Challenging HEPA Filters with Smoke: Current Capabilities and Testing at ICET

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ABSTRACT

The Institute for Clean Energy Technology (ICET) has developed testing infrastructure for evaluating the response of ASME AG-1 size 3 and size 9 FC high efficiency particulate air (HEPA) filters to smoke produced by combustion of fuels. The test stand supports testing with a prefilter upstream of a HEPA filter at flowrates of 25 to 250 cubic feet per minute (CFM). Previous testing consisted of smoke loading at 75 CFM, and future testing will include smoke loading at 125 and 250 CFM. Smoke production is provided by a combustion chamber that allows semi-continuous combustion. Fuel delivery is accomplished via trays and baskets that slide across rails through an updraft airflow. An ignitable propane pilot flame supports ignition of fuel packages in-situ. Smoke aerosol is sampled and conditioned with a rotating disk thermodiluter (RDD) and analyzed with a scanning mobility particle sizer (SMPS), an engine exhaust particle sizer (EEPS), and a quartz crystal microbalance micro-orifice uniform deposit impactor (QCM-MOUDI). A test plan of 70 tests has been completed, and the next test plan is in the final stages of development. A single, primarily plastic, fuel composition was used, but several other mixes will be tested. The test stand allows for filtering efficiency testing as well as preloading of filters with an aerosolized powder. The testing process consists of preconditioning and weighing, performing an initial filtering efficiency test on the HEPA filter, preloading and weighing if applicable, smoke loading to a specified differential pressure, weighing, and performing a final filtering efficiency test on the HEPA. Mass gained by the filters at the specified final differential pressure (dP) is the primary desired result. An estimated mass versus dP curve is created using data from the QCM-MOUDI. An interesting observation of the results is that prefilters, when preloaded, reduce the collective mass gain due to reaching a point of rapid acceleration of dP gain before the HEPA filter.

INTRODUCTION

Previous studies have been performed to evaluate the response of high efficiency particulate air (HEPA) filters to smoke but performance is still not fully characterized. A large set of studies was performed at Lawrence Livermore National Laboratory in the late 1970s and early 1980s [1]. In 2004 Clemson Environmental Technologies Laboratory performed a short study of the response to a fire of a three filter-element confinement ventilation system (CVS) in support of the Mixed Oxide Fuel Fabrication Facility project [2]. Several studies were published in support of the French nuclear industry [3, 4]. These studies sought to characterize smoke of a few representative fuels and the resultant response of HEPA filters using modern instrumentation and techniques. Primary parameters were identified for modeling, but the model only applies to mini-pleat format filters, which are not the primary type of HEPA filter used in the United States.

Mississippi State University (MSU) Institute for Clean Energy Technology (ICET) has completed a study on smoke loading of American Society of Mechanical Engineers Code on Nuclear Air and Gas Treatment (ASME AG-1), axial flow size 3 (12" x 12" x 5 7/8") and size 9 (12" x 12" x 11 1/2") axial flow HEPA filters with separators [6,7]. This work was executed to provide the Surplus Plutonium Disposition (SPD) project at the Savannah River Site (SRS) decision input for CVSs that could experience a fire scenario. These tests were conducted at a flowrate of 75 cubic feet per minute (CFM), which is significantly below the designed rated flowrate of the filters. Reports on this work can be found online [6, 7].

Size 3 and size 9 HEPA filters are rated for 125 and 250 standard cubic feet per minute (SCFM) of flow, respectively, which provide a medium face velocity, the linear velocity of a stream of air or gas at the face of the filter medium as defined in ASME AG-1 Section FC, of approximately five feet per minute (FPM) [5]. The filters tested for the SPD project experienced medium velocities closer to 1.5 FPM and 3 FPM, which is not representative of most filters used within the Department of Energy (DOE) complex. There is a need to characterize these section FC Type A HEPA filters at rated flows to better understand what effect, if any, medium velocity has on filter performance under smoke loading conditions.

DESIGN

A testing rig, the smoke loading test stand (SLTS), was developed for the purpose of generating and challenging filters with smoke. The following subsections describe the design of this test stand.

