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Infrastructure and Test Methods for Evaluation of AG-1 Section FK 2000 cfm Radial Flow Filters.

John A. Wilson, Charles A. Waggoner, Jaime Rickert, and Jay McCown
Institute for Clean Energy Technology, Mississippi State University
205 Research Blvd Starkville MS 39759

ABSTRACT

The Institute for Clean Energy Technology (ICET) at Mississippi State University is under contract to Bechtel National Incorporated for prequalification testing of ASME AG-1 Section FK 2000 cfm radial flow filters. Testing infrastructure is essential for establishing the performance envelope and qualifying these filters in accordance with ASME AG-1. ICET has designed, fabricated, assembled, and characterized multiple research grade test stands to accomplish qualification testing of both the remote and safe change 2000 cfm filters in accordance with ASME AG-1 Section FK requirements. Performance criteria for these test stands and associated infrastructure capable of covering a wide range of parameters utilizes nontraditional designs. Performance capabilities of each test stand have been demonstrated to meet all test parameters. Additionally, procedures for control and conduction of testing have been established in accordance with ASME NQA-1.

INTRODUCTION

High efficiency particulate air (HEPA) filters are used extensively throughout nearly every operating Department of Energy (DOE) site. These filters provide a final barrier to protect the environment, public, and employees from the release of airborne radioactive materials.

Currently, approximately 190 million curies in 54 million gallons of highly radioactive and mixed hazardous waste are stored in underground tanks at the Hanford Tank Waste Treatment and Immobilization Plant (WTP) located in southeastern Washington state. This tank waste that includes solids (sludge), liquids (supernatant), and salt cake (dried salts that will dissolve in water) needs to be processed into a stable waste form and properly confined for long term storage.

Bechtel National Incorporated (BNI) is the current management and operations (M&O) contractor for the DOE Hanford WTP. M&O responsibilities include overseeing design, construction, and commissioning of the WTP. The containment ventilation system for all five of the WTP facilities employs the AG-1 Section FK 2000 cfm filter [1]. ICET conducted testing of a prototype Section FK 2000 cfm radial flow filter under design basis conditions in 2011 that showed rapid, unexpected, and severe failure [2]. Although these filters met all of the requirements of the American Society of Mechanical Engineers (ASME) AG-1 Code, their performance was still not satisfactory for credited applications within the WTP. Filters loaded to four in. w. c. differential pressure suffered rapid pleat collapse when air flow changed from ambient (60 – 80° F and 40 – 60 % RH) conditions to elevated (130° F and 90% RH) conditions.

BNI has been tasked with providing a radial flow 2000 cfm FK filter(s) that can perform in the WTP environments. BNI awarded a contract to The Institute of Clean Energy Technology (ICET) at Mississippi State University to test developmental designs of Section FK radial flow 2000 cfm filters. ICET has developed a range of test stands to accommodate evaluation of Section FK filters to a wide range of operating conditions. The design components and performance capabilities of three test stands that ICET uses for evaluating the radial flow 2000 cfm FK filters are discussed below.

The first test stand discussed is the radial flow large-scale test stand (RLSTS). The RLSTS is used to determine differential pressure (dP) of clean filters and filtering efficiency at rated flow, and to conduct filter loading with a range of challenge aerosols. The second test stand discussed is the vertical test stand (VTS) used for testing flat sheet media and quadrant pack sections of radial flow filters. The third test stand discussed is the resistance to liquid pressure test stand (RLPTS) and is used for testing full-scale filters at elevated differential pressures (up to 225 in. w.c.) using a viscous aqueous solution. The bench scale test stand used for development of the RLPTS is discussed last.

TEST STANDS

Test Facilities

Infrastructure for conducting full scale testing of HEPA filters is located in the ICET high bay. Test filters are stored under Level B conditions until tested. Filters undergo receipt inspection, visual inspection, and tolerance measurements prior to testing. ICET also has the capability to conduct filter autopsying to determine physical parameters such as loading patterns and determination of post testing tensile strength of the media. Additional testing facilities such as a rough handling machine are also available.

