elevated temperature testing requires that a different aerosol be used to challenge the ceramic media filters. DOP exhibits a flash point temperature of 228.2°F (109°C), so the air inside the test stand must be at a cooler temperature in order to use this aerosol. KCl does not withstand elevated temperatures well, so, another solid particle aerosol such as Alumina would be ideal. Calculations are performed in Mathcad to determine the proper heater size to provide the desired temperatures. The minimum wattage required was calculated in order to determine an approximate heater size needed for the project applications. Equations listed from both Tutco Farnam and Tempco are referenced.

CHAPTER VII

FILTER WASHING SYSTEM

An attractive characteristic of ceramic filters is the potential to be loaded, washed, dried, and reused (regenerative media). In a previous project conducted at ICET, it was shown that ceramic membrane media have the potential to be used as regenerative filters. In this project, ceramic membrane media (CeraMem media with a porous ceramic support coated with a metal oxide ceramic membrane) is loaded to twice the initial differential pressure with a water-insoluble, iron-rich aerosol challenge, and regenerated with a weak acid solution and water. In between load and wash cycles, the media was tested for pressure drop and FE changes. Results from this testing showed filtering efficiencies in the range of 90-98%, and the MPPS was typically on the order of 100 nm [28].

Within the context of this study, a portion of the ceramic media filter project is aimed towards challenging the core six-element filter with KCl, washing it, drying it, and then challenging the filter again. Through these tests, filter data is collected, and the effect of loading and washing the filter can be determined. A washing apparatus holds the filter, and a deionized (DI) water line is extended from the water tanks inside the highbay to reach the washing system. The system, shown in Figure 7.1, is composed of a PVC housing.

Figure 7.1 Wash tank system (left) and drawings (right).

A metal base and frame is included to support the PVC housing. On the very bottom of the housing is an exit valve and hose that allows the dirty water to be dumped to a drain. The water line is extended downwards so that a valve and a six-way splitter could be attached as shown in Figure 7.2. Plastic tubing is connected to each of the fittings, which are then connected to each of the filter elements.

Figure 7.2 Tubing assembly to connect water line to filter elements.

The flowrate of the DI water is adjusted using a rotameter connected to a pump near the water tanks. Once water is flowing through the line, the valve in Figure 7.2 can be adjusted to fine-tune how much water is going through each filter element. Before a filter is installed onto the washing system, the tank must first be filled with DI water so that the filter is completely engulfed once it is inserted. The filter is installed, the plastic tubing is placed in each of the filter elements, and the DI water travels through the filters elements in the opposite direction of typical airflow (back-pulse cleaning). A complete procedure on filter washing is found in Appendix E.5.

CHAPTER VIII

CONCLUSIONS

Conclusions

There is a large amount of information and data gleaned from the ceramic media filter project. A large scale test stand, originally designed to evaluate metal media filters, is successfully modified to be able to evaluate ceramic media filter elements. Modifications that are necessary for this transition include the development of an induced draft airflow system capable of providing low flowrate ranges. An orifice plate is accurately sized and placed in the (shortened) upstream section of the test stand to control the airflow at low ranges of 5-25 CFM. The test stand control system allows for setpoints and monitoring of the test stand flowrate, heating processes, and test stand sensors, while also including a dedicated screen for data collection. An elevated temperature system is designed and developed to provide and monitor high temperatures inside the test stand. The sampling train system is added to the test stand to allow for simultaneous sampling of both upstream and downstream of the filter. Included in this system is an LAS particle sizer, SMPS particle sizer, and an ELPI system for aerosol measurement during filter tests.

Procedures are generated for many different ceramic filter testing activities including ceramic filter load tests, FE tests, load and wash tests, elevated temperature tests, aerosol generation, test stand startup and shutdown, control system operation, and many more that can be found in Appendix E. Data reduction from testing in this project shows that four out of five tests yield a decrease in filtering efficiency as the test progressed. This is a result of DOP, an oil-based substance, saturating the filter media as testing continues, which causes the FE to decrease. Trends from the test data show that the filters loaded with DOP very quickly in the initial stages of testing, which is highly correlated to the filter's small surface area. On the other hand, when KCl is injected into the test stand and onto the filter, we see some increases in FE and very quick increases in dP. Since KCl is a solid particle aerosol, it hits the filter media and productes dendritic formations on the fibers. This acts as an extension of surface area on the filter media, thus causing a higher dP and FE. During the loading tests, KCl impacts onto the filter media and then DOP is injected into the test stand. Because of its properties, DOP breaks up dendritic formations from the KCl, saturates the filter media, then decreases the FE. Throughout all the testing completed, high FE values are seen, but only one exponential curve fit analysis yielded an FE of 99.97% or greater. Important data is collected in the scope of this project concerning filter characteristics and test stand characterization.

Recommendations

A big factor that would positively influence test stand design in regards to ceramic media filter evaluation includes a decrease in size of the housing section. A reduction of flanges and overall diameter and height would not only benefit ceramic media filter testing, but also allow the target temperatures of 752°F (400°C) and 932°F (500°C) to be reached in the housing. Along with this modification, adding insulation to both the upstream and housing sections would be ideal in order to reach these temperatures. Generation of a solid particle aerosol in this project was not a simple task. Updating the equipment to produce a solid particle aerosol (KCl, NaCl, sugar, etc.) would be recommended to more efficiently load a ceramic media filter for an extended amount of time. Finally, further review and fine-tuning of the test procedures is recommended. The procedures generated as a result of this project are a good starting point in evaluation of ceramic media filters, but in order to qualify these filters, the procedures need to be reviewed and finalized.

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APPENDIX A

FILTER DIMENSIONS AND SURFACE AREA CALCULATIONS

Filter Media 1 6-element								2*pi*R*L		(2*pi*R*h) + (2*pi*r*h)	
Element	inner d (in)	inner d avg	inner r avg (	Length (in)	Outer D (in)	Outer R (in)	Outer R av	SA (in^2)	SA (ft^2)	SA hollow cylinder (in^2)	SA (ft^2)
1	1.352	1.33	0.665	9.625	1.606	0.803	0.8064	48.767608	0.338664	88.9839505	0.617944
	1.3085				1.6095	0.80475					
	1.3295				1.614	0.807					
					1.6185	0.80925					
					1.616	0.808					
2	1.391	1.3853333	0.69266667	9.625	1.617	0.8085	0.80705	48.806917	0.338937	90.69642084	0.629836
	1.363				1.6175	0.80875					
	1.402				1.614	0.807					
					1.612	0.806					
					1.61	0.805					
3	1.372	1.3706667	0.68533333	9.625	1.6235	0.81175	0.8106	49.021605	0.340428	90.4676211	0.628247
	1.383				1.6285	0.81425					
	1.357				1.626	0.813					
					1.617	0.8085					
					1.611	0.8055					
4	1.384	1.3645	0.68225	9.625	1.622	0.811	0.8127	49.148604	0.34131	90.40815332	0.627834
	1.362				1.6285	0.81425					
	1.3475				1.6255	0.81275					
					1.626	0.813					
					1.625	0.8125					
5	1.2695	1.2885	0.64425	9.625	1.6115	0.80575	0.80795	48.861345	0.339315	87.82281699	0.609881
	1.288				1.6225	0.81125					
	1.308				1.618	0.809					
					1.6155	0.80775					
					1.612	0.806					
6	1.3015	1.307	0.6535	9.625	1.6215	0.81075	0.80955	48.958106	0.339987	88.47897837	0.614437
	1.31				1.627	0.8135					
	1.3095				1.6265	0.81325					
					1.614	0.807			SA SUM (ft2)		SA SUM (ft2)
					1.6065	0.80325			2.03864		3.72818
	Note: SA-Surface Area, d-diameter, r-radius										
									flow (ft/min)		flow (ft/min)
									5		5
									rated flow (cfm) using first SA eqn		
									10.19320087		
									rated flow (cfm) using second SA equation		
									18.64090073		

Figure A.1 Dimensions and surface area calculations of Filter Media 1 six-element filter.

Core 6-element								2*pi*R*L		(2*pi*R*h) + (2*pi*r*h)	
Element	inner d (in)	inner d avg (in)	inner r avg (in)	Length (in)	Outer D (in)	Outer R (in)	Outer R avg (in)	SA (in^2)	SA (ft^2)	SA hollow cylinder (in^2)	SA hollow cylinder (ft^2)
1	1.073	1.073333333	0.536666667	10.875	1.5145	0.75725	0.75855	51.831487	0.359941	88.50175494	0.61459552
	1.0715				1.518	0.759					
	1.0755				1.5205	0.76025					
					1.517	0.7585					
					1.5155	0.75775					
2	1.0595	1.06	0.53	10.875	1.512	0.756	0.74895	51.175522	0.355386	87.39025862	0.606876796
	1.0605				1.4985	0.74925					
	1.06				1.496	0.748					
					1.49	0.745					
					1.493	0.7465					
3	1.0815	1.0775	0.53875	10.875	1.5155	0.75775	0.75485	51.578667	0.358185	88.3912886	0.613828393
	1.074				1.504	0.752					
	1.077				1.5165	0.75825					
					1.504	0.752					
					1.5085	0.75425					
4	1.055	1.056	0.528	10.875	1.52	0.76	0.76125	52.015977	0.361222	88.09405444	0.611764267
	1.0545				1.5195	0.75975					
	1.0585				1.5235	0.76175					
					1.5225	0.76125					
					1.527	0.7635					
5	1.0375	1.040833333	0.520416667	10.875	1.502	0.751	0.75025	51.264351	0.356002	86.82426102	0.602946257
	1.045				1.491	0.7455					
	1.04				1.5045	0.75225					
					1.503	0.7515					
					1.502	0.751					
6	1.0935	1.094333333	0.547166667	10.875	1.521	0.7605	0.75765	51.769991	0.359514	89.15771997	0.619150833
	1.0985				1.515	0.7575					
	1.091				1.516	0.758					
					1.514	0.757			SA SUM (ft2)		SA SUM (ft2)
					1.5105	0.75525			2.15025		3.669162067
									flow (ft/min)		flow (ft/min)
									5		5
				Note: SA-Surface Area, d-diameter, r-radius					rated flow (cfm) using first SA eqn		rated flow (cfm) using second SA equation
									10.75125		18.34581033

Figure A.2 Dimensions and surface area calculations of core six-element filter.

Filter Media 2 Single Elements									(2*pi*R*h) + (2*pi*r*h)	
Element	inner D (in)	inner D avg (in)	inner R avg (in)	Length (in)	Length avg (in)	Outer D (in)	Outer R (in)	Outer R avg (in)	SA hollow cylinder (in^2)	SA hollow cylinder (ft^2)
1	0.972	0.976	0.488	10.669	10.669	1.534	0.767	0.7627	83.84111739	0.582229982
	0.9755			10.669		1.5315	0.76575			
	0.9805			10.669		1.5285	0.76425			
						1.51	0.755			
						1.523	0.7615			
2	0.978	0.977166667	0.488583333	10.6299	10.64293333	1.523	0.7615	0.7613	83.58166368	0.58042822
	0.9785			10.6299		1.518	0.759			
	0.975			10.669		1.5155	0.75775			
						1.512	0.756			
						1.5445	0.77225			
3	0.981	0.9795	0.48975	10.709	10.69566667	1.5455	0.77275	0.7704	84.6857418	0.588095429
	0.9825			10.669		1.544	0.772			
	0.975			10.709		1.542	0.771			
						1.5365	0.76825			
		2*pi*R*L				1.536	0.768			
	Element	SA (in^2)	SA (ft^2)	flow (ft/min)	rated flow using first SA eqn (CFM)				flow (ft/min)	
	1	51.12786458	0.355054615	5	1.775273076				5	
	2	50.90932798	0.353537	5	1.767684999			element	rated flow using second SA eqn(CFM)	
	3	51.77311866	0.359535546	5	1.797677731			1	2.911149909	
								2	2.9021411	
								3	2.940477146	
	Note: SA-Surface Area, d-diameter, r-radius									

Figure A.3 Dimensions and surface area calculations of Filter Media 2 single element filter.

Filter Media 1 Single Elements								2*pi*R*L		(2*pi*R*h) + (2*pi*r*h)	
Element	inner d (in)	inner d avg (in)	inner r avg (in)	Length (in)	Outer D (in)	Outer R (in)	Outer R avg (in)	SA (in^2)	SA (ft^2)	SA hollow cylinder (in^2)	SA hollow cylinder (ft^2)
1	1.337	1.336333333	0.668166667	9.75	1.613	0.8065	0.81125	49.6980694	0.345125482	90.63069606	0.629379834
	1.3375				1.6235	0.81175					
	1.3345				1.6285	0.81425					
					1.6245	0.81225					
					1.623	0.8115					
								flow (ft/min)			
		Note: SA-Surface Area, d-diameter, r-radius						5			
								rated flow using first SA eqn (CFM)	rated flow using second SA eqn(CFM)		
								1.72562741	3.146899169		

Figure A.4 Dimensions and surface area calculations of Filter Media 1 single element filter.

APPENDIX B

TRAVERSE POINT MEASUREMENT DATA

Upstream	*averages of 10 samples from TSI Alnor velometer							
Test #	**Velocity (ft/min)**	**Flow (CFM)**						
5 CFM			Horizontal-measurements taken at new flange location for diffusion plate					
1	20	3.83						
2	14	2.8						
3	22	4.32						
4	38	7.46						
5	38	7.4	flow (cfm)	velocity (ft/min)				
6	29	5.62	5.23833333	26.83333333				
20 CFM								
7	131	25.62						
8	122	23.83						
9	140	27.32						
10	53	10.25						
11	88	17.2	flow (cfm)	velocity (ft/min)				
12	117	22.78	21.1666667	108.5				
5 CFM			Vertical-measurements taken at FI-UN-12					
13	22	4.35						
14	22	4.27						
15	25	4.8						
16	31	5.99						
17	28	5.54	flow (cfm)	velocity (ft/min)				
18	34	6.64	5.265	27				
20 CFM								
19	114	22.28						
20	117	22.94						
21	107	20.82						
22	81	15.88						
23	64	12.49	flow (cfm)	velocity (ft/min)				
24	121	23.56	19.6616667	100.6666667				

Figure B.1 Traverse measurement data for upstream section.

Downstream	*averages of 10 samples from TSI Alnor velometer					
5 CFM			Horizontal-measurements taken at FI-DP-01			
25	42	8.34				
26	31	6.14				
27	35	6.79				
28	28	5.42				
29	30	5.92	flow (cfm)	velocity (ft/min)		
30	15	2.91	5.92	30.16666667		
20 CFM						
43	147	28.77				
44	149	29.31				
45	79	15.45				
46	174	34.15				
47	147	28.77	flow (cfm)	velocity (ft/min)		
48	110	21.65	26.35	134.3333333		
5 CFM			Vertical-measurements taken at FI-DP-02			
31	32	6.22				
32	20	3.89				
33	11	2.09				
34	34	6.6				
35	26	5.03	flow (cfm)	velocity (ft/min)		
36	34	6.6	5.07166667	26.16666667		
20 CFM						
37	140	27.59				
38	157	30.8				
39	111	21.7				
40	61	12.06				
41	87	17.04	flow (cfm)	velocity (ft/min)		
42	108	21.2	21.7316667	110.6666667		

Figure B.2 Traverse measurement data for downstream section.

Housing	*averages of 10 samples from TSI Alnor velometer					
10 CFM			Horizontal-measurements taken at FI-HP-12			
50	36	28.53				
52	27	21.53				
54	34	26.35				
56	24	18.86				
58	67	52.85	flow (cfm)	velocity (ft/min)		
60	55	43.45	31.9283333	40.5		
20 CFM						
51	78	61.15				
53	38	29.98				
55	32	25.21				
57	34	26.53				
59	64	50.46	flow (cfm)	velocity (ft/min)		
61	100	78.63	45.3266667	57.66666667		
10 CFM			Vertical-measurements taken at FI-HP-13			
62	51	40.03				
64	59	46.63				
66	12	9.8				
68	13	10.58				
70	28	21.8	flow (cfm)	velocity (ft/min)		
72	42	32.83	26.945	34.16666667		
20 CFM						
63	122	95.56				
65	158	124.32				
67	29	22.77				
69	35	27.22				
71	38	29.73	flow (cfm)	velocity (ft/min)		
73	69	54.36	58.9933333	75.16666667		

Figure B.3 Traverse measurement data for housing section.

Test Stand Location	Measurement Orientation	Setpoint (CFM)	Averaged Measured Flow (CFM)	Averaged Measured Velocity (ft/min)
Upstream	Horizontal	5	5.238333333	26.83333333
		20	21.16666667	108.5
	Vertical	5	5.265	27
		20	19.66166667	100.6666667
Downstream	Horizontal	5	5.92	30.16666667
		20	26.35	134.3333333
	Vertical	5	5.071666667	26.16666667
		20	21.73166667	110.6666667
Housing	Horizontal	10	31.92833333	40.5
		20	45.32666667	57.66666667
	Vertical	10	26.945	34.16666667
		20	58.99333333	75.16666667

Figure B.4 Averaged data from traverse point measurement.