Combustion Chamber

The function of this subsystem is to accommodate a process which will produce a consistent smoke aerosol to load filter elements. The chamber is designed to direct the resulting smoke into the ducting system. Figure 1 is a schematic of the combustion chamber with several important features labeled.

A minimum footprint was chosen for the required fires, flows, and geometry of the available space. A 30" diameter schedule 10 stainless steel tube was selected for the chamber body. The inside diameter of this component is approximately 29", creating a cross-sectional area of approximately 660 in^2. The height of the chamber is 48". The velocity through the ignition area, while turbulent, is low enough to not extinguish a small fire based on preliminary investigation. Air enters at the bottom of the chamber and passes through a perforated plate designed to distribute airflow.

Fuel is inserted and removed through dedicated inlet and outlet airlocks. These each consist of a small chamber with inner and outer doors to prevent smoke escape. Fuel is supplied in 5.5" x 5.5" trays designed to be pushed with a rod across two rails. Baskets can be used in the trays to contain fuel and allow for airflow underneath the fuel.

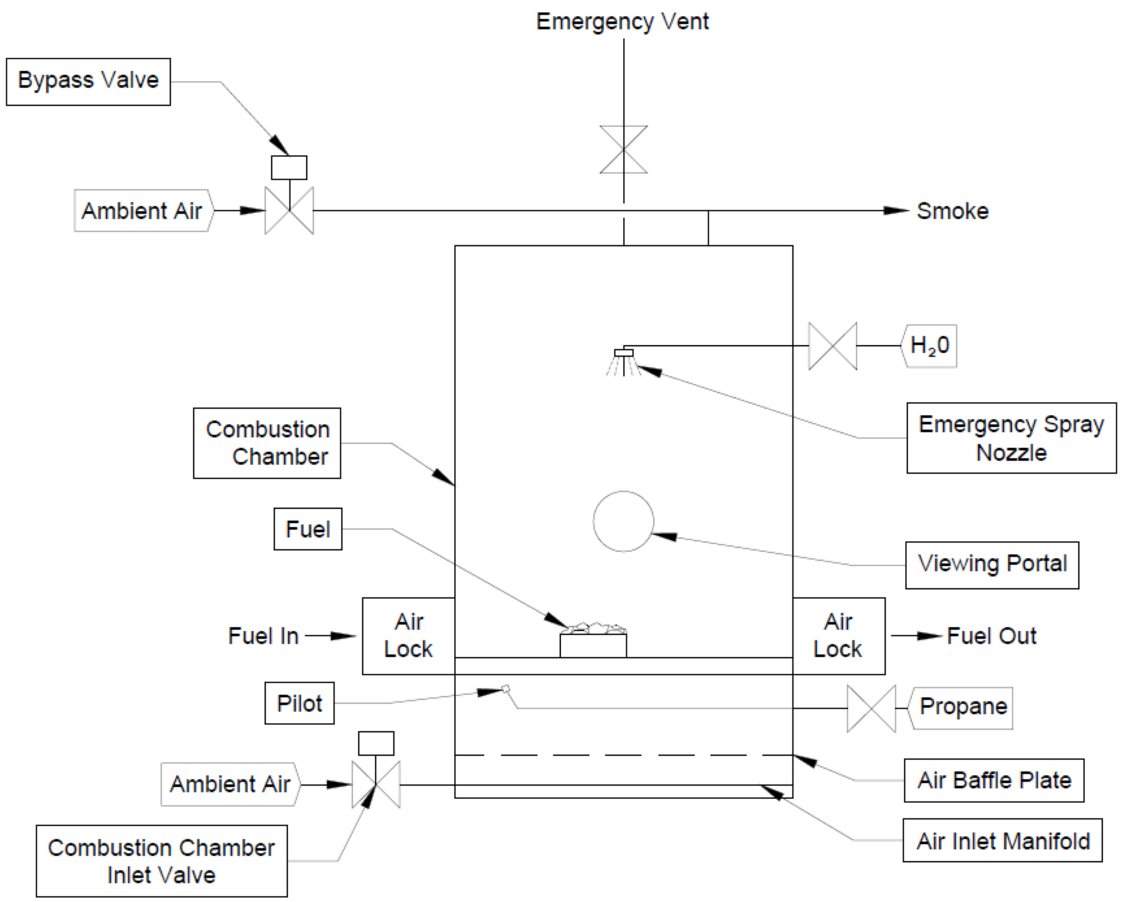

Figure 1. This schematic details the SLTS combustion chamber and key details.