ICET's ability to develop highly controlled testing infrastructure is vested in a suite of skilled craftsmen and engineers. Craftsmen provide drafting, machining, fitting, welding, electrical, and construction expertise. Engineering and science capabilities include mechanical system design, control system design, and measurement experts. Operations personnel include engineers and scientists that control the testing process, oversee data collection, data reduction and reporting of results.

Radial Flow Large Scale Test Stand

The radial flow large scale test stand (RLSTS) has been designed to simplify reconfiguration for testing remote or safe change filters. Separate housings are required to facilitate testing the two versions of filters in the proper orientation; safe change filters in the horizontal orientation and remote change filters in the vertical orientation.

The RLSTS has also been designed to test filters over a wide range of volumetric flow rates, temperatures, and relative humidity. Testing capabilities also include the ability to challenge filters with a variety of aerosols to determine performance with respect to loading capacity and filtering efficiency. The RLSTS consists of the following components:

- Interchangeable safe change and remote change filter housings
- Insulated ducts and piping
- Numerous ports for aerosol injection and aerosol sample measurements
- Ports for visual observation of the filter
- Variable speed drives to provide air flow control
- Large fan for induced draft flow at flow rates from 400 cfm to 5000 cfm
- Small fan for induced draft flow at low flow rates from 0 cfm to 400 cfm
- Boiler and injection port for steam
- Air heaters for raising temperature
- Inlet air filters
- Removable recirculation line for elevated conditions
- Flow, differential pressure, and temperature sensors
- Data acquisition system for recording testing conditions
- Camera system for taking pictures and videos of the inlet filter pleats

Figure 1 provides an illustration of the RLSTS. The filter housing is on the left and approximately one half of the test stand is located inside the ICET high bay. The fan, venturi, and inlet ducting is located outside the building.

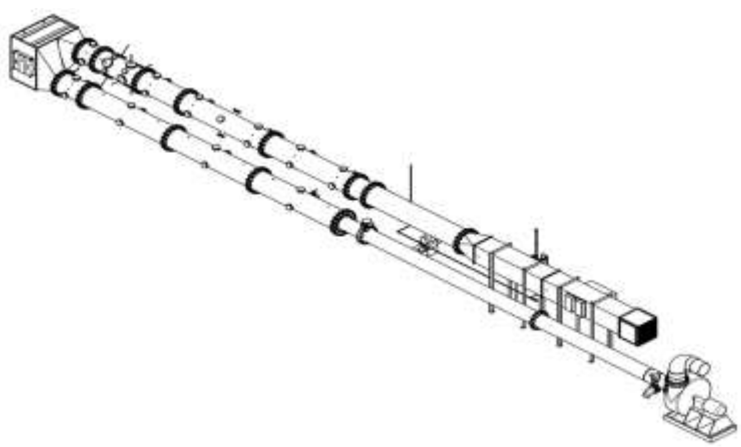

Figure 1. Overview of the RLSTS.

Figure 2 provides photographs of the RLSTS ducting inside and outside of the high bay. Photo A shows ductwork inside the building. The upper run of ducting is the upstream leg and the lower run is downstream ducting leading to the fan. Ductwork has been insulated to assist in testing at elevated temperatures and relative humidity. Up and downstream sections are fitted with ports to support injection of challenge aerosols and sampling. Ports are strategically located to provide access for sensors.

Figure 2. A.) Photo of RLSTS inside of the high bay laboratory. B.) Photo of RLSTS outside of the high bay laboratory.

Figure 3 provides a drawing of the remote and safe change housings. Each is designed for a single radial flow filter.