APPENDIX C

LIST OF ICET TECHNICAL AND QA PROCEDURES

Technical Procedures

1. HEPA-M&TE-011 LAS Particle Sizing Verification

2. HEPA-M&TE-009 LAS Readiness and Operation Procedure for the Laser Aerosol Spectrometer (LAS)

3. HEPA-M&TE-002 Readiness and Operation of Scanning Mobility Particle Sizer (SMPS) Spectrometer

4. HEPA-M&TE-004 ELPI Readiness and Operation

5. HEPA-M&TE-016 Diluter Characterization

QA Procedures

1. ICET-QA-009 Item Receipt and Control

APPENDIX D

TEST MATRIX

Table D.1 Test matrix for ceramic media filter project.

Type of Test	Filter Type Tested	Notes on Testing**
Differential Pressure vs. Flow Rate (dP vs. Q)	• Single element Filter Media 1 + Core • Six-element Filter Media 1 + Core • Six-element Core • Single element Filter Media 2 + Core	• Ambient Conditions • 5 CFM Airflow for single element • 20 CFM Airflow for six-element
Filtering Efficiency (FE) using DOP	• Single element Filter Media 1 + Core • Six-element Filter Media 1 + Core • Single element Filter Media 2 + Core	• Ambient Conditions • 5 CFM Airflow for single element • 20 CFM Airflow for six-element

Table D.1 (Continued)

Particle Loading *	• For 3 µm MMD KCl o Single element Filter Media 1 + Core o Core o Single element Filter Media 2 + Core • For 1 µm MMD KCl o Single element Filter Media 1 + Core o Core o Single element Filter Media 2 + Core	• Ambient Conditions • 5 CFM Airflow for single element • 20 CFM Airflow for six-element
High Temperature Testing 752°F – 932°F (400°C – 500°C)	• Single element Filter Media 1 + Core • Single element Filter Media 2 + Core	• This phase of testing is currently in development
*Filter Media exposed to both DOP and KCl, but the six-element core filter exposed to KCl only		**ambient conditions include temperatures from 60 – 80°F (15.556 – 26.667°C) and relative humidity from 40-60% RH

APPENDIX E

TEST PROCEDURES

Procedure for DOP and KCl aerosol generation for ceramic filter testing

1.0 PURPOSE

The purpose of this procedure is to ensure ICET personnel follow the correct instructions to prepare a DOP and/or KCl challenge aerosol and use this challenge aerosol for ceramic filter testing.

2.0 SCOPE

This procedure covers the steps necessary to generate a KCl and DOP aerosol for testing of ceramic filters.

3.0 TERMS / DEFINITIONS

- 3.1 KCl- Potassium Chloride
- 3.2 DOP- Dioctyl Phthalate
- 3.3 LPM- Liters Per Minute

4.0 RESPONSIBILITIES

- 4.1 Principal Investigator (PI) is responsible for supervising the project team in the areas of project planning, test plan development, fabrication of test stand, measurement and test equipment calibration, coordination of testing, testing, data quality review, and reporting.
- 4.2 The Measuring and Test Equipment Coordinator (M&TEC) is responsible for review of the test procedure and for calibration of M&TE required for testing.
- 4.3 The Quality Assurance Coordinator (QAC) is responsible for reviewing controlled design documents and assisting in records management.
- 4.4 Test personnel are responsible for review of the test procedure and conduct of testing.
- 4.5 Testing Supervisor is responsible for supervision of test personnel and control of testing process.

5.0 EQUIPMENT

- 5.1 Steel-toed Boots
- 5.2 Safety glasses
- 5.3 Gloves

6.0 SAFETY AND ENVIROMENTAL CONCERNS

- 6.1 Safety glasses and steel toed boots are required in the high bay during testing activities
- 6.2 Hard hats are required past signage
- 6.3 Di-octyl Phthalate (DOP) is considered a possible carcinogen. Read Safety Data Sheet (SDS) and use caution when working with DOP. Wear safety glasses, lab jacket, gloves, and respirator when adding DOP liquid to the aerosol generator, removing DOP waste, or cleaning the upstream section of the FI/FO test stand.
- 6.4 Wear gloves when handling KCl

7.0 PROCEDURE

7.1 KCl Challenge Agent

7.1.1 KCl Solution Preparation Procedure

7.1.1.1 Place appropriate sized beaker on a scale and zero the scale

7.1.1.2 Pour de-ionized water into the container until the scale reads 1000 grams

7.1.1.3 Add the desired amount of the KCl powder until the correct weight is reached on the scale

7.1.1.3.1 A 30% KCl solution by weight requires 1000 grams of de-ionized water and 300 grams of KCl powder, which will read 1300 grams total on the scale

7.1.1.4 Each solution mixture should be heated using a hot plate and stirred to ensure complete dissolution

7.1.1.5 Each solution will be stored in a sealed glass jar with a label indicating the contents and date mixed

7.1.2 Experimental Procedure

7.1.2.1 Ensure that the atomizing assembly is clean

7.1.2.1.1 If it needs to be cleaned, rinse all the components with water and dry

7.1.2.2 Attach the atomizing plate to the top of the aerosol generator with bolts and nuts using a wrench

7.1.2.3 If the aerosol generation exit nozzle needs to be cleaned or unclogged, detach the tubing, clean the components with water and let dry

7.1.2.4 Turn on the entire aerosol generation system by plugging in the two power strips into the wall outlets and switching them on

7.1.2.5 Connect the air hose from the air drier to the bottom mass flow controller

7.1.2.6 Make sure the mass flow controller shows the correct flow rate by adjusting the regulators on the air drier:

7.1.2.6.1 Air sheath in spray tower shows approximately 130 LPM

7.1.2.7 Keep the aerosol generator exit valve slightly open so that the pressure inside the generator tank does not increase too much

7.1.2.8 Wait for the system to heat for approximately 30 minutes to one hour to reach the proper temperatures

7.1.2.8.1 If the target temperatures are not reached in this time, check to ensure that the heating elements inside the aerosol generator heating box are not burned out

7.1.2.9 The particle generation system is ready for testing when the temperature of the particle generator has reached the following levels:

7.1.2.9.1 Temperature inside the heater box (T1) is approximately 650 °F (343.33°C)

7.1.2.9.2 Temperature of air exiting heater box and entering air sheath (T2) is approximately 450 °F (232.22°C)

7.1.2.9.3 Temperature of spray tower surface (T3) is approximately 180 °F – 200 °F (82.222°C – 93.333°C)

7.1.2.9.4 Temperature of exiting air sheath in spray tower (T4) is approximately 160 °F (71.111°C)

7.1.2.9.5 Air temperature just before exiting spray tower (T5) is approximately 150 °F (65.556°C)

7.1.2.9.6 Tube temperature on exit of spray tower (T6) is approximately 230 °F (110°C)

7.1.2.10 The solution to be aerosolized should be stirred if necessary

7.1.2.11 The peristaltic pump to be used for the test should be prepared for use and unclogged by running water through it

7.1.2.12 Connect the second air hose from the air drier to the mass flow controller that is located on top of the aerosol generator tank

7.1.2.13 The liquid line should be connected to the atomizing nozzle followed by the compressed air line when testing begins

7.1.2.14 Open the aerosol generator exit valve to release the aerosol into the test stand airstream

7.1.2.15 Adjust the two mass flow controllers to read the correct flowrates:

7.1.2.15.1 Atomizing nozzle shows approximately 28 LPM

7.1.2.15.2 Air sheath in spray tower shows approximately 130 LPM

7.1.3 Cleaning Procedure

7.1.3.1 Disconnect the liquid line and the compressed air line from the atomizing nozzle

7.1.3.2 Turn off the two power strips to shut down the entire system

7.1.3.3 When the components have cooled, begin disassembling the particle generator system and open valve on bottom of stainless steel tank

7.1.3.4 Use a wrench to unbolt the atomizing nozzle from the top of the aerosol generator tank

7.1.3.5 Rinse the atomizing nozzle components and let dry

7.1.3.6 The particulate catch in the cyclone should be carefully discarded or rinsed while wearing gloves

7.1.3.6.1 Use two crescent wrenches to disconnect the cyclone from the heated transfer line and the aerosol generator exit valve

7.1.3.7 Unclog the heated transfer line that extends to the inside of the aerosol generator

7.1.3.8 The peristaltic pump used for the test should be cleaned in preparation for the next test

7.1.3.9 Any spills in the area should be cleaned

7.2 DOP Challenge Agent

7.2.1 Obtain an available six-jet atomizer that has DOP in it

7.2.2 Connect the DOP generator tubing to the test stand aerosol injection site

7.2.3 Connect the air hose from the air drier to the DOP generator air hose fitting

7.2.4 Once testing begins, turn the knob on the DOP generator to the desired pressure setting

7.2.5 Switch on the desired number of jets to be used for testing

7.2.6 If a bleed-off valve is used, adjust it to the appropriate settings

7.2.7 Open the exit valve to allow the aerosol to be injected into the test stand

<u>Procedure for Ceramic Media Test Stand Aerosol Measurement Instrumentation</u>

1.0 PURPOSE

The purpose of this procedure is to ensure ICET personnel follow correct steps to prepare and operate the aerosol measurement instrumentation for the ceramic media test stand.

2.0 SCOPE

This procedure covers the steps necessary for preparation and operation of the aerosol measurement instrumentation on the ceramic media test stand when performing ceramic filter testing.

3.0 TERMS / DEFINITIONS

3.1 ELPI – Electrical Low Pressure Impactor

3.2 SMPS- Scanning Mobility Particle Sizer

3.3 CPC- Condensation Particle Counter

3.4 EC- Electrostatic Classifier

3.5 LAS – Laser Aerosol Spectrometer

3.6 nm – Nanometer

3.7 LPM – Liters Per Minute

4.0 RESPONSIBILITIES

4.1 Principal Investigator (PI) is responsible for supervising the project team in the areas of project planning, test plan development, fabrication of test stand, measurement and test equipment calibration, coordination of testing, testing, data quality review, and reporting.

4.2 The Measuring and Test Equipment Coordinator (M&TEC) is responsible for review of the test procedure and for calibration of M&TE required for testing.

4.3 The Quality Assurance Coordinator (QAC) is responsible for reviewing controlled design documents and assisting in records management.

4.4 Test personnel are responsible for review of the test procedure and conduct of testing.

4.5 Testing Supervisor is responsible for supervision of test personnel and control of testing process.

5.0 EQUIPMENT

5.1 Steel-toed Boots

5.2 Gloves

5.3 Safety Glasses

5.4 Crescent Wrench

6.0 SAFETY AND ENVIROMENTAL CONCERNS

6.1 Safety glasses and steel toed boots are required in the high bay during testing activities

6.2 Hearing protection is required when the impact wrench is in use

6.3 Hardhats are required past the signage

7.0 PROCEDURE

7.1 Laser Aerosol Spectrometer (LAS) Operation

7.1.1 Turn LAS power on

7.1.2 Ensure that a zero-count filter is connected to the LAS tubing

7.1.3 Open the LAS software

7.1.4 Ensure that the flowrates and the reference voltage look reasonable in the LAS software

7.1.5 Set the correct parameters within the software

7.1.5.1 For data collection during testing

7.1.5.1.1 99 bins

7.1.5.1.2 90 to 7500 nm particle size range

7.1.5.1.3 Sampling time of 1 minute and 15 seconds

7.1.5.2 For aerosol concentration check

7.1.5.2.1 1 bin

7.1.5.2.2 90 nm to 1000 nm

7.1.5.2.3 Sampling time of 10 seconds

7.1.6 If diluters are needed
7.1.6.1 Plug in the sampling train vacuum pump
7.1.6.2 Verify that the flow controller is pulling 4.65 LPM through the diluters
7.1.6.2.1 Adjust the flowrate if only the LAS or SMPS are being used and not both at the same time
7.1.6.3 Connect the LAS tubing to the splitter
7.1.6.4 Ensure the sampling train valve configuration is set to purge
7.1.7 If diluters are not needed
7.1.7.1 Connect sampling tubing directly to the sampling nozzle installed in the test stand
7.1.8 Click “Run” to start sampling
7.1.9 Click “Record” to start saving the data
7.1.10 Input the desired file name to save the data
7.1.11 Press OK if all instruments have been prepared to start sampling for the test
7.1.12 After testing is completed, connect the LAS tubing back to the zero-count filter
7.1.13 To retrieve the data, insert a USB drive into the port on the LAS and find the desired file
7.1.14 Turn off the LAS computer first
7.1.15 Turn LAS power off using the switch on the back of the instrument

7.2 Scanning Mobility Particle Sizer (SMPS) Operation
7.2.1 Turn the power on to both the CPC and EC
7.2.1.1 Allow the CPC to warm up for approximately 10 minutes
7.2.2 Ensure that the SMPS sampling line is connected to a HEPA capsule filter
7.2.3 Ensure that the impactor on the EC is clean and installed on the SMPS system
7.2.3.1 If the impactor needs to be cleaned
7.2.3.1.1 The operator should put on latex gloves
7.2.3.1.2 Place the funnel over the chemical waste jar located in the highbay
7.2.3.1.3 Apply ethanol to the impactor surface over the waste jar
7.2.3.1.4 Apply acetone to the impactor surface over the waste jar
7.2.3.1.5 Apply a small amount of grease to the impactor surface
7.2.4 Open the SMPS software and select/input the parameters for each category:

7.2.4.1 CPC Model and Flow Rate: 3772
7.2.4.2 Classifier Model: 3080
7.2.4.3 DMA: 3081
7.2.4.4 Sheath Flow: 3.00 LPM
7.2.4.5 Aerosol Sample Flow: 0.30 L/min
7.2.4.6 Impactor Type: 0.071 cm
7.2.4.7 Scan Time
7.2.4.7.1 Up: 135
7.2.4.7.2 Retrace: 15

7.2.5 If diluters are needed
7.2.5.1 Plug in the sampling train vacuum pump
7.2.5.2 Verify that the flow controller is pulling 4.65 LPM through the diluters
7.2.5.2.1 Adjust the flowrate if only the LAS or SMPS are being used and not both at the same time
7.2.5.3 Connect the SMPS tubing to the splitter
7.2.5.4 Ensure the sampling train valve configuration is set to purge

7.2.6 If diluters are not needed
7.2.6.1 Connect sampling tubing directly to the sampling nozzle installed in the test stand

7.2.7 Turn on the CPC external vacuum pump
7.2.8 Adjust the sample flow rate using the flow controller so that it reads 0.3 LPM on the SMPS screen
7.2.9 Press the green button on the SMPS software to start recording data
7.2.10 Monitor the sample flow rate throughout testing to ensure it stays close to 0.3 L/min
7.2.11 After testing is completed, connect a HEPA capsule to the SMPS sampling line for purging
7.2.12 Turn off the CPC external vacuum pump
7.2.13 Retrieve the data by connecting a USB drive to the computer and finding the desired file
7.2.14 Shut down the SMPS system and the computer
7.2.15 Clean the impactor by following step 7.2.3.