A pilot flame is implemented to ignite the fuel while contained within the combustion chamber. Once fuel is ignited, the pilot flame can be turned off. The fuel then burns naturally under the conditions provided by the apparatus. The pilot flame apparatus consists of a nozzle with an electric igniter mounted to the interior of the chamber. Heat produced by the pilot flame is minimized by the short length of time required to start the primary fuel combustion. The heat and soot from the propane used in the combustion process is negligible.

Combustion can be monitored through 4” threaded glass portals located on the front and back of the combustion chamber.

An exhaust port in the top of the combustion chamber is connected to the overhead duct system with duct. A slide-vent on this port, normally closed, allows evacuation of smoke at the end of each test. This will reduce the available oxygen inside the combustion chamber, thus facilitating extinguishment of burning fuel packages at the end of a test. The system is being modified to allow nitrogen purging of the chamber for faster extinguishment.

A conical spray nozzle is installed as an emergency stop for the combustion process. A hand-operated valve is in place for activation if immediate extinguishment of the flame is required.

Temperature of the smoke plume and the speed at which filters are loaded are the limiting factors of smoke production rate for this system. The mass of premixed fuel loaded was determined through size constraints and potential for smoke and heat production. Fuel package size was based on shakedown testing and restricted so that the fire could not grow to a size where the flowrate through the duct system could not capture all products of combustion or that would produce hot gasses sufficient for the airflow temperature at the filters to rise above 250 °F. The air temperature at the filter housing and downstream sections are restricted to 250 °F due to the limits of the HEPA filters being tested [5]. An estimate assuming no heat losses gave a starting point for burn rate. The allowable heat generation is the heat required to raise the temperature of 75 CFM of air from 70 °F to 250 °F, estimated to be 3 kilowatts (kW). Ignoring any heat loss between combustion and the filter housing and assuming uniform temperature air at the filter housing, the estimated maximum fuel burn rate is 7.6 grams per minute. Shakedown testing began with this value and experimentally determined the optimal amount of fuel to be 150 g. Frequency of the addition of fuel was determined based on conditions at the time of the test to achieve the highest smoke production rate achievable within the goals. A limit of two actively burning packages within the chamber was recommended due to the accelerating pace of filter differential pressure (dP) increase as failure or the maximum allowable dP of the filter approached.

Ducting and Ventilation

The function of this subsystem is to draw smoke and other applicable aerosols through the filter housing at a controlled flowrate and facilitate data collection and aerosol sampling. This subsystem is composed of stainless steel pipe ducting with flanged fittings and connections and threaded connection ports, filter housing, and a blower to induce flow. A variable frequency drive (VFD) controls the blower motor. A flowrate measurement and control loop are used to ensure the required flowrate is achieved. The ducting is sized to ensure that airflow is well-developed at the point of measurement. A simplified airflow path with venturi locations is shown in Figure 2.