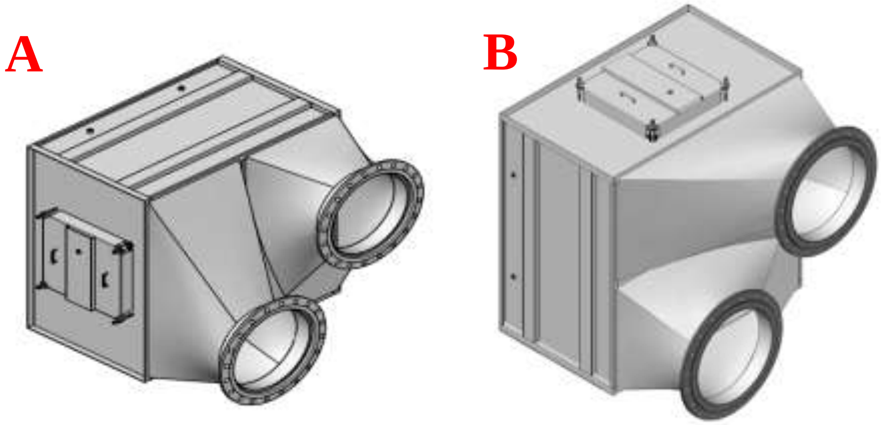

Figure 3. Drawings of radial flow filter test housings.
A.) Safe change. B.) Remote change.

Notice the uniform location of up and downstream flanges on the remote and safe change housings for attaching to ductwork. The housings are attached to mobile platforms that have been designed to match the height of the test stand ducts. One housing can be disconnected from ducting, rolled away and the other can be rolled into place and installed. Figure 4 provides a photograph of the safe change filter housing installed on up and downstream ductwork. The housing is built to equivalent dimensions of units used in the Hanford WTP.

Figure 4. Photo of the safe change filter housing on the RLSTS.

The 2000 cfm filters are tested over a wide range of media velocities. Volumetric flow rates ranging from 100 to 2000 cfm require different flow measurement devices and fans. The separate fans require individual variable frequency drives (VFD) to achieve control. Figure 5 provides photos of the VFDs for the two fans.

Figure 5. Photo of the variable speed drives for the fans on the RLSTS. A.) Large fan. B.) Small fan.

Two Spencer fans are on the test stand to cover a wide range of flow rates. The large fan is used for any flow rates from 400 cfm to 5000 cfm and is capable being used for loading filters to 50 in. w. c. differential pressure at 2000 cfm. The smaller Spencer fan capable of producing flow rates up to 400 cfm is connected to the RLSTS by a 3 inch duct. Ducting going to each fan is fitted with a butterfly valve for closing off the duct when the other fan is in use or when the test stand is being leak checked. Figure 6 provides photographs of the fans used on the RLSTS.

Figure 6. A.) RLSTS large fan. B.) RLSTS small fan.

A short spool piece can be removed from the upstream ductwork to allow use of house air for testing for testing at ambient conditions. Ambient conditions are defined as 40-60% relative humidity (RH) and 60-80° F. The spool piece section of upstream ducting shown in Figure 7 can be removed when outdoor temperature and humidity are not within the conditions defined as ambient.

Figure 7. Removable spool piece.

Outside air is used for testing at elevated temperatures and humidity. The RLSTS is equipped with an inlet filter housing that uses a 24" x 24" HEPA filter and a 24" x 24" ASHRAE filter.

A set of resistance heaters are located downstream of the inlet filters and serve as the primary temperature control units, particularly when testing at low relative humidities. Figure 8 provides a photograph of the inlet filter housing and the air heaters used on the RLSTS. The air heaters downstream of the inlet filters are capable of delivering up to 160 kW of heat to air coming into the test stand.

Figure 8. A.) Inlet filters housing. B.) Air heaters.

A removable recirculation loop is installed on the test stand to increase capabilities of maintaining and stabilizing elevated conditions of high temperature and high humidity. Flexible ducting is used for the recirculation ducting to allow for quick removal and installation. Figure 9 provides a photograph of the removable recirculation loop.

Figure 9. Removable recirculation loop.

To reduce cool down time of the test stand for sampling, the recirculation loop can be removed when outdoor conditions are within testing prescribed ambient conditions.