7.3 Electrical Low-Pressure Impactor (ELPI) Operation

7.3.1 ELPI Impactor Preparation
7.3.1.1 Insert all the impactor components except screws, O-rings, corona needle, trap BNC, or HV BNC in ultrasonic bath as per Dekati ELPI manual Version 4.12 for 20 minutes
7.3.1.2 Separately wash the Teflon insulators in the ultrasonic bath for 20 minutes

7.3.1.3 Allow all contents to completely dry (charger core needs to dry for one hour)

7.3.1.4 Wear latex gloves and a grounding bracelet when preparing impactor jet stages

7.3.1.5 Remove substrate holder rings from impaction plate using positioning tool

7.3.1.6 Punch out smooth aluminum plates with the TruPunch punch and die set

7.3.1.7 Insert substrate onto impaction plate and push holder ring into place using positioning tool

7.3.1.8 Use positioning tool to take off the holder ring

7.3.1.9 Use tweezers to place substrate into the substrate holder template

7.3.1.10 Repeat this until 13 substrates are installed into the holder template

7.3.1.11 Spray the Dekati grease evenly throughout all of the substrates

7.3.1.12 Let grease dry for approximately 5 to 10 minutes

7.3.1.13 Dessicate substrates for at least 3 hours (ideally overnight)

7.3.1.14 Weigh the substrate on a mass balance three times each

7.3.1.15 Record the pre-test masses of each substrate

7.3.1.16 Place substrate on impaction collection plate

7.3.1.17 Push holder ring into place

7.3.1.18 Repeat this for all 13 jet plates and substrates

7.3.1.19 Place all 13 into the dessicator until ready to install into the impactor

7.3.1.20 Check to ensure correct order of impactor stages

7.3.1.21 Check to ensure O-rings are placed in the impactor and impactor stages as per Dekati ELPI manual Version 4.12

7.3.1.22 Load the impactor starting from stage 1 to stage 12 as per Dekati ELPI manual Version 4.12

7.3.1.23 Be sure not to handle the Teflon insulators with the latex gloves (use bare hand)

7.3.1.24 Ensure that all of the jet plates and springs are pushed down completely to prevent any possible leakage problems

7.3.1.25 Assemble the corona charger

7.3.1.25.1 Place O-rings in correct locations on charger shell

7.3.1.25.2 Insert charger core into charger shell

7.3.1.25.3 Insert screws in correct locations
7.3.1.25.4 Insert corona needle into charger core
7.3.1.25.5 Insert HV BNC and Trap BNC in correct locations

7.3.2 Impactor Installation
7.3.2.1 Fill out ELPI Readiness and Operation Checklist
7.3.2.2 Insert corona charger into top of ELPI housing
7.3.2.3 Connect charger HV connector and ion-trap connector to the corona charger HV BNC and Trap BNC, respectively
7.3.2.4 Ensure that the small gasket is installed inside the ELPI housing
7.3.2.5 Slide impactor into place using positioner inside the ELPI housing
7.3.2.6 Ensure the larger gasket is installed between charger and impactor
7.3.2.7 Use the clamp to connect the charger and impactor
7.3.2.8 Clamp the impactor down using the assembly clamps inside the ELPI housing

7.3.3 Readiness and Operation
7.3.3.1 Turn ELPI system ON and let warm up for one hour
7.3.3.2 Record the impactor ID number
7.3.3.3 Verify proper connections to ELPI (electrical, computer, and vacuum)
7.3.3.4 Turn vacuum pump ON
7.3.3.5 Open vacuum outlet valve and allow pressure reading to reach 100 mbar (+/- 5 mbar acceptable)
7.3.3.6 Perform leak check
7.3.3.6.1 Place leak check cap on impactor inlet and tighten
7.3.3.6.2 Allow pressure to reach 5 mbar
7.3.3.6.3 Close outlet valve
7.3.3.6.4 Turn vacuum pump OFF
7.3.3.6.5 Wait one minute and record the pressure
7.3.3.6.6 If pressure increase is less than 10 mbar, the impactor passes the leak check
7.3.3.6.7 If pressure increase is more than 10 mbar, the impactor failed the leak check and the entire system must be check for leaks
7.3.3.6.8 If the leak check fails, procedure 8.3.6 must be repeated again until the leak check passes
7.3.3.7 Connect ELPI inlet to aerosol source (test stand)
7.3.3.8 Start ELPI software
7.3.3.8.1 Start a new measurement

7.3.3.8.2 Insert the necessary information into the Measurement tab such as data file name, location, operator/run, description, last cleaned, and sampling

7.3.3.8.3 Load the necessary Setup file that contains the values for the impactor being used and verify that all the values are correct based off of the impactor calibration sheets

7.3.3.8.4 If a Setup file does not exist for the impactor, then one must be created

7.3.3.8.4.1 Insert the necessary information into the Charger tab such as charger setup, charger setup values, and charger efficiency values

7.3.3.8.4.2 Insert the necessary information into the Impactor tab such as impactor number, flow rate, pressure (mbar), cutoff diameter, pressure (kPa), and resolution time

7.3.3.8.4.3 If needed, modify the parameters listed in the Communications and Program tabs

7.3.3.8.4.4 In the Defaults tab, select the proper voltage range and verify that all the parameters are correct for the specific application

7.3.3.9 Turn charger ON

7.3.3.10 Turn vacuum pump ON

7.3.3.11 Adjust vacuum outlet valve so the pressure reads 100 mbar

7.3.3.12 Wait one minute for voltage to stabilize

7.3.3.13 Turn flush pump ON

7.3.3.14 Turn ON zeroing routine in the ELPI software

7.3.3.15 Wait for zeroing routine to complete in the ELPI software

7.3.3.16 Turn flush pump OFF

7.3.3.17 Turn save ON

7.3.3.18 Ensure proper procedures during the ELPI measurement

7.3.3.18.1 Maintain vacuum at 100 mbar (range of +/- 5 mbar acceptable)

7.3.3.18.2 Monitor charger voltage (range of 4.5 to 5.5 fA acceptable)

7.3.3.18.3 If voltage exceeds 5.5 fA, make sure vacuum is in acceptable range

7.3.3.18.4 Record any time of any deviations in parameters

7.3.3.19 At the end of the measurement, turn flush pump ON

7.3.3.20 Wait for concentration to drop near zero in the ELPI software

7.3.3.21 Turn save OFF in the ELPI software

7.3.3.22 Close vacuum outlet

7.3.3.23 Turn vacuum pump OFF

7.3.3.24 Stop the measurement software

7.3.3.25 Shutdown the ELPI software

Procedure for ceramic media test stand control system and operation

1.0 PURPOSE

The purpose of this procedure is to ensure ICET personnel follow correct steps to understand and operate the control system for the ceramic media test stand.

2.0 SCOPE

This procedure covers the steps necessary for operation of the ceramic media test stand control system and describes the system components.

3.0 TERMS / DEFINITIONS

4.0 RESPONSIBILITIES

- 4.1 Principal Investigator (PI) is responsible for supervising the project team in the areas of project planning, test plan development, fabrication of test stand, measurement and test equipment calibration, coordination of testing, testing, data quality review, and reporting.
- 4.2 The Measuring and Test Equipment Coordinator (M&TEC) is responsible for review of the test procedure and for calibration of M&TE required for testing.
- 4.3 The Quality Assurance Coordinator (QAC) is responsible for reviewing controlled design documents and assisting in records management.
- 4.4 Test personnel are responsible for review of the test procedure and conduct of testing.
- 4.5 Testing Supervisor is responsible for supervision of test personnel and control of testing process.

5.0 EQUIPMENT

- 5.1 Steel-toed Boots
- 5.2 Gloves
- 5.3 Safety Glasses

6.0 SAFETY AND ENVIROMENTAL CONCERNS

- 6.1 Safety glasses and steel toed boots are required in the high bay during testing activities
- 6.2 Hardhats are required past the signage

7.0 PROCEDURE

- 7.1 Ensure that the main CPU power is turned on and the touch screen is working properly
- 7.2 Verify that the sensors are reading values by examination of the main screen

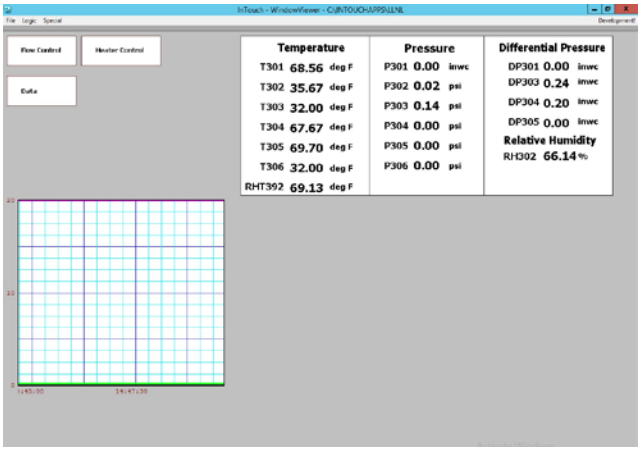


Figure 1. Control system main screen.

7.3 To turn on the test stand flow rate, click the Flow Control tab

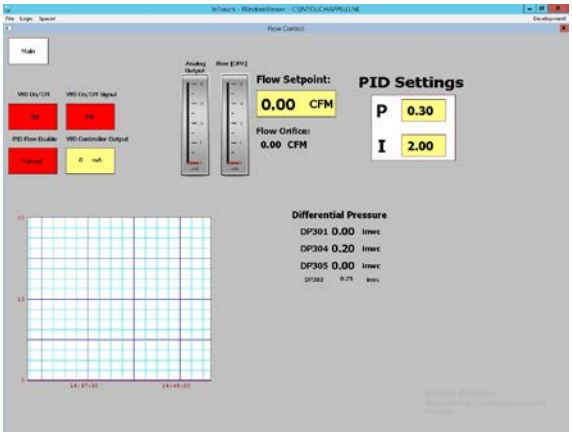


Figure 3. Flow control screen.

7.3.1 Push the VFD On/Off button to turn the VFD on and off

7.3.1.1 The VFD On/Off Signal block should turn green after turning the VFD on and should turn red after turning the VFD off

7.3.2 Push the PID Flow Enable button

7.3.2.1 The VFD Controller Output block should turn white after turning the PID Flow Enable button on and turn yellow after turning the PID Flow Enable button off

7.3.3 Input the PI values in the boxes under the PID Settings block

7.3.3.1 The “P” (proportional) value should be 0.30

7.3.3.2 The “I” (integral) value should be 2.00

7.3.4 Input the desired flow rate (CFM) into the Flow Setpoint block

7.3.5 Monitor the data on the screen and make sure the flow rate reaches and remains at the setpoint

7.3.6 Monitor the differential pressure values to make sure they are reasonable

7.4 To turn on the test stand heating system, click the Heater Control tab to input the desired parameters in the screen shown in Figure 4

Figure 4. Heater control screen.

7.4.1 Push the Heater On/Off button to turn the heater on and off

7.4.1.1 The Heater On/Off Signal block should turn green after turning the heater on and should turn red after turning the heater off

7.4.2 Push the PID Heater Enable button

7.4.2.1 The Heater Controller Output block should turn white after turning the PID Heater Enable button on and turn yellow after turning the PID Heater Enable button off

7.4.3 Input the desired PID values in the boxes under the PID Settings block

7.4.4 Input the maximum heater temperature limit in the Heater Temperature Limit block to 1300°F (704.44°C)

7.4.5 Input the desired temperature (in °F) into the Heater Setpoint block

7.4.6 Monitor the data on the screen and make sure the heater reaches and remains at the setpoint

7.4.7 Monitor the temperatures to make sure they are reasonable

7.5 Once testing has been completed, click the Data tab on the control system main screen to bring up the screen shown in Figure 2

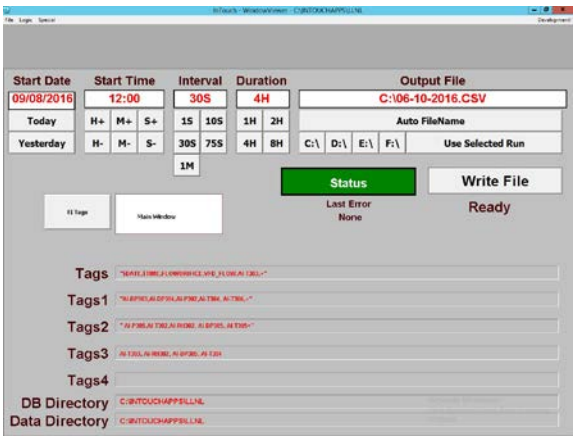


Figure 2. Control system data screen.

7.5.1 Input the following parameters into the data screen:

7.5.1.1 Start Date

7.5.1.2 Start Time

7.5.1.3 Interval

7.5.1.4 Duration

7.5.1.5 Output File

7.5.1.6 Tags (as many as needed for the testing activity)

7.5.2 After all the parameters are input into the data screen, click each box again

7.5.3 Click the Write File block

7.5.4 Insert a USB drive into the test stand computer to retrieve the test stand data

Procedure for Core Ceramic Filter Loading and Washing Tests

1.0 PURPOSE

The purpose of this procedure is to ensure ICET personnel follow correct steps to load and wash core ceramic filters tested on the ceramic media test stand.

2.0 SCOPE

This procedure covers the steps necessary for preparation and operation of the ceramic media test stand in order to load and wash core ceramic filters.

3.0 TERMS / DEFINITIONS

- 3.1 dP- Differential Pressure
- 3.2 ELPI- Electrical Low-Pressure Impactor
- 3.3 LAS- Laser Aerosol Spectrometer
- 3.4 GPM- Gallons Per Minute
- 3.5 LPM- Liters Per Minute

4.0 RESPONSIBILITIES

- 4.1 Principal Investigator (PI) is responsible for supervising the project team in the areas of project planning, test plan development, fabrication of test stand, measurement and test equipment calibration, coordination of testing, testing, data quality review, and reporting.
- 4.2 The Measuring and Test Equipment Coordinator (M&TEC) is responsible for review of the test procedure and for calibration of M&TE required for testing.
- 4.3 The Quality Assurance Coordinator (QAC) is responsible for reviewing controlled design documents and assisting in records management.
- 4.4 Test personnel are responsible for review of the test procedure and conduct of testing.
- 4.5 Testing Supervisor is responsible for supervision of test personnel and control of testing process.

5.0 EQUIPMENT

- 5.1 Steel-toed Boots
- 5.2 Gloves
- 5.3 Safety Glasses

6.0 SAFETY AND ENVIROMENTAL CONCERNS

- 6.1 Safety glasses and steel toed boots are required in the high bay during testing activities
- 6.2 Hardhats are required past the signage
- 6.3 Gloves should be worn when handling KCl

7.0 PROCEDURE

- 7.1 Procedures to be followed prior to filter testing
  - 7.1.1 RTV 116 sealant should be applied to the filter end caps and wherever else that has potential for a leak

7.1.1.1 Allow at least 24 hours for the sealant to fully cure

7.1.2 The mass of the filter should be measured at least six times and recorded

7.1.3 Pre-test images should be taken of the filter

7.1.4 The operator should ensure that the correct aerosol to be used is made and installed onto the test stand aerosol injection site by following the Aerosol Generation procedure

7.1.5 The Tube Sheet and Filter Element Installation procedure should be referenced so that the filter is installed onto the tube sheet at least a day prior to testing

7.2 Procedures for Loading and Washing Tests

7.2.1 Follow the Test Stand Startup/Shutdown procedure to turn on the test stand airflow system

7.2.2 Follow the Control System Operation procedure to setup the data acquisition screen for data collection during testing

7.2.3 Install the filter by following the Tube Sheet and Element Installation and Disassembly procedure

7.2.4 Run filtered air through the test stand for approximately one hour

7.2.5 While the filter is exposed to ambient air, an initial (clean) dP test can be run if not already completed

7.2.5.1 If initial dP vs. flowrate (Q) data is desired, start the test stand air flow rate at 16 CFM and work up to 21 CFM in increments of 0.5 CFM

7.2.6 Ensure the desired aerosol measurement instruments are turned on and are operating correctly by following the Aerosol Measurement Instrumentation procedure

7.2.7 Collect background data for both upstream and downstream using the aerosol measurement instruments and the sampling train system

7.2.7.1 First set the sampling train to collect downstream samples with a 100:1 diluter included in the sampling line

7.2.7.2 Next, allow 2-3 samples for purging

7.2.7.3 Then, set the sampling train to collect upstream samples with both 100:1 and 20:1 diluters included in the sampling line

7.2.8 Inject the KCl into the test stand after the steps in the Aerosol Generation procedure have been completed

7.2.9 The differential pressure should be monitored to ensure the filter does not clog or burst; If the dP of the filter does not significantly change over an extended period, a predetermined testing time (or maximum dP value) will be used to stop the test

7.2.10 Start sampling with the ELPI from the initial dP up to a predetermined dP value (typically 30 minutes to one hour)

7.2.11 Perform Initial Filtering Efficiency Measurement

7.2.11.1 After the aerosol is turned on, the instruments should be set to sample downstream

7.2.11.2 Wait 3-5 samples before collecting test data to ensure the aerosol concentrations are consistent

7.2.11.3 Downstream aerosol samples are collected (4 samples for LAS and 2 samples for SMPS)

7.2.11.4 Adjust the sampling train to purge the aerosol measurement instrumentation

7.2.11.5 Upstream aerosol samples are collected (4 samples for LAS and 2 samples for SMPS)

7.2.12 Set the sampling train to sample upstream while loading the filter with KCl

7.2.13 Load the filter with KCl up to approximately 40 inches of water

7.2.14 Any deviations from the testing activities need to be recorded with the sample number(s) and time(s) in a lab notebook

7.3 Procedures to be followed at the conclusion of testing

7.3.1 Follow the Test Stand Startup/Shutdown procedure to turn off the test stand airflow system

7.3.2 Turn off the aerosol generation systems used for testing by following the Aerosol Generation procedure

7.3.3 Collect the desired data from aerosol measurement instruments using a USB drive

7.3.4 Turn off any aerosol measurement instrumentation, vacuum pumps, or flow controllers that do not need to be on

7.3.5 Remove the filter element(s) and tube sheet by following the procedures in the Tube Sheet and Element Installation and Disassembly document

7.3.6 At the end of the test, the mass of the filter will be measured at least six times and recorded

7.3.7 Post-test images should be taken of the filter

7.3.8 Insert a USB into a port to collect the desired data from the test stand

7.4 Washing of Filter Elements Loaded with KCl

7.4.1 The tube sheet, with filter attached, should be placed onto the wash tank system as shown in Figure 1.

Figure 1. Wash tank system.