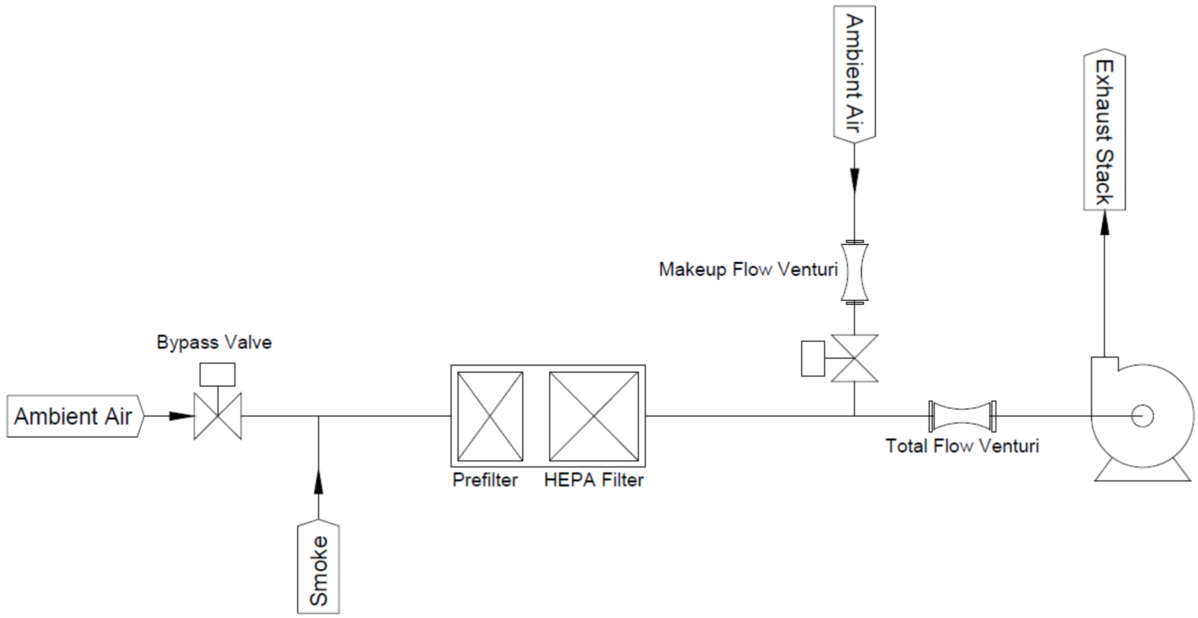

Figure 2. This drawing shows the simplified airflow paths for the SLTS.

The sections of duct between the combustion chamber and the housing and from the housing to the vertical elbow are 4” nominal schedule 10 stainless steel pipe. This size facilitates aerosol sampling while remaining small enough to minimize test stand overall length. The section of pipe at the total flow venturi is 3” nominal schedule 40 pipe, and the section at the makeup air venturi is 2” nominal schedule 40 pipe. These sizes facilitate measuring the airflow utilizing appropriately sized venturis while also minimizing the required length of the test stand. The section of pipe at the combustion chamber bypass is 3” nominal schedule 40 pipe. This size was chosen to facilitate using a 3” adjustable valve to control the airflow through the combustion chamber.

Aerosol sampling requires minimum distances from disturbances upstream and downstream of the sampling probe to facilitate mixing of aerosol. For this design, lengths of 10 duct diameters upstream and 5 duct diameters downstream were used for aerosol sampling locations.

Mass flowrate measurement with venturi meters also requires minimum distances from flow disturbances. The distances are a function of the duct diameter, geometry of flow disturbance, and venturi beta ratio. ASME MFC-3M Table 4-1 specifies these values [8]. This design requires 10 duct diameters upstream and 4 duct diameters downstream of each venturi.

The test stand blower specification requires generation of 250 CFM with a static pressure of 27.8 inches of water column (in. w. c.). The flowrate is set by the requirement to test size 9 HEPA filters at 100% rated flow (250 CFM). The static pressure value was set by a pressure-loss estimate of each section of test stand. Since this flow is on the suction side of the blower, an adjustment was necessary according to the manufacturer’s technical literature. The expected density of the gas is also relevant to this calculation. The requirement of 250 CFM at a static head pressure of 27.8 in. w. c. is a result of these considerations.

A conservative maximum pressure drop value for the filter housing of 20 in. w.c. at design flowrate was specified for this test stand. This is based on the maximum dP of the prefilter and HEPA filter, each being 10 in. w. c.

Flowrate is measured at two metering sections, each with a venturi meter. Both venturis have a temperature limit of 140 °F. One venturi, the total flow venturi, is located just upstream of the blower. It is used to measure the total flowrate of the system. A second venturi, the makeup flow venturi, is located at a secondary intake (makeup flow) that allows an intake of ambient air that can be used to cool the airstream below the allowable limit of the venturi, as necessary. It is also possible for this cooling flow to be near the dewpoint of condensable products present within the hot flow. Water loss due to condensation was monitored, and shakedown testing revealed no detectible change in airflow or excessive drainage at the venturi.