ICET utilizes a natural gas fired boiler capable of producing up to 750 lbs/hour of steam to achieve test conditions as high as 170 ^{0}F and 80% RH. Steamlines are in place for injection into both of ICET's large scale test stands simultaneously. Steam is injected into upstream ductwork, downstream of the air heaters. Figure 10 provides a photograph of the boiler and steam injection system on the RLSTS used for testing at elevated RH and temperature.

Figure 10. A.) Boiler. B.) Steam injection valve on the RLSTS.

The RLSTS has multiple ports for injecting aerosols. Photo A in Figure 11 shows the DOP aerosol injection port with a DOP aerosol generator. Photo B shows the dry powder aerosol generator and aerosol injection port. Air used for atomization of the dry powders can cause condensation when injected into hot, humid airflows in the test stand. The powder feeder is equipped with a preheater for the compressed air to ensure condensation does not occur when test aerosol is injected at elevated conditions. For generation of soot aerosols acetylene burners utilize four ports on both sides of the test stand duct.

Figure 11. A.) DOP aerosol injection port. B.) Powder aerosol injection port on the RLSTS.

Venturis, pressure sensors, and humidity and temperature probes are used at several locations on the test stand to monitor conditions. Venturis are located in the downstream section of the test duct to measure flow rates generated by the test stand fans. Humidity and temperature probes are used in three locations on the RLSTS. One unit is used upstream of the filter, another downstream of the filter and the last just upstream of the venturi. Pressure sensors are used on the RLSTS in several locations for multiple purposes. There are dP gauges on both the venturis for flow measurements and on the housing to measure pressure across the filter. A static pressure sensor on the downstream section measures the downstream pressure in the duct. Measurements from all the sensors are used to determine and control the flow rate according to pressure, temperature and relative humidity. Flow rate is calculated in accordance with ASME standard MFC-3M 2004 [3]. Figure 12 shows a relative humidity and temperature probe, a dP gauge on one of the venturis, and a venturi outside of the test stand.

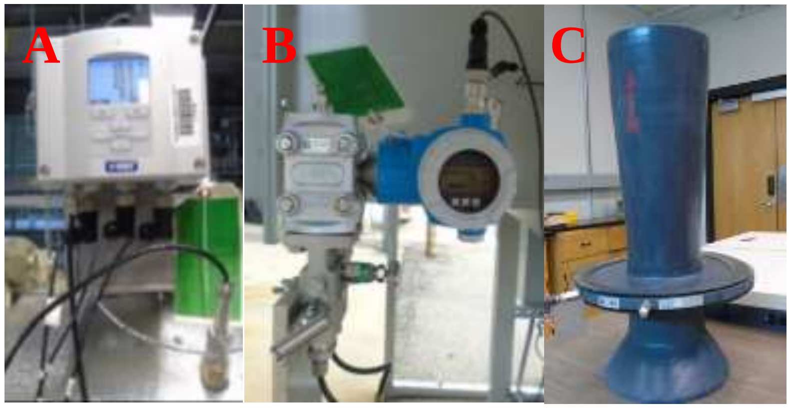

Figure 12. A.) Relative humidity and temperature probe. B.) Differential pressure sensor. C.) Venturi.

The RLSTS has a section designed for inserting a Pilat impactor and up to eight in-duct coupon samplers containing the same filtering media used in the large scale test filter. The samplers are used for loading flat sheet medium samples with a diameter of 2.37 in. (60 mm). The in-duct coupon samplers are attached to different flanges so individual samplers can be replaced during testing. A blind can be installed on the port if a new sampler is not installed. The RLSTS control is also designed to control and monitor the flow rates through the induct coupon samplers. Sampling rates are adjusted to correspond to the media velocity of the full scale filter. Direct comparison of dP and mass loading data from in-duct coupon samples with that of the full scale filter reveals insight into effects of filter pack geometry and pleat configuration on loading. Figure 13 shows a photo of the upstream section in photo A, where in-duct coupon samples are used and in photo B the samplers attached to blinds. The flat coupon section and data collected for this test section is further discussed in Matthew Wong's paper "Design and Performance of an In-Place Flat Media Particle Loading Testing System"[4].