7.4.2 Ensure that the wash tank outlet hose is placed in the drain

7.4.3 Ensure that the pump switch is turned on near the Type II water tanks in the highbay

7.4.4 Open the valve to allow the Type II water to flow into the wash tank and fill it until the filters are fully submerged with water

7.4.5 Adjust the rotameter to the appropriate flow rate through the tested filter (in GPM or LPM)

7.4.6 Insert the plastic tubing lines from the Type II water pipe into each of the filter element(s) as shown in Figure 2.

Figure 2. Tubing connecting the Type II water line to the filter elements.

7.4.7 Open the valve shown in Figure 2 to allow the Type II water to flow into the filter element(s)

7.4.8 Simultaneously, open the valve at the bottom of the wash tank system to allow the water to flow from the tank to the drain

7.4.9 Wait until the water is drained completely, then close the Type II water valve.

7.4.10 Visually inspect that there is no KCl still on the filter

7.4.10.1 If there is still KCl still visible on the filter surface, run the wash again

7.4.11 Take the tubesheet, with filter attached, off the wash tank system

7.4.12 Remove the filter from the tubesheet

7.4.13 Place in the oven to be dried appropriately for the next test or allow the filters to dry overnight

7.4.14 Weigh the filter after being dried

7.5 Repeat Steps 7.2 and 7.4 until there is enough data for analysis

Procedure for ceramic filter elevated temperature testing

1.0 PURPOSE

The purpose of this procedure is to ensure ICET personnel follow correct steps to perform a filtering efficiency (FE) test after a ceramic media filter has been exposed to elevated temperatures

2.0 SCOPE

This procedure covers the steps necessary for preparation and operation of the ceramic media test stand in order to perform an elevated temperature tests on ceramic media filters.

3.0 TERMS / DEFINITIONS

- 3.1 dP- Differential Pressure
- 3.2 SMPS- Scanning Mobility Particle Sizer
- 3.3 LAS- Laser Aerosol Spectrometer
- 3.4 FE- Filtering Efficiency

4.0 RESPONSIBILITIES

- 4.1 Principal Investigator (PI) is responsible for supervising the project team in the areas of project planning, test plan development, fabrication of test stand, measurement and test equipment calibration, coordination of testing, testing, data quality review, and reporting.
- 4.2 The Measuring and Test Equipment Coordinator (M&TEC) is responsible for review of the test procedure and for calibration of M&TE required for testing.
- 4.3 The Quality Assurance Coordinator (QAC) is responsible for reviewing controlled design documents and assisting in records management.
- 4.4 Test personnel are responsible for review of the test procedure and conduct of testing.
- 4.5 Testing Supervisor is responsible for supervision of test personnel and control of testing process.

5.0 EQUIPMENT

- 5.1 Steel-toed boots
- 5.2 Gloves
- 5.3 Safety glasses
- 5.4 Heat resistant gloves

6.0 SAFETY AND ENVIROMENTAL CONCERNS

- 6.1 Safety glasses and steel toed boots are required in the high bay during testing activities
- 6.2 Hardhats are required past the signage
- 6.3 Gloves should be worn when handling KCl
- 6.4 Heat resistant gloves need to be worn when handling anything that has been exposed to the elevated temperatures of the test stand air and heating element

7.0 PROCEDURE

7.1 Procedures to be followed prior to filter testing

7.1.1 RTV 116 sealant should be applied to the filter end caps and wherever else that has potential for a leak

7.1.1.1 Allow at least 24 hours for the sealant to fully cure

7.1.2 The mass of the filter should be measured at least six times and recorded

7.1.3 Pre-test images should be taken of the filter

7.1.4 The operator should ensure that the correct aerosol to be used is made and installed onto the test stand aerosol injection site by following the Aerosol Generation procedure

7.1.5 The Tube Sheet and Filter Element Installation procedure should be referenced so that the filter is installed onto the tube sheet at least a day prior to testing

7.2 Procedures to be followed when testing begins

7.2.1 Follow the Test Stand Startup/Shutdown procedure to turn on the test stand airflow system

7.2.2 Follow the Control System Operation procedure to setup the data acquisition screen for data collection during testing

7.2.3 Install the filter by following the Tube Sheet and Element Installation and Disassembly procedure

7.2.4 Run filtered air through the test stand for approximately one hour

7.2.5 While the filter is exposed to ambient air, an initial (clean) dP test can be run if not already completed

7.2.5.1 If initial dP vs. flowrate (Q) data is desired, start the test stand air flow rate at 0.5 CFM and work up to 5 CFM in increments of 0.5 CFM

7.2.6 Ensure the desired aerosol measurement instruments are turned on and are operating correctly by following the Aerosol Measurement Instrumentation procedure

7.2.7 Collect background data for both upstream and downstream using the aerosol measurement instrument and the sampling train system

7.2.7.1 First set the sampling train to collect downstream samples with a 100:1 diluter included in the sampling line

7.2.7.2 Next, allow 2-3 samples for purging

7.2.7.3 Then, set the sampling train to collect upstream samples with both 100:1 and 20:1 diluters included in the sampling line

7.2.8 The aerosol should be injected into the test stand by referencing the Aerosol Generation procedure

7.2.9 The dP should be monitored throughout the entire test so that the filter does not clog or burst and to ensure FE measurements at the correct points

7.2.10 Initial (Ambient) Filtering Efficiency Measurement

7.2.10.1 After the aerosol is turned on, the instruments should be set to sample downstream

7.2.10.2 Wait 3-5 samples before collecting test data to ensure the aerosol concentrations are consistent

7.2.10.3 Downstream aerosol samples (6 samples for LAS and 3 samples for SMPS) are then collected

7.2.10.4 Next, adjust the sampling train to purge the aerosol measurement instrumentation

7.2.10.5 Upstream aerosol samples (6 samples for LAS and 3 samples for SMPS) are then collected

7.2.11 Ensure that no instruments are sampling by adjusting the sampling train valves to the proper orientation

7.2.12 Input a setpoint of 392°F (200°C) into the heater control screen on the test stand CPU

7.2.13 Allow the temperature of the air inside the test stand to reach approximately 392°F (200°C)

7.2.14 Perform Procedure 7.2.8 for the next FE measurement

7.2.15 Ensure that no instruments are sampling by adjusting the sampling train valves to the proper orientation

7.2.16 Input a setpoint of 482°F (250°C) into the heater control screen on the test stand CPU

7.2.17 Allow the temperature of the air inside the test stand to reach approximately 482°F (250°C)

7.2.18 Perform Procedure 7.2.8 for the next FE measurement

7.2.19 Ensure that no instruments are sampling by adjusting the sampling train valves to the proper orientation

7.2.20 Input a setpoint of 527°F (275°C) into the heater control screen on the test stand CPU

7.2.21 Allow the temperature of the air inside the test stand to reach approximately 527°F (275°C)

7.2.22 Perform Procedure 7.2.8 for the next FE measurement

7.2.23 If the dP of the filter does not significantly change over an extended period of time, a predetermined testing time or dP value will be used to stop the test

7.2.24 Any deviations from the testing activities need to be recorded with the sample number(s) and time(s) in a lab notebook

7.2.24.1 If the DOP generator exit valve needs to be closed for any reason, the operator needs to adjust the test stand flowrate in order to diminish any discrepancies in the test stand data

7.3 Procedures to be followed at the conclusion of testing

7.3.1 Follow the Test Stand Startup/Shutdown procedure to turn off the test stand airflow system and to shut down the test stand

7.3.2 Turn off the aerosol generation system used during testing by following the Aerosol Generation procedure

7.3.3 Collect any desired data from aerosol measurement instruments

7.3.4 Turn off any aerosol measurement instrumentation, vacuum pumps, or flow controllers that do not need to be on

7.3.5 Remove the filter element(s) and tube sheet by following the procedures in the Tube Sheet and Element Installation and Disassembly document

7.3.6 At the end of the test, the mass of the filter will be measured at least six and recorded

7.3.7 Post-test images of the filter should be taken

7.3.8 Insert a USB into a port to collect the desired data from the test stand

Procedure for ceramic filter FE (filtering efficiency) testing

1.0 PURPOSE

The purpose of this procedure is to ensure ICET personnel follow correct steps to perform a filtering efficiency (FE) test using the ceramic media test stand to collect meaningful data.

2.0 SCOPE

This procedure covers the steps necessary for preparation and operation of the ceramic media test stand in order to perform an FE test on ceramic media filters.

3.0 TERMS / DEFINITIONS

- 3.1 dP- Differential Pressure
- 3.2 SMPS- Scanning Mobility Particle Sizer
- 3.3 LAS- Laser Aerosol Spectrometer

4.0 RESPONSIBILITIES

- 4.1 Principal Investigator (PI) is responsible for supervising the project team in the areas of project planning, test plan development, fabrication of test stand, measurement and test equipment calibration, coordination of testing, testing, data quality review, and reporting.
- 4.2 The Measuring and Test Equipment Coordinator (M&TEC) is responsible for review of the test procedure and for calibration of M&TE required for testing.
- 4.3 The Quality Assurance Coordinator (QAC) is responsible for reviewing controlled design documents and assisting in records management.
- 4.4 Test personnel are responsible for review of the test procedure and conduct of testing.
- 4.5 Testing Supervisor is responsible for supervision of test personnel and control of testing process.

5.0 EQUIPMENT

- 5.1 Steel-toed Boots
- 5.2 Gloves
- 5.3 Safety Glasses

6.0 SAFETY AND ENVIROMENTAL CONCERNS

- 6.1 Safety glasses and steel toed boots are required in the high bay during testing activities
- 6.2 Hardhats are required past the signage
- 6.3 Gloves should be worn when handling KCl

7.0 PROCEDURE

- 7.1 Procedures to be followed prior to filter testing
  - 7.1.1 RTV 116 sealant should be applied to the filter end caps and wherever else that has potential for a leak
    - 7.1.1.1 Allow at least 24 hours for the sealant to fully cure

7.1.2 The mass of the filter should be measured at least six times and recorded

7.1.3 Pre-test images of the filter should be taken

7.1.4 The operator should ensure that the correct aerosol to be used is made and installed onto the test stand aerosol injection site by following the Aerosol Generation procedure

7.1.5 The Tube Sheet and Filter Element Installation procedure should be referenced so that the filter is properly installed onto the tube sheet

7.2 Procedures to be followed when testing begins

7.2.1 Follow the Test Stand Startup/Shutdown procedure to turn on the test stand airflow system

7.2.2 Follow the Control System Operation procedure to setup the data acquisition screen for data collection during testing

7.2.3 Install the filter by following the Tube Sheet and Element Installation and Disassembly procedure

7.2.4 Run filtered air through the test stand for approximately one hour

7.2.5 While the filter is exposed to ambient air, an initial (clean) dP test can be run if not already completed

7.2.5.1 If initial dP vs. flowrate (Q) data is desired, start the test stand air flow rate at 0.5 CFM and work up to 5 CFM in increments of 0.5 CFM for a single element filter

7.2.5.2 If initial dP vs. flowrate (Q) data is desired, start the test stand air flow rate at 0.5 CFM and work up to 16 CFM in increments of 21 CFM for a six-element filter

7.2.6 Ensure the desired aerosol measurement instruments are turned on and are operating correctly by following the Aerosol Measurement Instrumentation procedure

7.2.7 Collect background data for both upstream and downstream using the aerosol measurement instruments and the sampling train system

7.2.7.1 First set the sampling train to collect downstream samples with a 100:1 diluter included in the sampling line

7.2.7.2 Next, allow 2-3 samples for purging

7.2.7.3 Then, set the sampling train to collect upstream samples with both 100:1 and 20:1 diluters included in the sampling line

7.2.8 The aerosol should be injected into the test stand by referencing the Aerosol Generation procedure

7.2.9 The dP should be monitored throughout the entire test so that the filter does not clog or burst and to ensure FE measurements at the correct points

7.2.10 Initial Filtering Efficiency Measurement

7.2.10.1 After the aerosol is turned on, the instruments should be set to sample downstream

7.2.10.2 Wait 3-5 samples before collecting test data to ensure the aerosol concentrations are consistent

7.2.10.3 Downstream aerosol samples (6 samples for LAS and 3 samples for SMPS) are then collected

7.2.10.4 Next, adjust the sampling train to purge the aerosol measurement instrumentation

7.2.10.5 Upstream aerosol samples (6 samples for LAS and 3 samples for SMPS) are then collected

7.2.11 Set the valve configuration to sample upstream until the next FE interval

7.2.12 Filtering Efficiency Measurement at 4 Inches of Water

7.2.12.1 Repeat Procedure 7.2.8

7.2.13 Set the valve configuration to sample upstream until the next FE interval

7.2.14 Filtering Efficiency Measurement at 10 Inches of Water

7.2.14.1 Repeat Procedure 7.2.8

7.2.15 Set the valve configuration to sample upstream until the next FE interval

7.2.16 Filtering Efficiency Measurement at 10 Inches of Water

7.2.16.1 Repeat Procedure 7.2.8

7.2.17 Set the valve configuration to sample upstream until the next FE interval

7.2.18 Filtering Efficiency Measurement at 20 Inches of Water

7.2.18.1 Repeat Procedure 7.2.8

7.2.19 Set the valve configuration to sample upstream until the next FE interval

7.2.20 Filtering Efficiency Measurement at 30 Inches of Water

7.2.20.1 Repeat Procedure 7.2.8

7.2.21 Set the valve configuration to sample upstream until the next FE interval

7.2.22 Filtering Efficiency Measurement at 40 Inches of Water

7.2.22.1 Repeat Procedure 7.2.8

7.2.23 Set the valve configuration to sample upstream

7.2.24 If the dP of the filter does not significantly change over an extended period, a predetermined testing time or dP value will be used to stop the test

7.2.25 Any deviations from the testing activities need to be recorded with the sample number(s) and time(s) in a lab notebook

7.2.25.1 If the DOP generator exit valve needs to be closed for any reason, the operator needs to adjust the test stand flowrate to diminish any discrepancies in the collected data

7.3 Procedures to be followed at the conclusion of testing

7.3.1 Follow the Test Stand Startup/Shutdown procedure to turn off the test stand airflow system and to shut down the test stand

7.3.2 Turn off the aerosol generation system used during testing by following the Aerosol Generation procedure

7.3.3 Collect any desired data from aerosol measurement instruments using a USB drive

7.3.4 Turn off any aerosol measurement instrumentation, vacuum pumps, or flow controllers that do not need to be on

7.3.5 Remove the filter element(s) and tube sheet by following the procedures in the Tube Sheet and Element Installation and Disassembly document

7.3.6 At the end of the test, the mass of the filter will be measured at least six times and recorded

7.3.7 Post-test images of the filter should be taken

7.3.8 Insert a USB into a port to collect the desired data from the test stand

Procedure for ceramic filter loading test

1.0 PURPOSE

The purpose of this procedure is to ensure ICET personnel follow correct steps to load ceramic media filters tested on the ceramic media test stand.

2.0 SCOPE

This procedure covers the steps necessary for preparation and operation of the ceramic media test stand in order to load ceramic media filters.

3.0 TERMS / DEFINITIONS

- 3.1 dP- Differential Pressure
- 3.2 ELPI- Electrical Low-Pressure Impactor
- 3.3 LAS- Laser Aerosol Spectrometer
- 3.4 GPM- Gallons Per Minute
- 3.5 LPM- Liters Per Minute

4.0 RESPONSIBILITIES

- 4.1 Principal Investigator (PI) is responsible for supervising the project team in the areas of project planning, test plan development, fabrication of test stand, measurement and test equipment calibration, coordination of testing, testing, data quality review, and reporting.
- 4.2 The Measuring and Test Equipment Coordinator (M&TEC) is responsible for review of the test procedure and for calibration of M&TE required for testing.
- 4.3 The Quality Assurance Coordinator (QAC) is responsible for reviewing controlled design documents and assisting in records management.
- 4.4 Test personnel are responsible for review of the test procedure and conduct of testing.
- 4.5 Testing Supervisor is responsible for supervision of test personnel and control of testing process.