The mass flowrate is calculated at each venturi according to ASME MFC-3M. Conversion to volumetric flowrate (filter flowrate is specified in volumetric units) requires measurement of temperature, static pressure, and relative humidity (RH) at each point of interest. Temperature and RH are measured at the filter housing and at each venturi. Static pressure is measured indirectly. The static pressure at the total flow venturi is taken as standard atmospheric pressure minus the dP of the combustion chamber, prefilter, and HEPA filter. Static pressure at the makeup venturi is taken as standard atmospheric pressure. The flowrate through the filters is calculated as the difference between the two measured flowrates. For airflows that do not require cooling, the valve at the makeup flow leg may be closed so that the total flow is the same as the flowrate through the filter housing.

This system is designed to produce a steady, controlled airflow at 20% and 100% of rated flow for 125 CFM and 250 CFM rated flow filters. These flowrates equate to 25, 50, 125, and 250 CFM.

The ducting is outfitted with access ports for sampling. These ports allow the use of multiple sample nozzles. The sample nozzle diameter was chosen such as to have sample flow velocity as close to duct velocity as reasonably possible. The nozzles are stainless steel for temperature, chemical resistance, and durability considerations. Three nozzles are installed within a 3" stainless steel blind flange located at the upstream sample port for sampling combustion aerosols with multiple instruments. Additionally, there is an aerosol sampling port located on the downstream section of the test stand that uses a single sample probe.

A Flanders filter housing allows for testing of a HEPA filter and a prefilter simultaneously. DPs are measured across each filter element (HEPA filter and prefilter). The prefilter is located upstream of the HEPA filter. The housing is sized to accommodate ASME AG-1 HEPA filter standard sizes 9 and 3 and 12" x 12" x 2" and 12" x 12" x 5 7/8" prefilters.

A schematic with instrumentation locations is shown in Figure 3. Note that temperature transmitters are marked as TT, relative humidity transmitters as RH, differential pressure transmitters as DP, and venturi meters as FO.