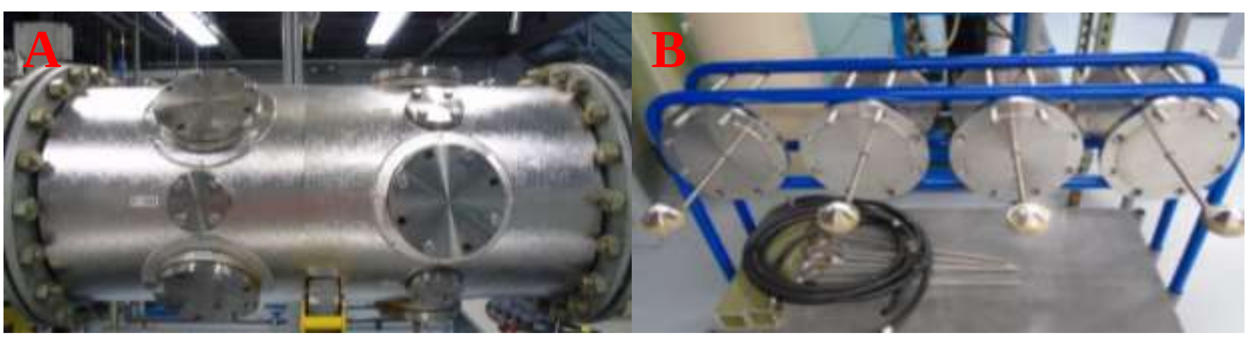

Figure 13. A.) In-duct coupon and Pilat Impactor sampling section of the RLSTS. B.) In-duct coupon samplers.

The user enters inputs on the touch screen display on the control computer as shown in Photo A of Figure 14. All the measured conditions on the test stand are displayed on the test stand control computer touch screen. The large fan can be run in manual or automatic mode. In automatic mode the flow rate set point is entered and the programmable logic controller (PLC) controls fan speed to maintain the target flow rate. The user can set fan speed manually without entering a set point. The small fan is run in manual mode and the user must adjust the fan speed to maintain the required flow rate. Input of the full size filter media area is required to maintain media velocity through in-duct coupon samplers equivalent to that through the full size filter. The steam and electric air heaters are controlled on a percent of total capability basis.

The ICET RLSTS control system continuously logs data from all test stand sensors. Control of volumetric flow rates involves integrating data from venturi flow measurements and temperature and relative humidity sensors to maintain control to acfm set points. However, critical data describing filter performance parameters are also logged using a calibrated Keysight data acquisition system (DAQ). These data meet the requirements of ICET's NQA-1 quality assurance program (Q) and are used for generating loading curves and other reduced data sets included in reports. This accomplished two objectives; Redundant sets of data are stored during testing and use of the Keysight DAQ prevents having to implement ICET-QA-036, *Software Control*. This reduces the time required to update the system when minor changes are made to the graphical user interface on the control system display. The DAQ saves all data from the test stand instruments onto a flash drive that is later transferred to the data reduction computer. The DAQ scales a voltage output from the test stand instruments to read the appropriate units for each instrument. Figure 14 shows the test stand control system and the DAQ system.

Figure 14. A.) Test stand control system. B.) Data Acquisition System.

ICET makes extensive use of cameras to observe filters during testing. Figure 15 provides a photograph of the camera system used to take images of a filter while it is installed into the RLSTS.

Figure 15. Camera system used inside of the RLSTS.

Particle size distributions and particle number densities in challenge aerosols must be measured to determine filtering efficiency and to interpret loading curves. ICET uses a suite of aerosol measurement instruments in conjunction with data logged from test stand sensors to document filter performance. A TSI Scanning Mobility Particle Sizer (SMPS), a TSI Laser Aerosol Spectrometer (LAS), and a TSI Aerosol Particle Sizer (APS) comprise the suite of instruments used. The SMPS and LAS are primarily used to characterize the particle size distribution for sizes less than one micrometer and for determining filtering efficiency.