5.0 EQUIPMENT

- 5.1 Steel-toed Boots
- 5.2 Gloves
- 5.3 Safety Glasses

6.0 SAFETY AND ENVIROMENTAL CONCERNS

- 6.1 Safety glasses and steel toed boots are required in the high bay during testing activities
- 6.2 Hardhats are required past the signage
- 6.3 Gloves should be worn when handling KCl and DOP
- 6.4 Lab coats and safety glasses should be worn when handling DOP

7.0 PROCEDURE

- 7.1 Procedures to be followed prior to filter testing

7.1.1 RTV 116 sealant should be applied to the filter end caps and wherever else that has potential for a leak
7.1.1.1 Allow at least 24 hours for the sealant to fully cure
7.1.2 The mass of the filter should be measured at least six times and recorded
7.1.3 Pre-test images should be taken of the filter
7.1.4 The operator should ensure that the correct aerosol to be used is made and installed onto the test stand aerosol injection site by following the Aerosol Generation procedure
7.1.5 The Tube Sheet and Filter Element Installation procedure should be referenced so that the filter is installed onto the tube sheet at least a day prior to testing

7.2 Procedures to be followed when testing begins
7.2.1 Follow the Test Stand Startup/Shutdown procedure to turn on the test stand airflow system
7.2.2 Follow the Control System Operation procedure to setup the data acquisition screen for data collection during testing
7.2.3 Install the filter by following the Tube Sheet and Element Installation and Disassembly procedure
7.2.4 Run filtered air through the test stand for approximately one hour
7.2.5 While the filter is exposed to ambient air, initial (clean) dP data can be run if not already completed
7.2.6 Ensure the desired aerosol measurement instruments are turned on and are operating correctly by following the Aerosol Measurement Instrumentation procedure
7.2.7 Collect background data for both upstream and downstream using the aerosol measurement instruments and the sampling train system
7.2.7.1 First set the sampling train to collect downstream samples with a 100:1 diluter included in the sampling line
7.2.7.2 Next, allow 2-3 samples for purging
7.2.7.3 Then, set the sampling train to collect upstream samples with both 100:1 and 20:1 diluters included in the sampling line
7.2.8 Inject the aerosol into the test stand by referencing the Aerosol Generation procedure
7.2.9 The differential pressure should be monitored to ensure the filter does not clog or burst. If the dP of the filter does not significantly change over an extended period of time, a predetermined testing time (or maximum dP value) will be used to stop the test
7.2.10 Start sampling with the ELPI from the initial dP up to a predetermined dP value (typically 30 minutes to one hour)

7.2.11 Perform Initial Filtering Efficiency Measurement using DOP

7.2.11.1 After the DOP is turned on, the instruments should be set to sample downstream

7.2.11.2 Wait 3-5 samples before collecting test data to ensure the aerosol concentrations are consistent

7.2.11.3 Downstream aerosol samples are collected (6 samples for LAS and 3 samples for SMPS)

7.2.11.4 Next, adjust the sampling train to purge the aerosol measurement instrumentation

7.2.11.5 Upstream aerosol samples are collected (6 samples for LAS and 3 samples for SMPS)

7.2.12 Start the KCl generator by following the Aerosol Generation procedure

7.2.13 Load the filter with KCl up to the desired differential pressure value

7.2.14 Adjust the flowrate in the test stand to accommodate for the KCl generator valve being closed

7.2.15 Close the exit valve of the KCl generator and disconnect the KCl generator line from the aerosol injection site

7.2.16 Connect the DOP generator to the test stand aerosol injection site

7.2.17 Perform the next FE measurement using DOP

7.2.17.1 After the DOP is turned on, the instruments should be set to sample downstream

7.2.17.2 Wait 3-5 samples before collecting test data to ensure the aerosol concentrations are consistent

7.2.17.3 Downstream aerosol samples are collected (6 samples for LAS and 3 samples for SMPS)

7.2.17.4 Next, adjust the sampling train to purge the aerosol measurement instrumentation

7.2.17.5 Upstream aerosol samples are collected (6 samples for LAS and 3 samples for SMPS)

7.2.18 Disconnect the DOP generator from the aerosol injection site

7.2.19 Connect the KCl generator to the aerosol injection site

7.2.20 Load the filter with KCl up to the next desired differential pressure value

7.2.21 Complete Steps 7.2.15 through 7.2.18 until the desired number of FE measurements and KCl loading intervals are complete

7.2.22 Any deviations from the testing activities need to be recorded with the sample number(s) and time(s) in a lab notebook

7.3 Procedures to be followed at the conclusion of testing

7.3.1 Follow the Test Stand Startup/Shutdown procedure to turn off the test stand airflow system

7.3.2 Turn off the aerosol generation systems used for testing by following the Aerosol Generation procedure

7.3.3 Collect the desired data from aerosol measurement instruments using a USB drive

7.3.4 Turn off any aerosol measurement instrumentation, vacuum pumps, or flow controllers that do not need to be on

7.3.5 Remove the filter element(s) and tube sheet by following the procedures in the Tube Sheet and Element Installation and Disassembly document

7.3.6 At the end of the test, the mass of the filter will be measured at least six times and recorded

7.3.7 Insert a USB into a port to collect the desired data from the test stand

Procedure for startup and shutdown of ceramic media test stand

1.0 PURPOSE

The purpose of this procedure is to ensure ICET personnel follow correct steps to properly startup and shutdown the ceramic media test stand.

2.0 SCOPE

This procedure covers the steps necessary for startup and shutdown of the ceramic media test stand to enable testing of ceramic filter media.

3.0 TERMS / DEFINITIONS

3.1 Differential pressure- dP

4.0 RESPONSIBILITIES

4.1 Principal Investigator (PI) is responsible for supervising the project team in the areas of project planning, test plan development, fabrication of test stand, measurement and test equipment calibration, coordination of testing, testing, data quality review, and reporting.

4.2 The Measuring and Test Equipment Coordinator (M&TEC) is responsible for review of the test procedure and for calibration of M&TE required for testing.

4.3 The Quality Assurance Coordinator (QAC) is responsible for reviewing controlled design documents and assisting in records management.

4.4 Test personnel are responsible for review of the test procedure and conduct of testing.

4.5 Testing Supervisor is responsible for supervision of test personnel and control of testing process.

5.0 EQUIPMENT

5.1 Steel-toed Boots

5.2 Safety glasses

5.3 Impact wrench

5.4 Pipe wrench

6.0 SAFETY AND ENVIROMENTAL CONCERNS

6.1 Safety glasses and steel toed boots are required in the high bay during testing activities

6.2 Hearing protection is required when the impact wrench is in use

6.3 Hardhats are required past the signage

7.0 PROCEDURE

7.1 Test stand startup

7.1.1 If a filter is to be tested, follow the Tube Sheet and Element Installation to properly install the filter element(s) onto the necessary tube sheet

7.1.2 Turn on all aerosol measurement instruments to be used on the test stand and follow the Aerosol Measurement Instrumentation procedure

7.1.3 Ensure that the test stand CPU is turned on and the sensors are reading

7.1.4 If an aerosol generation system is to be used, follow the Aerosol Generation procedure

7.1.5 Verify that all blinds and bolts are tightened, and that all ports and sampling tubes are either capped or being used to prevent leaks in the system

7.1.6 Perform a leak check on the test stand

7.1.6.1 Remove the test stand inlet filter with a pipe wrench

7.1.6.2 Insert a threaded plug into the inlet of the test stand

7.1.6.3 Ensure that the VFD On/Off and VFD On/Off Signal buttons are green on the test stand computer screen. The PID Flow Enable button should be red, and the VFD Controller Output box should be yellow

7.1.6.4 Input a value of 4 in the VFD Controller Output box to start the blower

7.1.6.5 Verify that the differential pressure (dP) is remaining at a constant value

7.1.6.6 Increase the input value into the VFD Controller Output box and ensure that the dP is relatively close to the original value

7.1.6.7 Repeat Procedure 7.1.6.6 to verify that there are no leaks in the test stand

7.1.6.8 If a leak is suspected after completing all steps in Procedure 7.1.6, tighten all bolts around the area of concern using an impact wrench

7.1.7 Verify that all of the instrument sampling lines are connected to the correct instrument or to a HEPA capsule filter

7.1.8 Turn test stand air flow on using the Control System and Operation procedure

7.1.9 Verify that the test stand sensors (flow, temperature, relative humidity, etc.) are outputting reasonable values

7.1.10 If needed, let the test stand purge by running air through it for 30 minutes to one hour

7.2 Test stand shutdown

7.2.1 Once testing is completed, close the valve to the aerosol generation system that was being used

7.2.2 Follow the Aerosol Generation procedure to turn off the aerosol generation system used for testing

7.2.3 Turn test stand air flow off by following the Control System and Operation procedure

7.2.4 If a filter was being tested and needs to be immediately taken out, follow the Tube Sheet and Element Installation procedure to remove the filter and tube sheet

7.2.5 If any aerosol measurement instrumentation was used, follow the Aerosol Measurement Instrumentation procedure to turn off the instruments

7.2.6 Collect the desired data from the test stand computer by connecting a USB drive to the port on the side of the monitor

7.2.7 Collect the desired data from the aerosol instrumentation using a USB drive

7.2.8 Turn off any aerosol measurement instrumentation, vacuum pumps, or flow controllers that do not need to be on

Procedure for ceramic media filter tube sheet and element installation

1.0 PURPOSE

The purpose of this procedure is to ensure ICET personnel follow correct steps to properly install the ceramic filters onto the correct tube sheet and into the test stand for filter testing.

2.0 SCOPE

This procedure covers the steps necessary for tube sheet and element installation in order to perform testing on ceramic filters.

3.0 TERMS / DEFINITIONS

4.0 RESPONSIBILITIES

- 4.1 Principal Investigator (PI) is responsible for supervising the project team in the areas of project planning, test plan development, fabrication of test stand, measurement and test equipment calibration, coordination of testing, testing, data quality review, and reporting.
- 4.2 The Measuring and Test Equipment Coordinator (M&TEC) is responsible for review of the test procedure and for calibration of M&TE required for testing.
- 4.3 The Quality Assurance Coordinator (QAC) is responsible for reviewing controlled design documents and assisting in records management.
- 4.4 Test personnel are responsible for review of the test procedure and conduct of testing.
- 4.5 Testing Supervisor is responsible for supervision of test personnel and control of testing process.

5.0 EQUIPMENT

- 5.1 Steel-toed Boots
- 5.2 Hard Hats
- 5.3 Gloves
- 5.4 Safety Glasses
- 5.5 Nuts and bolts for tube sheet
- 5.6 Nuts and bolts for filter element attachment to tube sheet
- 5.7 RTV 116 sealant
- 5.8 Crescent wrench
- 5.9 Impact wrench

6.0 SAFETY AND ENVIROMENTAL CONCERNS

- 6.1 Safety glasses and steel toed boots are required in the high bay during testing actitivies
- 6.2 Hearing protection is required when the impact wrench is in use
- 6.3 Hardhats are required past the signage

7.0 PROCEDURE

- 7.1 Single Element Filter Installation

7.1.1 Procedures to be completed prior to day of testing

7.1.1.1 Attach the hoist and sling to the housing cap of the test stand

7.1.1.2 Unbolt the middle section from the test stand base using an impact wrench

7.1.1.3 Unbolt the housing cap from the test stand downstream section using a crescent wrench

7.1.1.4 Use the hoist to lift the middle section and housing cap and place to the side of the test stand base

7.1.1.5 Unbolt the housing cap from the test stand middle section using an impact wrench

7.1.1.6 Use hoist and sling to remove housing cap off middle section of test stand

7.1.1.7 Place the housing cap on the platform that is secured to the test stand support structure

7.1.1.8 Obtain the single element tube sheet that the filter will be attached to

7.1.1.9 Obtain the filter element to be tested while wearing latex gloves

7.1.1.10 Obtain the square plate that the filter element will be sealed to in order to be installed onto the tube sheet

7.1.1.11 Spread RTV 116 sealant around the end cap to ensure a complete seal

7.1.1.12 Spread RTV 116 sealant onto the open edge of the filter element

7.1.1.13 Center the single element filter onto the metal plate from step 7.1.1.10

7.1.1.14 Spread more RTV 116 sealant on the surrounding circumference of the filter to seal it to the metal plate and be sure to get as little as possible on the filter paper

7.1.1.15 Allow the sealant to fully cure at least 24 hours before testing

7.1.2 Procedures to be performed after RTV sealant has cured

7.1.2.1 Place the gasket down onto the tubesheet

7.1.2.2 Align the four holes of the tube sheet, gasket, and square metal plate with filter attached

7.1.2.3 Use the set of four nuts, bolts, and washers to secure the metal plate onto the tube sheet

7.1.2.4 Tighten the two wingnuts to secure the other end of the filter with the end cap

7.1.2.5 Ensure that the two eyebolts are tightened down in the tube sheet

7.1.2.6 Run the sling through the eyebolts of the ceramic filter tube sheet

7.1.2.7 Use hoist to lift the tube sheet and filter element

7.1.2.8 Ensure the first gasket is placed onto the test stand housing section

7.1.2.9 Place the tube sheet and filter element onto the housing

7.1.2.10 Ensure the second gasket is placed onto the tubesheet

7.1.2.11 Place housing cap back on the housing using hoist and sling

7.1.2.12 Secure the housing cap by tightening the nuts and bolts using an impact wrench

7.1.2.13 Use hoist to lift the middle section and housing with the installed filter element onto the test stand base

7.1.2.14 Place entire assembly on test stand base and tighten the nuts and bolts using an impact wrench

7.2 Six-Element Filter Installation

7.2.1 Procedures to be completed prior to day of testing

7.2.1.1 Attach the hoist and sling to the housing cap of the test stand

7.2.1.2 Unbolt the middle section from the test stand base using an impact wrench

7.2.1.3 Unbolt the housing cap from the test stand downstream section using a crescent wrench

7.2.1.4 Use the hoist to lift the middle section and housing cap and place to the side of the test stand base

7.2.1.5 Unbolt the housing cap from the test stand middle section using an impact wrench

7.2.1.6 Use hoist and sling to remove housing cap off middle section of test stand

7.2.1.7 Place the housing cap on the platform that is secured to the test stand support structure

7.2.1.8 Obtain the multiple element tube sheet that the filter will be attached to

7.2.1.9 If the RTV 116 sealant has cracked on any of the filter elements, reapply more RTV 116 sealant to ensure a better seal

7.2.1.9.1 Allow the sealant to fully cure for at least 24 hours

7.2.1.10 Obtain the filter to be tested while wearing latex gloves

7.2.1.11 Place the gasket onto the tube sheet

7.2.1.12 Align the holes of the tube sheet, gasket, and filter together

7.2.1.13 Using a wrench, bolt down these components with the appropriate nuts, bolts, and washers

7.2.1.14 Verify that the eye bolts are tightened into the tube sheet holes and run the sling through the eyebolts

7.2.1.15 Use hoist to lift the tube sheet and filter element

7.2.1.16 Place the first gasket onto the test stand housing

7.2.1.17 Place the tube sheet and filter onto the housing

7.2.1.18 Place the second gasket onto the tube sheet

7.2.1.19 Attach the hoist and sling to the housing cap

7.2.1.20 Place housing cap back on the housing section

7.2.1.21 Secure the housing cap by tightening the nuts and bolts using an impact wrench

7.2.1.22 Use hoist to lift the middle section and housing with the installed filter element onto the test stand base

7.2.1.23 Obtain the nuts and bolts to secure the assembly together and tighten with an impact wrench

7.3 Disassembly of Test Stand to Remove Filters

7.3.1 Attach the hoist and sling securely to the housing cap of the test stand

7.3.2 Unbolt the middle section from the test stand base using an impact wrench

7.3.3 Unbolt the housing cap from the test stand downstream section using a crescent wrench

7.3.4 Use the hoist to lift the middle section and housing cap and place the assembly to the side of the test stand base

7.3.5 Unbolt the housing cap from the test stand middle section using an impact wrench

7.3.6 Use hoist and sling to remove housing cap off middle section of test stand

7.3.7 Place the housing cap on the platform that is secured to the test stand support structure

7.3.8 Run the hoist and sling through the tube sheet eyebolts to remove the filter element and tube sheet assembly

7.3.9 Carefully take the sling off of the tube sheet and place the tube sheet and filter element in a secure location

APPENDIX F

DATA REDUCTION SHEETS

Mathcad data reduction sheet for filter testing

The following section imports data from the Excel file of raw data. Each block is importing the correspondingly named sheet.

TLAS :=

Below are user inputs taken from the Lab Notebook and raw data file.