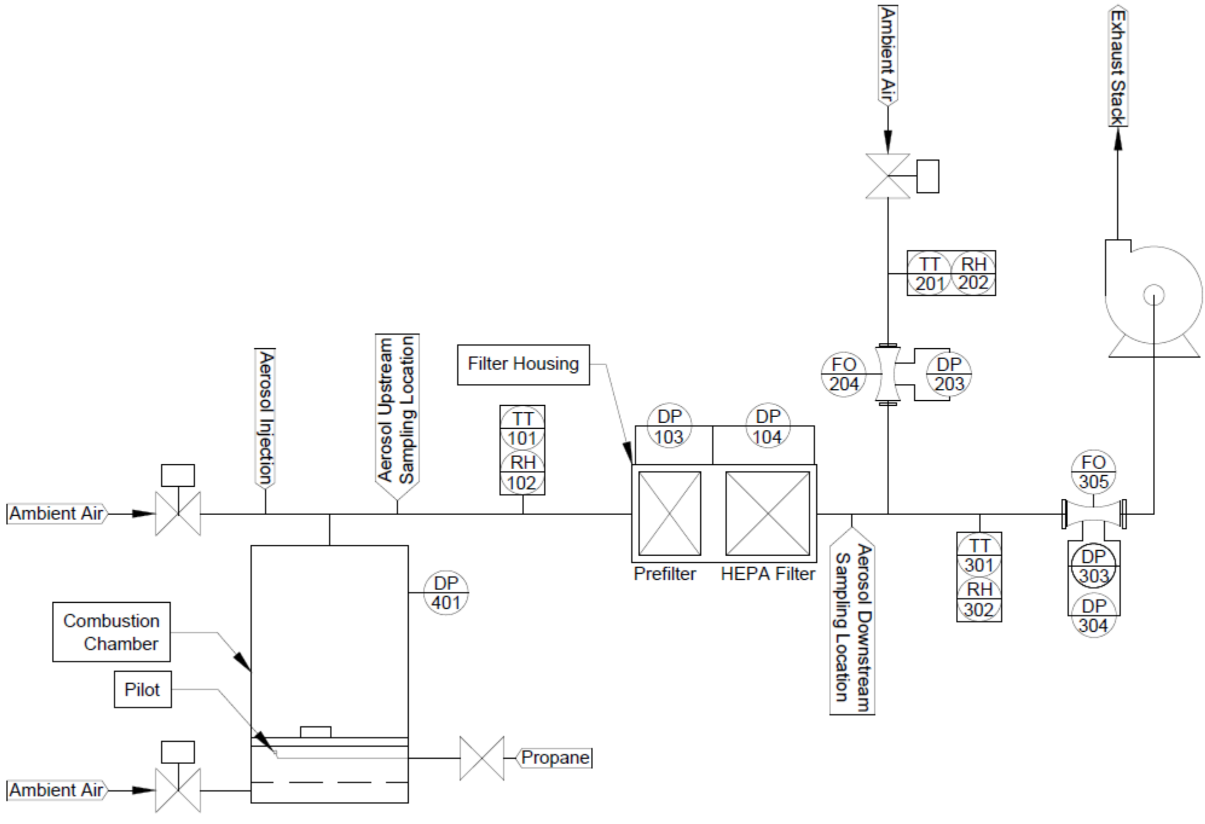

Figure 3. This schematic illustrates the flow paths and instrumentation locations of the SLTS.

Preloading

The function of this subsystem is to produce an aerosolized powder for preloading filters. This subsystem utilizes compressed air, a powder feeder, a venturi vacuum nozzle, and an injection nozzle. The powder aerosol is injected into the ducting system such that the filter elements can be loaded to a specified dP. A schematic of the subsystem for generating preloading aerosol is shown in Figure 4.

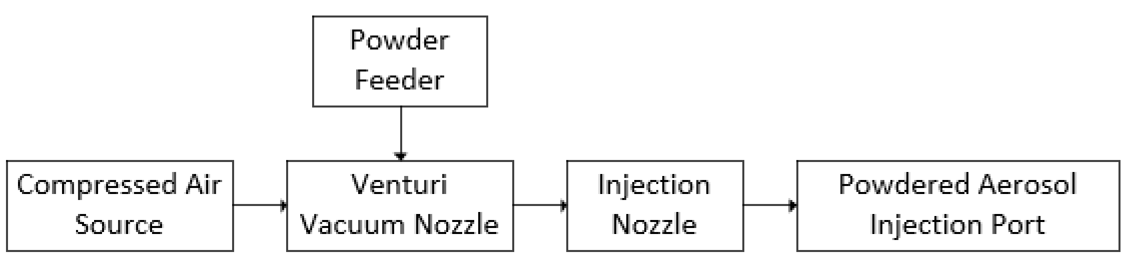

Figure 4. This schematic illustrates the powder aerosol generation system.

The powdered aerosol used for preloading is introduced to the airflow via use of a dual-auger powder feeder and a venturi nozzle. The nozzle utilizes compressed air to create a vacuum that is connected to the output of the powder feeder. The high-velocity meeting point aerosolizes the powder. This aerosol is then introduced into the test stand with an injection nozzle inserted between the bypass valve and the combustion chamber tee. Design of the powder feeder and turbulence for which the duct was sized promote a well-mixed aerosol at the filter housing.

Other Subsystems

Other subsystems of the SLTS include control and electronic data collection. A programmable logic controller (PLC) is used with a VFD to control flowrate via fan speed. The PLC is also used to control the actuated bypass valve, combustion chamber inlet valve, and makeup flow valve. The signals from the instrumentation are measured by both the PLC and a data acquisition system (DAQ). The DAQ is a calibrated unit used to collect data for data reduction. While the PLC calculates flow as part of the control process, the reported flowrate is calculated during data reduction using data recorded by the DAQ.

METHODOLOGY

Filter Testing

The sequence of testing is listed below. Key processes are described below the list.

- Filter preconditioning
- Instrument readiness and operation procedures
- Resistance to airflow
- Filter tare mass determination
- Initial filtering efficiency (FE)
- Preloading filter(s), as applicable
- Mass determination of preloaded filter(s), as applicable
- Smoke loading
- Post test filter mass determination
- Final FE

Preconditioning is performed to ensure the filter elements are at equilibrium with the room conditions. This is done prior to mass determination to ensure an accurate tare mass is measured.

Resistance to airflow consists of measuring the stabilized dP of the filter elements at five different flowrates between 20% and 100% of the test flowrate.

Mass determination is performed by using an appropriately sized balance to measure the mass for each filter element. This is done multiple times throughout testing to allow calculation of mass changes due to the testing process.

FE is performed after tare mass determination and after smoke loading to determine what effect smoke loading has on the filtering capability. This is performed without the prefilter installed. An aerosolized polyalphaolefin is used as the challenge aerosol, and upstream/downstream measurements are made with a Laser Aerosol Spectrometer (LAS). These FE tests are performed at the test flowrate.

Preloading consists of challenging a filter element with aerosolized powder until a target dP is reached. This is done to each filter element individually. Preloading is performed to simulate filter elements that have been in use as opposed to new, clean filters.

Smoke loading consists of a repetitive process of inserting and igniting a fuel package in the combustion chamber. As that fuel package is nearly finished burning, as determined visually as well as via a drop in smoke mass concentration, the next fuel package is inserted and ignited. This is continued until the dP of the HEPA filter reaches the target dP for that test. Smoke loading may be stopped before the HEPA filter target dP is reached due to the prefilter reaching a maximum allowable dP or in case of emergency. The smoke aerosol is sampled continuously for the duration of smoke loading.

Aerosol Characterization

The continuous smoke aerosol sample is distributed to a suite of aerosol measuring and test equipment (M&TE) for characterization. Each instrument used with the SLTS and the primary purpose of each are listed below.

- Scanning Mobility Particle Sizer (SMPS) Spectrometer – A standard for high resolution particle size distribution (PSD) measurement
- Engine Exhaust Particle Sizer (EEPS) – Designed for rapid response measurement of soot
- LAS – Light-scattering methodology, only required for measurement of FE
- Quartz Crystal Microbalance Micro-Orifice Uniform Deposit Impactor (QCM-MOUDI) – Rapid response, direct measurement of aerosol mass.

In addition to measuring aerosol M&TE, there are some M&TE used to condition the sample flows. These are listed below.

- 3302A Diluter – Used to dilute, or decrease particle concentration, sample without significant losses of large aerosol particles
- Rotating Disk Thermodiluter (RDD) – Used to dilute a hot aerosol sample in a way which will decrease particle concentration and reduce condensation of volatiles

The path of the smoke aerosol sample can be seen in Figure 5. An RDD is used to dilute the smoke aerosol with hot, clean air immediately upon exiting the test stand. The sample is then split to feed the SMPS. The remaining sample is diluted with a measured amount of clean air in order to match the volumetric flow requirements of the QCM-MOUDI and EEPS.

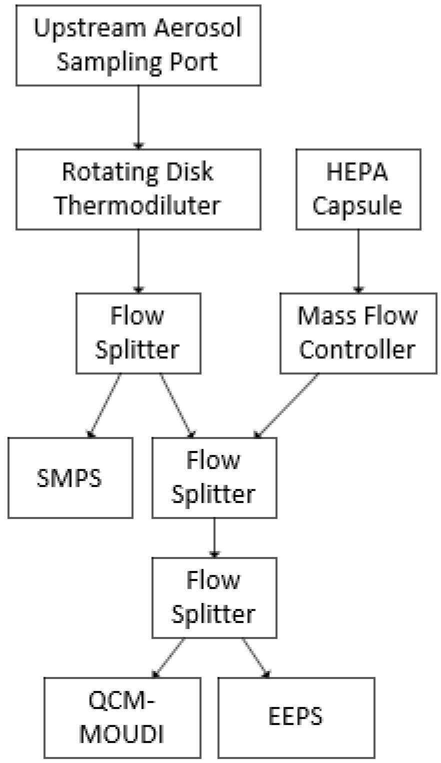

Figure 5. This schematic demonstrates the smoke aerosol sample flow path to each aerosol instrument.