First Sample of the LAS Downstream data

LAS_DS_1st := 2

First Sample of the LAS Upstream data

LAS_US_1st := 9

Number of LAS samples

LAS_nos := 4

Dilution Ratio of the 20:1 and 100:1 diluters

"DR" indicates the dilution ratio for upstream measurements and "DR2" indicates dilution ratio for downstream measurements.

$$DR := 95.71 \cdot 18.234 = 1.745 \times 10^{3}$$

$$DR2 := 18.234$$

$$LAS\_US := submatrix(TLAS, 16, 114, LAS\_US\_1st + 1, LAS\_US\_1st + LAS\_nos)$$

$$LAS\_DS := submatrix(TLAS, 16, 114, LAS\_DS\_1st + 1, LAS\_DS\_1st + LAS\_nos)$$

The functions below create vectors from the TLAS raw data sheet corresponding to the lower and upper diameters of each bin of the LAS. The diameters are the zeroth and first columns of the sheet.

$$LAS\_Lower := submatrix(TLAS, 16, 114, 0, 0)$$

$$LAS\_Upper := submatrix(TLAS, 16, 114, 1, 1)$$

The function below creates a vector of the midpoint diameter of each bin and converts units from nm to μm.

$$LAS\_Dp := \frac{LAS\_Upper + LAS\_Lower}{2} \cdot \frac{1}{1000}$$

The functions below creates vectors from the TLAS raw data sheet corresponding to the flowrate during each sample taken by the LAS. This will be used to convert from number per sample to number per cc.

$$Flow\_US := submatrix(TLAS, 5, 5, LAS\_US\_1st + 1, LAS\_US\_1st + LAS\_nos)$$

$$Flow\_DS := submatrix(TLAS, 5, 5, LAS\_DS\_1st + 1, LAS\_DS\_1st + LAS\_nos)$$

The functions below define vectors from the TLAS raw data sheet corresponding to the samples indicated in the lab notebook. 16 and 114 correspond to the first and last, respectively, row of the data sheet that represent count-data. LAS_US_1st is the sample number from the lab notebook, the +1 accounts for a shift between the sample number and data sheet column number, and the +6 accounts for the shift and the use of 6 LAS samples.

The following functions convert the samples from number per sample to number per cc by dividing by the flowrate (cc/min) and the sample time (75s) and multiplying by 60s/min. First a range variable is created (j) to index the new vector of vectors.

$$j := 0..LAS\_nos - 1$$

$$US_j := LAS\_US^{\langle j \rangle} \cdot \frac{60}{75 \cdot Flow\_US^{\langle j \rangle}}$$

$$DS_j := LAS\_DS^{\langle j \rangle} \cdot \frac{60}{75 \cdot Flow\_DS^{\langle j \rangle}}$$

The functions below calculate the average of the samples and applies the dilution ratio to the upstream sample data.

$$USavg := \frac{\sum_j US_j}{LAS\_nos} \cdot DR$$

$$DSavg := \frac{\sum_j DS_j}{LAS\_nos} \cdot DR2$$

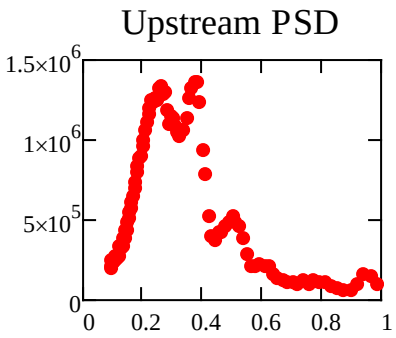
The function below creates a vector of normalization factors to properly distribute the counts to the midpoint diameter.

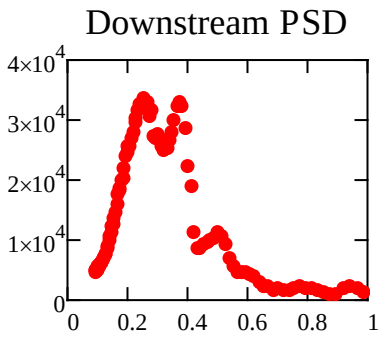
$$NormFactor := \frac{1}{\log(LAS\_Upper) - \log(LAS\_Lower)}$$

The functions below apply the normalization factor to the averaged data.

$$LAS\_US := \overrightarrow{(USavg \cdot NormFactor)} \qquad LAS\_DS := \overrightarrow{(DSavg \cdot NormFactor)}$$

The graphs below show the upstream and downstream particle size distributions (PSD).

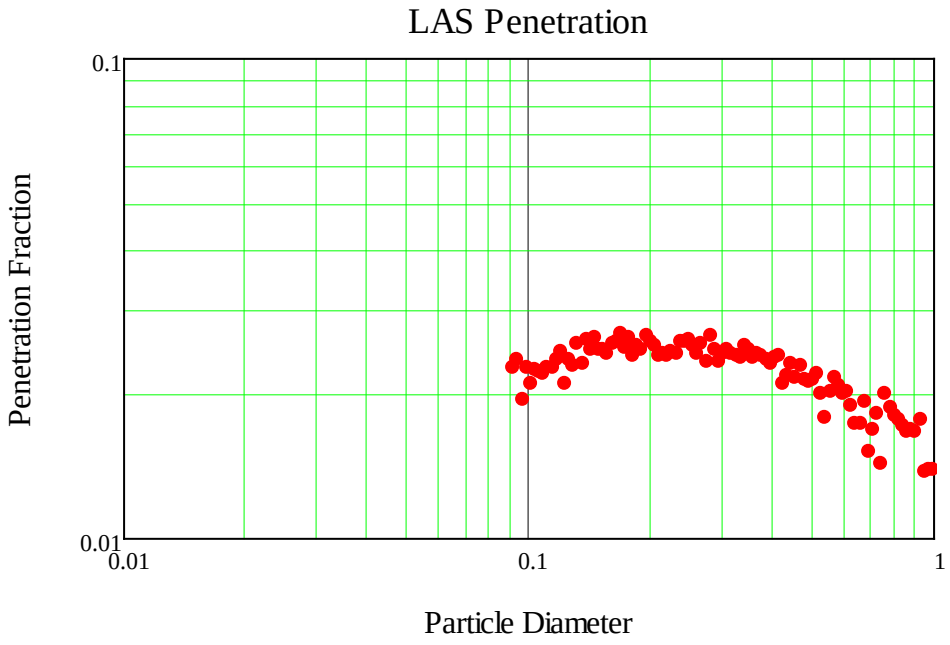




The function below defines penetration as the number of particles that penetrate the filter over the number of particles that the filter was challenged with.

$$LAS\_Pen := \frac{LAS\_DS}{LAS\_US}$$

The graph below shows penetration calculated from LAS data.



This section calculates the Geometric Mean Diameter (GMD) and the Geometric Standard Deviation (GSD) of the LAS upstream and downstream particle size distributions (PSD). The equations for these values were obtained from Appendix C of "Aerosol Instrument Manager Software for Scanning Mobility Particle Sizer (SMPS) Spectrometers" and are defined below.

Geometric Mean

$$GM = \exp\left[\frac{\sum(n \cdot \ln \cdot Dp)}{N}\right]$$

Geometric Standard Deviation

$$GSD = \exp\left[\frac{\sum\left[n \cdot (\ln \cdot Dp - \ln \cdot GM)^2\right]}{N}\right]^{\frac{1}{2}}$$

where n is the vector of particle counts, Dp is vector of particle diameters, and N is the total count.

The calculations are performed below. Σ finds the sum of a vector. The arrow above a term tells MathCAD to perform a calculation including a vector term by term (the result is a vector, not a scalar).

$$LAS\_GM\_US := \exp\left[\frac{\sum\left[\overrightarrow{(LAS\_US \cdot \ln(LAS\_Dp))}\right]}{\sum LAS\_US}\right]$$

$$LAS\_GM\_US = 0.2677$$

$$LAS\_GSD\_US := \exp\left[\left[\sum\left[\frac{\overrightarrow{\left[LAS\_US \cdot (\ln(LAS\_Dp) - \ln(LAS\_GM\_US))^2\right]}}{\left(\sum LAS\_US\right)}\right]\right]^{\frac{1}{2}}\right]$$

$$LAS\_GSD\_US = 1.5886$$

$$LAS\_GM\_DS := \exp\left[\sum\left[\frac{\overrightarrow{(LAS\_DS \cdot \ln(LAS\_Dp))}}{\sum LAS\_DS}\right]\right]$$

$LAS\_GM\_DS = 0.2619$

$$LAS\_GSD\_DS := \exp\left[\left[\sum\left[\frac{\overrightarrow{\left[LAS\_DS \cdot (\ln(LAS\_Dp) - \ln(LAS\_GM\_DS))^2\right]}}{\left(\sum LAS\_DS\right)}\right]\right]^{\frac{1}{2}}\right]$$

$LAS\_GSD\_DS = 1.5542$

$$LAS\_GM\_Pen := \exp\left[\sum\left[\frac{\overrightarrow{(LAS\_Pen \cdot \ln(LAS\_Dp))}}{\sum LAS\_Pen}\right]\right]$$

$LAS\_GM\_Pen = 0.2796$

$$LAS\_GSD\_Pen := \exp\left[\left[\sum\left[\frac{\overrightarrow{\left[LAS\_Pen \cdot (\ln(LAS\_Dp) - \ln(LAS\_GM\_Pen))^2\right]}}{\left(\sum LAS\_Pen\right)}\right]\right]^{\frac{1}{2}}\right]$$

$LAS\_GSD\_Pen = 1.94$

This section creates a lognormal curve fit to the LAS upstream PSD data.

First, the lognormal equation is defined as:

$$lognorm(x, a, \sigma, \mu) := \frac{a}{\sqrt{2\pi} \cdot \ln(\sigma)} \cdot \exp\left[\frac{-(\ln(x) - \ln(\mu))^2}{2 \cdot \ln(\sigma)^2}\right]$$

Initial values are set for each parameter.

$a_{init} := \max(LAS\_US)$ $\sigma_{init} := LAS\_GSD\_US$ $\mu_{init} := LAS\_GM\_US$

An equation for residual error is defined. The error in this case is the difference between the vector of penetration values and the lognormal curve, defined above, as a function of the vector of diameters.

$$\text{resid}_{LAS\_US}(a,\sigma,\mu) := LAS\_US - \overrightarrow{(\text{lognorm}(LAS\_Dp,a,\sigma,\mu))}$$

The following code is a Given block. Given tells MathCAD a set of equations is being defined. The equation given is that the residual error is equal to zero. Then the MathCAD function Minerr is used to optimize the parameters such that the equation is as close to satisfied as possible.

Given

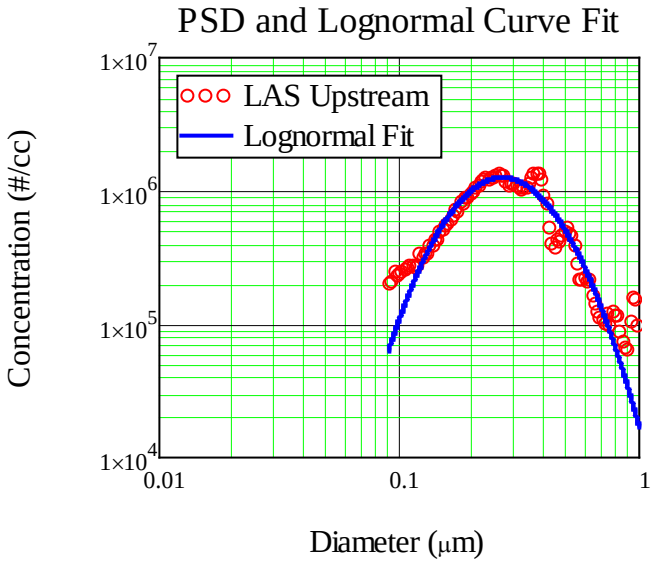
$$0 = \text{resid}_{LAS\_US}\left(a_{init},\sigma_{init},\mu_{init}\right)$$

$$\begin{pmatrix} a_{LAS\_US} \\ \sigma_{LAS\_US} \\ \mu_{LAS\_US} \end{pmatrix} := \text{Minerr}\left(a_{init},\sigma_{init},\mu_{init}\right) \qquad \begin{pmatrix} a_{LAS\_US} \\ \sigma_{LAS\_US} \\ \mu_{LAS\_US} \end{pmatrix} = \begin{pmatrix} 1.412 \times 10^{6} \\ 1.565 \\ 0.269 \end{pmatrix}$$

The lognormal curve equation then uses the optimized parameters to become the curve fit.

$$LNC_{LAS\_US}(x) := \left(lognorm\left(x, a_{LAS\_US}, \sigma_{LAS\_US}, \mu_{LAS\_US}\right)\right)$$

Below are graphs of the penetration vector and the curve fit.



This section creates a lognormal curve fit to the LAS downstream PSD data.

First, the lognormal equation is defined as:

$$\text{lognorm}(x, a, \sigma, \mu) := \frac{a}{\sqrt{2\pi}\cdot\ln(\sigma)}\cdot\exp\left[\frac{-(\ln(x)-\ln(\mu))^2}{2\cdot\ln(\sigma)^2}\right]$$

Initial values are set for each parameter.

$$a_{init} := \max(LAS\_DS) \qquad \sigma_{init} := LAS\_GSD\_DS \qquad \mu_{init} := LAS\_GM\_DS$$

An equation for residual error is defined. The error in this case is the difference between the vector of penetration values and the lognormal curve, defined above, as a function of the vector of diameters.

$$\text{resid}_{LAS\_DS}(a, \sigma, \mu) := LAS\_DS - \overrightarrow{(\text{lognorm}(LAS\_Dp, a, \sigma, \mu))}$$

The following code is a Given block. Given tells MathCAD a set of equations is being defined. The equation given is that the residual error is equal to zero. Then the MathCAD function Minerr is used to optimize the parameters such that the equation is as close to satisfied as possible.

Given

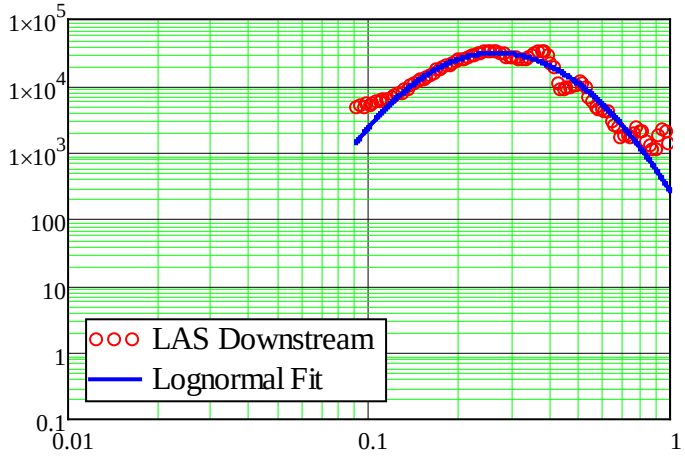
$$0 = \text{resid}_{LAS\_DS}(a_{init}, \sigma_{init}, \mu_{init})$$

$$\begin{pmatrix} a_{LAS\_DS} \\ \sigma_{LAS\_DS} \\ \mu_{LAS\_DS} \end{pmatrix} := \text{Minerr}(a_{init}, \sigma_{init}, \mu_{init}) \qquad \begin{pmatrix} a_{LAS\_DS} \\ \sigma_{LAS\_DS} \\ \mu_{LAS\_DS} \end{pmatrix} = \begin{pmatrix} 3.398\times 10^4 \\ 1.537 \\ 0.265 \end{pmatrix}$$

The lognormal curve equation then uses the optimized parameters to become the curve fit.

$$LNC_{LAS\_DS}(x) := \left(lognorm\left(x, a_{LAS\_DS}, \sigma_{LAS\_DS}, \mu_{LAS\_DS}\right)\right)$$

Below are graphs of the downstream data and the curve fit.



This section creates a lognormal curve fit to the LAS penetration data.

First, the lognormal equation is defined as:

$$\text{lognorm}(x, a, \sigma, \mu) := \frac{a}{\ln(\sigma)} \cdot \exp\left[\frac{-(\ln(x) - \ln(\mu))^2}{2 \cdot \ln(\sigma)^2}\right]$$

Initial values are set for each parameter.

$a_{init} := \max(\text{LAS\_Pen})$ $\sigma_{init} := \text{LAS\_GSD\_Pen}$ $\mu_{init} := \text{LAS\_GM\_Pen}$

An equation for residual error is defined. The error in this case is the difference between the vector of penetration values and the lognormal curve, defined above, as a function of the vector of diameters.

$$\text{resid}(a, \sigma, \mu) := \text{LAS\_Pen} - \overrightarrow{(\text{lognorm}(\text{LAS\_Dp}, a, \sigma, \mu))}$$

The following code is a Given block. Given tells MathCAD a set of equations is being defined. The equation given is that the residual error is equal to zero. Then the MathCAD function Minerr is used to optimize the parameters such that the equation is as close to satisfied as possible.

Given

$$0 = \text{resid}\left(a_{init}, \sigma_{init}, \mu_{init}\right)$$

$$\begin{pmatrix} a \\ \sigma \\ \mu \end{pmatrix} := \text{Minerr}\left(a_{init}, \sigma_{init}, \mu_{init}\right) \qquad \begin{pmatrix} a \\ \sigma \\ \mu \end{pmatrix} = \begin{pmatrix} 0.038 \\ 4.376 \\ 0.211 \end{pmatrix}$$

The lognormal curve equation then uses the optimized parameters to become the curve fit.

$$LNC_{LAS\_Pen}(x) := (lognorm(x, a, \sigma, \mu))$$

The penetration at 0.3 µm can be calculated with this function. Because of the difference in refractive index of PSL spheres, with which the LAS is calibrated, and DOP, the penetration at 0.3 µm is calculated as the penetration at 0.27 µm DOP.

$$LNPen\_LAS_{0.3} := LNC_{LAS\_Pen}(0.27)$$

$$LNPen\_LAS_{0.3} = 0.025085$$

$$FE\_LAS_{0.3} := 1 - LNC_{LAS\_Pen}(0.27)$$

$$FE\_LAS_{0.3} = 97.491527 \cdot \%$$

The most penetrating particle can also be found by finding the maximum penetration and then the corresponding diameter. An initial guess is provided and then the MathCAD function Maximize is employed to find the diameter at which the log curve fit is a maximum.