FUTURE TESTING

A test plan for further testing is being developed. The primary objective of this testing is to determine if previous lessons learned are applicable when testing is performed at the rated flowrate of the HEPA filters. Table I contains the test parameters for testing planned to meet this primary objective. The rated flowrate of size 3 and size 9 HEPA filters are 125 CFM and 250 CFM, respectively. Prefilters and HEPA filters for this testing are manufactured by Camfil. Prefilters used are minimum efficiency reporting value (MERV) 8.

Table I. Testing Matrix

Number of Tests	**Prefilter**	**HEPA Filter**	**Preload Target Mass Gain (g)**		**HEPA Filter Target Smoke Loading dP (in. w. c.)**
			Prefilter	**HEPA Filter**	
3	None	Size 3	N/A	None	10
1		Size 9			
3		Size 3		21	10
1		Size 9		173	
3	Yes	Size 3	None	None	10
1		Size 9			
3		Size 3	18.9	21	10
1		Size 9	18.9	173	

The chosen preload mass targets are equivalent to previous testing targets of 0.3 in. w. c. and 0.7 in. w. c. for the prefilter and HEPA filter, respectively. These targets were chosen due to having both size 3 and size 9 data available as well as being on the upper end of prefilter target dP.

The testing outlined in Table I will utilize the standard fuel mixture identified in Table II. This fuel combination was used for the previous testing conducted and is used to assist with correlating results with previously collected data; however, this mixture may not be representative of materials present in other facilities within the DOE complex. Alternative fuel mixtures suggested by the technical working group (TWG) can be found in Tables III, IV, V, and VI. Additional fuel mixtures may be modified or substituted at the suggestion of the TWG. These forms may include solid bulk material, shredded, and powdered materials. Fuel package masses used during the combustion process will be based on previous testing, lessons learned, or input from the TWG. Use of a large-scale laboratory grade aerosol soot generator for filter loading will also be evaluated.

Table II. Standard Fuel Mixture

Percentage (mass)	**Component**	**Physical Forms**
25%	Borated Polyethylene	Solid
25%	Polyvinyl Chloride	Shredded
25%	Polymethyl Methacrylate	Solid
15%	Polyurethane/Chlorosulfonated Polyethylene	Shredded
10%	Cellulosic material	Shredded

Table III. Fuel Mixture Two

Percentage (mass)	**Components**	**Physical Forms**
70%	Wood Based Cellulose	Solid/Shredded/Powder
10%	Polyvinyl Chloride	Solid/Shredded/Powder
10%	Non-wood Cellulose	Solid/Shredded/Powder
10%	Polymethyl Methacrylate	Shredded

Table IV. Fuel Mixture Three

Percentage (mass)	**Components**	**Physical Forms**
35%	Polyurethane/Chlorosulfonated Polyethylene	Solid/Shredded/Powder
35%	Polymethyl Methacrylate	Solid/Shredded/Powder
20%	Wood Based Cellulose	Solid/Shredded/Powder
10%	Non-wood Cellulose	Shredded

Table V. Fuel Mixture Four

Percentage (mass)	Components	Physical Forms
30%	Vulcanized Rubber	Solid/Shredded/Powder
30%	Liquid Fuel (Diesel)	Liquid
30%	Polymethyl Methacrylate	Solid/Shredded/Powder
10%	Mixed Cellulose	Shredded/Powder

Table VI. Fuel Mixture Five

Percentage (mass)	Components	Fuel Forms
40%	Polyethylene	Solid/Shredded/Powder
40%	Polymethyl Methacrylate	Solid/Shredded/Powder
15%	Aluminum Powder	Powder
5%	Mixed Cellulose, Misc. Electrical Components	Shredded

In addition to filter smoke loading testing, testing of flat HEPA media will be performed to support a better understanding of performance based on media area. This will support scaling current and future data to other filter sizes.

Additional testing may be performed to investigate the point of filter failure. This testing would be comprised of smoke loading a HEPA filter until failure or a dP of 20 in. w. c., whichever comes first. This testing can give insight for choosing smoke loading targets in future work with larger filters.

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