Initial Guess $MPP\_guess := 0.1$

The MPP and maximum penetration are found to be

$$MPP_{LAS} := Maximize(LNC_{LAS\_Pen}, MPP\_guess) \qquad MPP_{LAS} = 0.211 \ \mu m$$

$$MPP\_Pen_{LAS} := LNC_{LAS\_Pen}(MPP_{LAS}) \qquad MPP\_Pen_{LAS} = 0.025$$

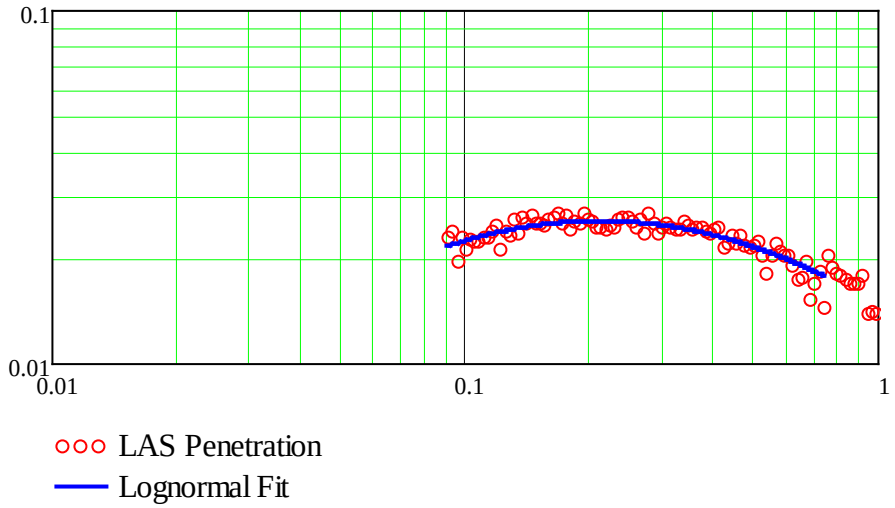
$$MPP\_FE_{LAS} := 1 - LNC_{LAS\_Pen}(MPP_{LAS}) \qquad MPP\_FE_{LAS} = 97.4569 \cdot \%$$

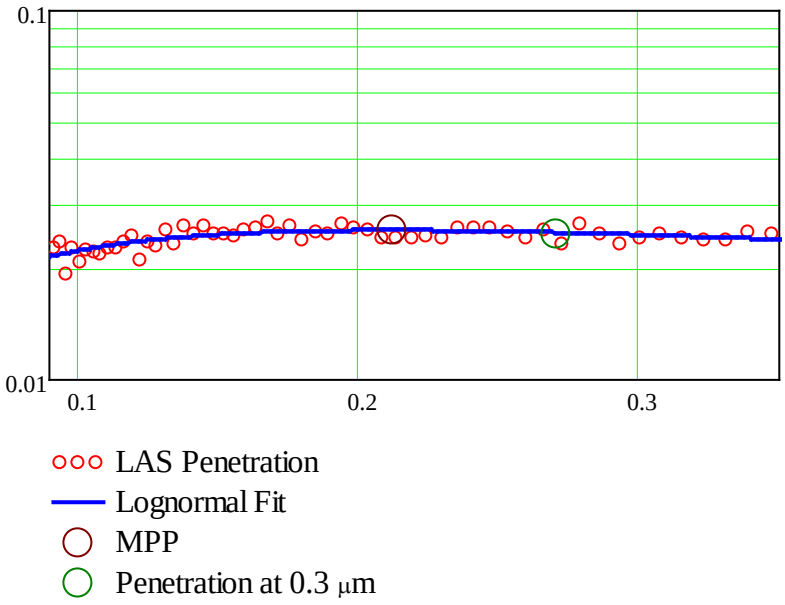
This function extends beyond the bounds of the data that it is fit to. To make prettier graphs, the below section converts the curve fit function into a vector of points in the same range of diameters of the source data.

$$i := 0..650 \qquad y_i := \frac{i + 90}{1000}$$

$$LNC_{LAS\_Pen_i} := LNC_{LAS\_Pen}(y_i)$$

Below are graphs of the penetration vector and the curve fit.





This section creates an exponential curve fit of the LAS penetration data from 0.23 - 0.35 μm.

First, a sub-vector is made of the LAS diameter data for the smaller range of diameters.

$$LAS\_Dp_{sub} := submatrix(LAS\_Dp, 38, 56, 0, 0)$$

$$X := LAS\_Dp_{sub}$$

Next, a sub-vector is made of the LAS penetration data for the smaller range of diameters.

$$LAS\_Pen_{sub} := submatrix(LAS\_Pen, 38, 56, 0, 0)$$

$$Y := LAS\_Pen_{sub}$$

First, the exponential equation is defined as:

$$expc(x, k1, k2) := k1 \cdot \exp(k2 \cdot x)$$

The following equations for the parameters k1 and k2 were found using the least squares method.

$$k1 := \exp\left[\frac{\sum((\ln(Y))) \cdot \sum\left(X^2\right) - \sum(X) \cdot \sum\left[\overrightarrow{(X \cdot \ln(Y))}\right]}{19 \cdot \sum\left(X^2\right) - \left[\sum(X)\right]^2}\right] \qquad k1 = 0.027$$

$$k2 := \frac{19 \cdot \sum\left[\overrightarrow{(X \cdot \ln(Y))}\right] - \sum(X) \cdot \sum(\ln(Y))}{19 \cdot \sum\left(X^2\right) - \left[\sum(X)\right]^2} \qquad k2 = -0.355$$

The exponential curve equation then uses the optimized parameters to become the curve fit.

$$EXPC_{LAS\_Pen}(x) := (expc(x, k1, k2))$$

The penetration at 0.3 µm can be calculated with this function. Because of the difference in refractive index of PSL spheres, with which the LAS is calibrated, and DOP, the penetration at 0.3 µm is calculated as the penetration at 0.27 µm DOP.

$$Pen\_LAS_{0.3} := EXPC_{LAS\_Pen}(0.27) \qquad Pen\_LAS_{0.3} = 0.024977$$

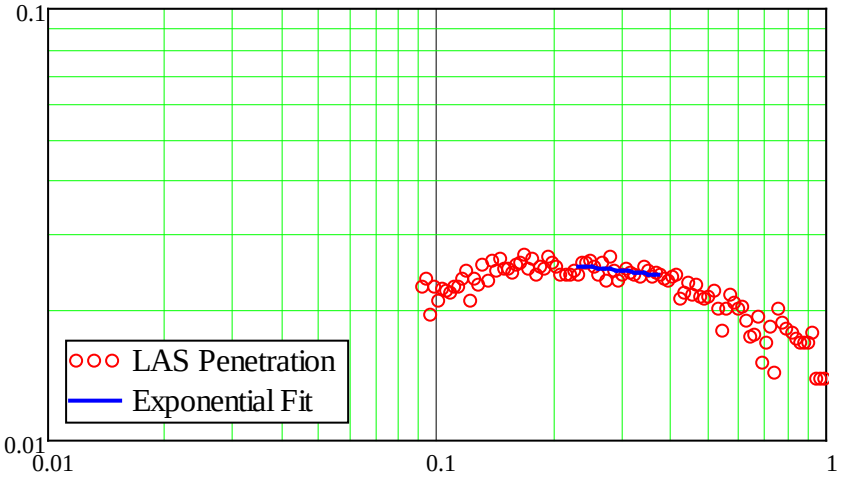
$$FE\_LAS_{0.3} := 1 - EXPC_{LAS\_Pen}(0.27) \qquad FE\_LAS_{0.3} = 97.502331 \cdot \%$$

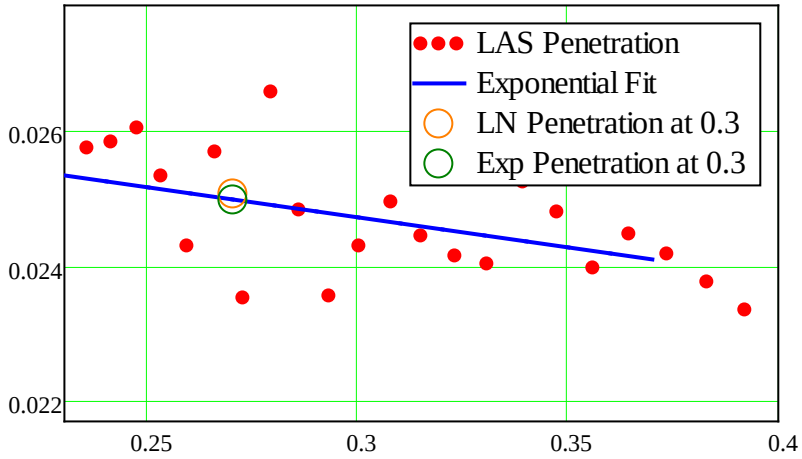
This function extends beyond the bounds of the data that it is fit to. To make prettier graphs, the below section converts the curve fit function into a vector of points in the same range of diameters of the source data.

$$i := 0..14 \qquad z_i := \frac{i + 23}{100}$$

$$EXPC_{LAS\_Pen_i} := EXPC_{LAS\_Pen}(z_i)$$

Below are graphs of the penetration vector and the curve fit.





LAS

At 0.3µ m

Penetration Fraction $Pen\_LAS_{0.3} = 0.025$

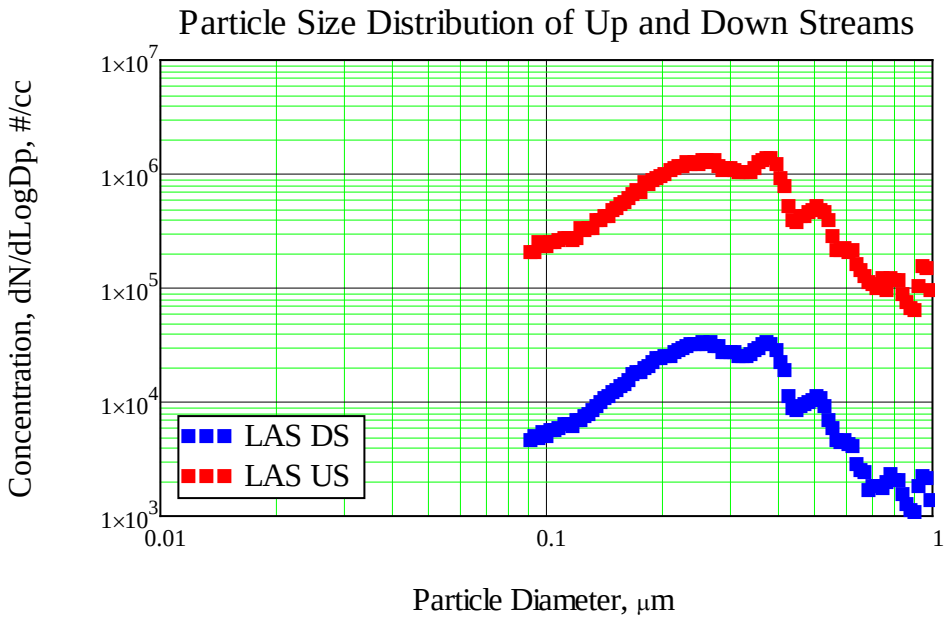
Filtering Efficiency $FE\_LAS_{0.3} = 97.50233 \cdot \%$

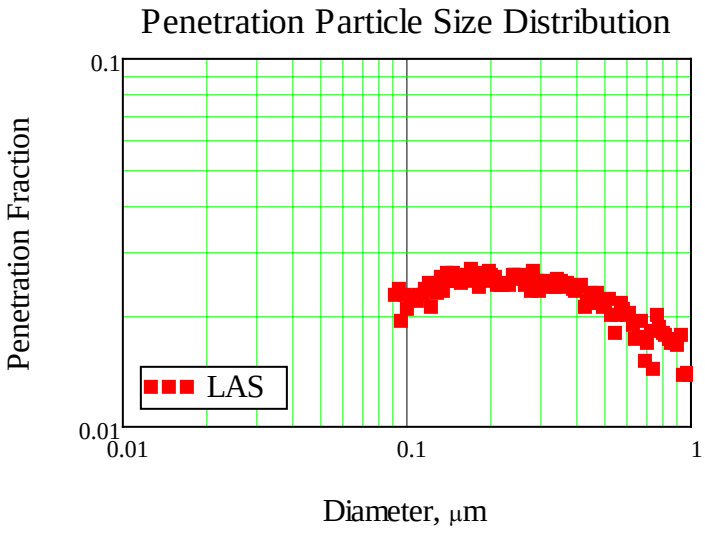
At MPPS

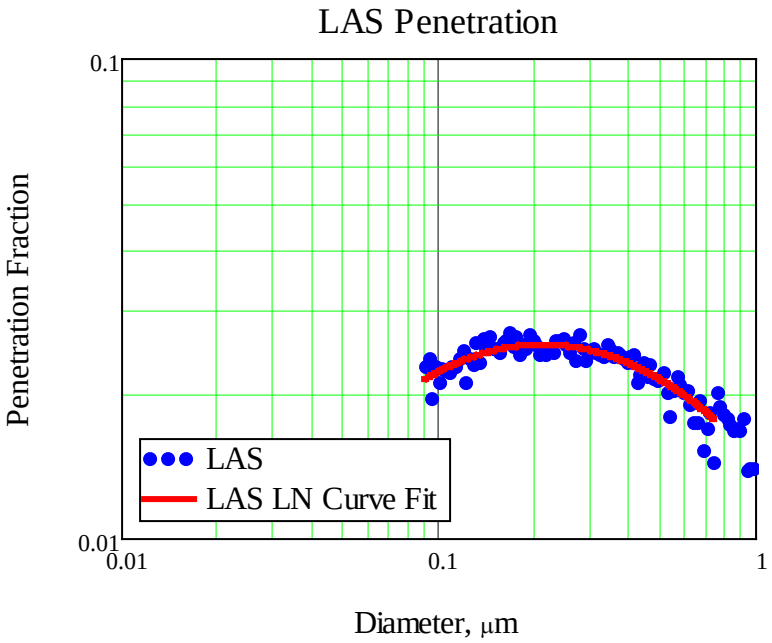
MPPS $MPP_{LAS} = 0.2115 \quad \mu m$

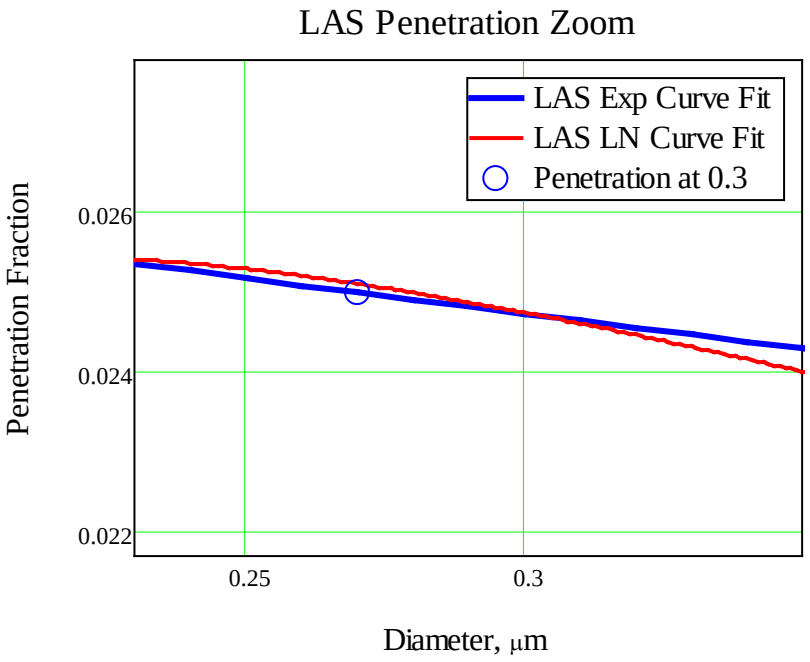
Penetration Fraction $MPP\_Pen_{LAS} = 0.0254$

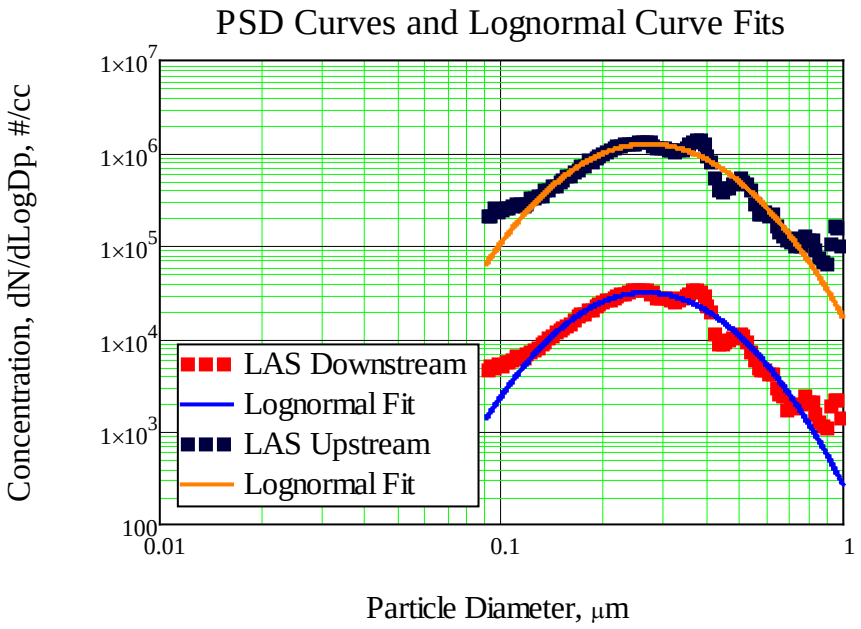
Filtering Efficiency $MPP\_FE_{LAS} = 97.4569 \cdot \%$

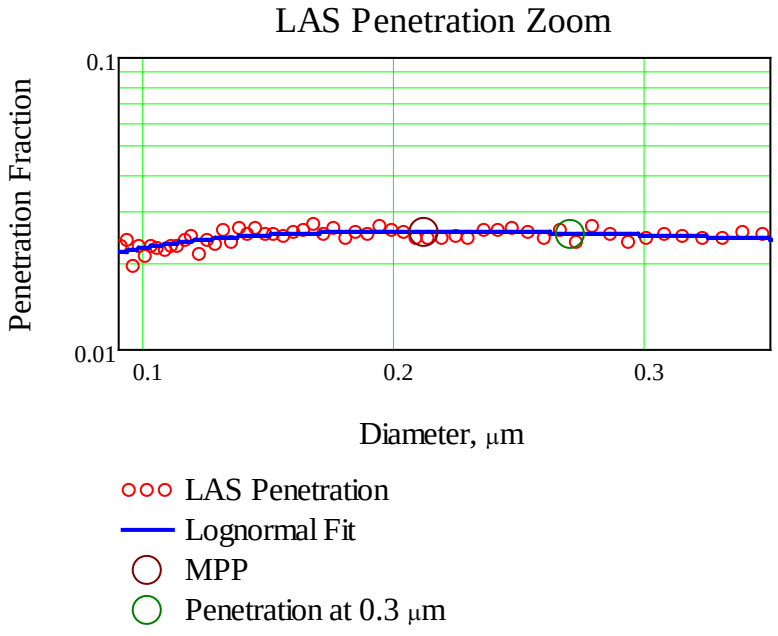

Particle Size Distribution of Up and Down Streams
Concentration, dN/dLogDp, #/cc
1×10^7
1×10^6
1×10^5
1×10^4
1×10^3
LAS DS
LAS US
0.01
0.1
1
Particle Diameter, μm


Penetration Particle Size Distribution
Penetration Fraction
0.1
0.01
LAS
0.01
0.1
1
Diameter, μm


LAS Penetration
0.1
0.01
Penetration Fraction
LAS
LAS LN Curve Fit
0.01
0.1
1
Diameter, μm


LAS Penetration Zoom
LAS Exp Curve Fit
LAS LN Curve Fit
Penetration at 0.3
0.026
0.024
0.022
Penetration Fraction
0.25
0.3
Diameter, μm


PSD Curves and Lognormal Curve Fits
Concentration, dN/dLogDp, #/cc
1×10^7
1×10^6
1×10^5
1×10^4
1×10^3
100
0.01
0.1
1
LAS Downstream
Lognormal Fit
LAS Upstream
Lognormal Fit
Particle Diameter, μm


LAS Penetration Zoom
Penetration Fraction
0.1
0.01
0.1
0.2
0.3
Diameter, μm
LAS Penetration
Lognormal Fit
MPP
Penetration at 0.3 μm

Diluter Characterization Procedure:

First, the sample collection starts for the no diluter measurement. Then, a 20:1 diluter is added, and the sample collection starts for the 20:1 diluter. Next, the concentration is reset with the 20:1 diluter still installed and a new file is created in the LAS. Then, sample collection starts again with the 20:1 diluter. Finally, a 100:1 diluter is added onto the 20:1 diluter, and the sampling collection starts for the 100:1 diluter. The first two sections, TLAS and TLAS2, are where the LAS data files are imported into Mathcad.

TLAS :=

TLAS2 :=

The next section is where the sample numbers are input.

LAS_Only1 := 4 ...sample number for LAS only

Hundred := 16 ...sample number for the 100:1 diluter

Twenty := 15 ...sample number for the 20:1 diluter

LAS_Only2 := 4 ...sample number for LAS only reset

Next, a section is generated to create the matrices of the LAS data.

LAS_Only_1 := submatrix(TLAS, 16, 114, LAS_Only1 + 1, LAS_Only1 + 6)

LAS_100 := submatrix(TLAS2, 16, 114, Hundred + 1, Hundred + 6)

LAS_20 := submatrix(TLAS, 16, 114, Twenty + 1, Twenty + 6)

LAS_Only_2 := submatrix(TLAS2, 16, 114, LAS_Only2 + 1, LAS_Only2 + 6)

LAS_Lower := submatrix(TLAS, 16, 114, 0, 0)

LAS_Upper := submatrix(TLAS, 16, 114, 1, 1)

Diluter characterization data reduction sheet

$$LAS\_100 := \frac{\sum_i LAS\_100^{\langle i \rangle}}{6}$$ ...this equation averages the LAS_100 samples

This section averages the samples:

$i := 0..5$ ...an index is created to average 6 samples

$$LAS\_Only\_1 := \frac{\sum_{i} LAS\_Only\_1^{\langle i \rangle}}{6}$$ ...this equation averages the LAS_Only_1 samples

$$LAS\_20 := \frac{\sum_{i} LAS\_20^{\langle i \rangle}}{6}$$ ...this equation averages the LAS_20 samples

$$LAS\_Only\_2 := \frac{\sum_{i} LAS\_Only\_2^{\langle i \rangle}}{6}$$ ...this equation averages the LAS_Only_2 samples

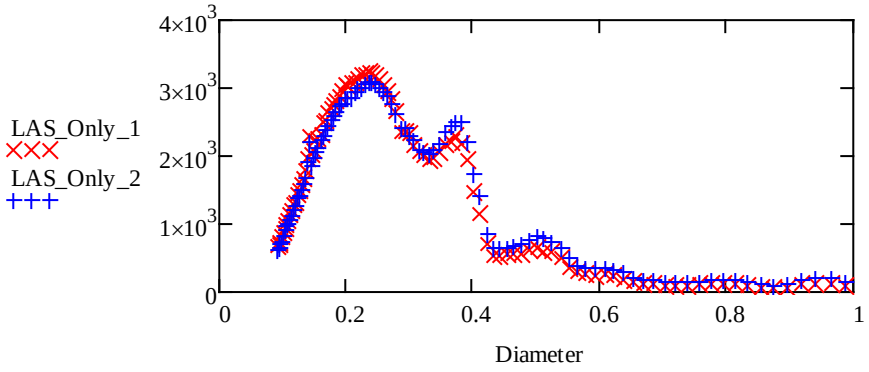
The definition "NormFactor" creates a vector of normalization factors.

$$NormFactor := \frac{1}{\log(LAS\_Upper) - \log(LAS\_Lower)}$$

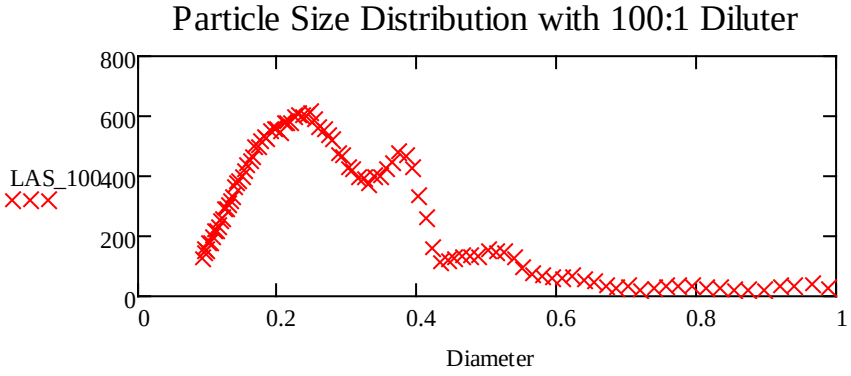
The definition "Diameter" creates a vector of LAS bin diameters and converts the values from nm to µ m.

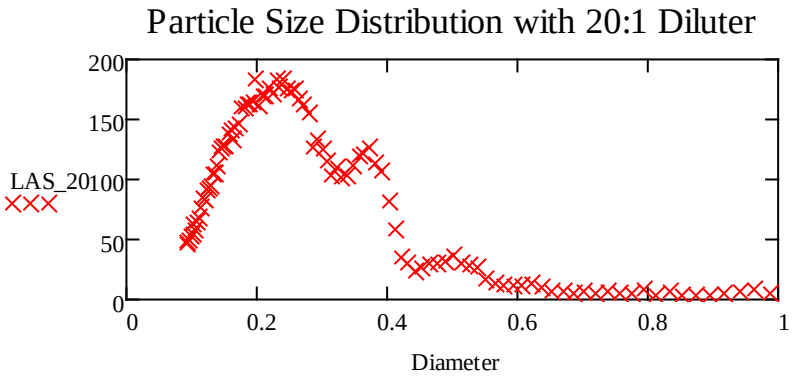
$$Diameter := \frac{LAS\_Upper + LAS\_Lower}{2} \cdot \frac{1}{1000}$$

The plot below shows the PSD curves for LAS_Only_1 and LAS_Only_2. This should indicate that the aerosol challenge did not change much over the test period.



The following plots show the PSD curve with the 100:1 diluter and 20:1 diluter.





Next, the dilution ratio for the 20:1 diluter is defined as:

$$DR\_20 := \frac{LAS\_Only\_1}{LAS\_20}$$

These definitions create vectors for the approximate diameter size range of 0.25-0.35 µm

$$Diameter_{0.3} := submatrix(Diameter, 41, 56, 0, 0)$$

$$DR\_20_{0.3} := submatrix(DR\_20, 41, 56, 0, 0)$$

The following definitions calculate the slope and intercept of the LAS data to generate a linear curve fit.

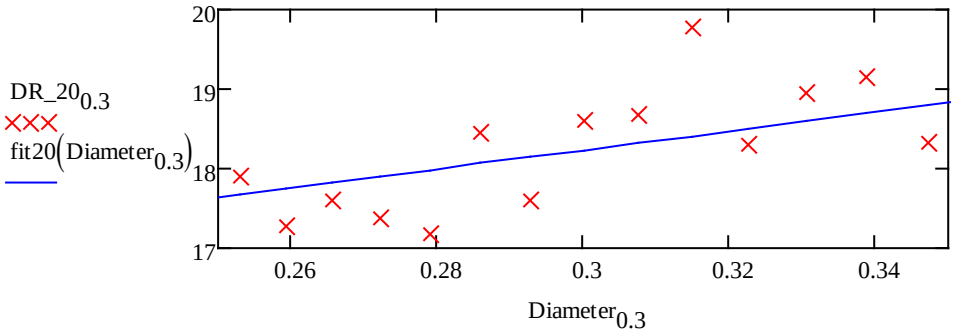
$$m20 := slope\left(Diameter_{0.3}, DR\_20_{0.3}\right) = 11.823$$

$$b20 := intercept\left(Diameter_{0.3}, DR\_20_{0.3}\right) = 14.687$$

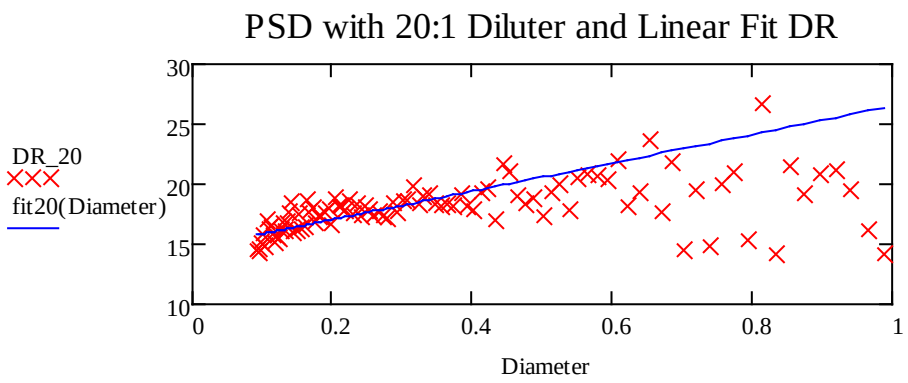
$$fit20(x) := m20 \cdot x + b20$$

$fit20(0.3) = 18.234$ The dilution ratio for the 20:1 diluter.

A plot is created to show the linear curve fit along with the DR_20 data at the 0.25-0.35 µm size range.



This plot displays the curve fit and includes the DR_20 data.



Next, the dilution ratio for the 100:1 diluter is defined as:

$$DR\_100 := \frac{\overrightarrow{(LAS\_Only\_2 \cdot DR\_20)}}{LAS\_100}$$

These definitions create vectors for the approximate diameter size range of 0.25-0.35 µm

$$Diameter_{0.3} := submatrix(Diameter, 41, 56, 0, 0)$$

$$DR\_100_{0.3} := submatrix(DR\_100, 41, 56, 0, 0)$$

$$DR\_20_{0.3} := submatrix(DR\_20, 41, 56, 0, 0)$$

The following definitions calculate the slope and intercept of the LAS data to generate a linear curve fit.

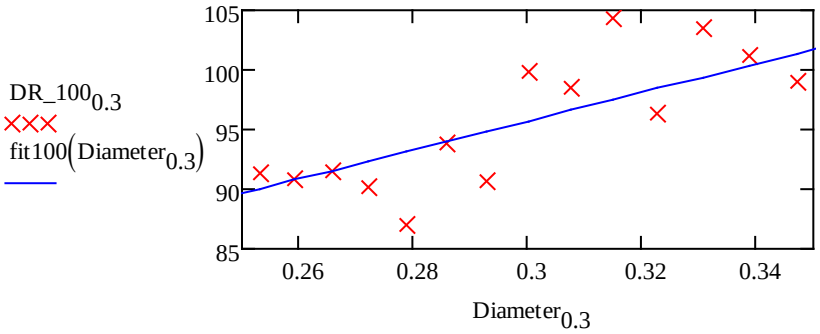
$$m100 := slope\left(Diameter_{0.3}, DR\_100_{0.3}\right) = 120.496$$

$$b100 := intercept\left(Diameter_{0.3}, DR\_100_{0.3}\right) = 59.561$$

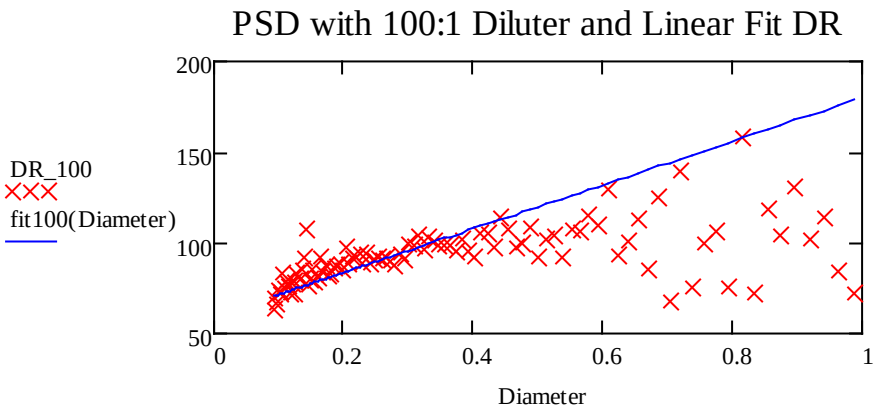
$$fit100(x) := m100 \cdot x + b100$$

$fit100(0.3) = 95.71$ The dilution ratio for the 100:1 diluter.

A plot is created to show the linear curve fit along with the DR_100 data at the 0.25-0.35 µm size range.



This plot displays the curve fit and includes the DR_100 data.


PSD with 100:1 Diluter and Linear Fit DR
DR_100
fit100(Diameter)
200
150
100
50
0
0.2
0.4
0.6
0.8
1
Diameter