The LAS is the accepted unit for measuring filtering efficiency [1]. It requires controlling particle concentrations below 3000 particles per second [5]. Upstream and downstream measurements have particle concentrations differing by almost four orders of magnitude, making the use of a single instrument for both measurements difficult. Figure 16 shows the LAS with two diluters necessary for measuring the high concentration of upstream particles. The APS excels in measuring particle sizes larger than one micrometer and is used on the upstream to measure particle size for filter loading studies. The SMPS and LAS sampling system and the APS can be seen in Figure 16.

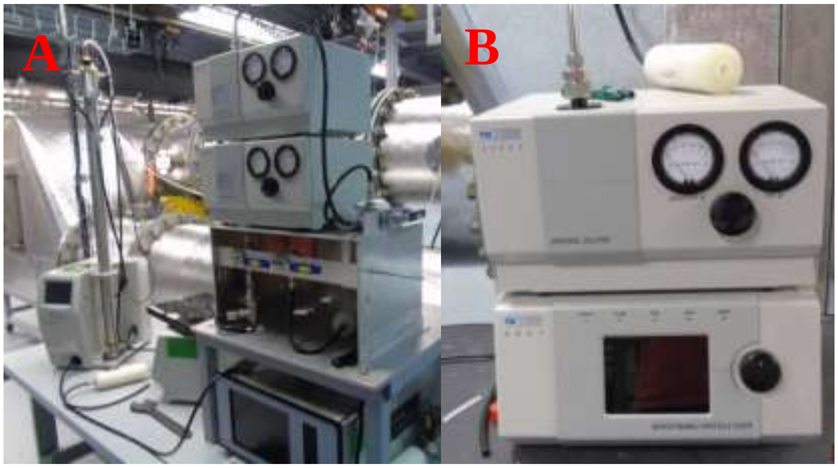

Figure 16. A.) SMPS and LAS sampling system. B.) APS.

Vertical Test Stand

A vertical test stand (VTS) has been designed, fabricated, and assembled to accommodate the testing of flat sheet media samples and quadrant pack sections of full scale filters for resistance to air flow, loading, and filtering efficiency. The test stand was designed with interchangeable test sections to accommodate flat sheet media samples or representative sections of full scale filters. The flat sheet test section is designed to use 180 mm (7.1 mm) circles of flat sheet media, effective area of 0.017 m^2 (0.183 ft^2). The VTS is equipped with a venturi, mass flow meter, dP gauges, RH and T probes and aerosol measurement instrumentation. All sensors can be calibrated to meet Q requirements [6]. The flat sheet and quadrant pack sections of the test stand can be seen in Figure 17.

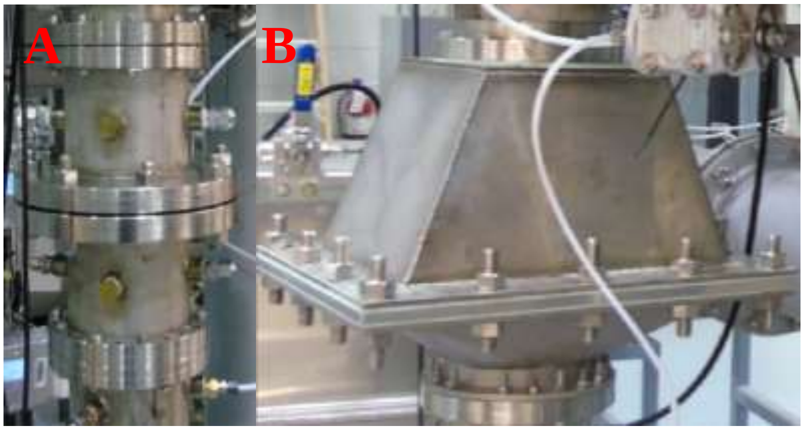

Figure 17. A.) Flat sheet test section. B.) Quadrant pack test section. [6]

Resistance to Liquid Pressure Test Stand

The ICET resistance to liquid pressure test stand (RLPTS) has been designed to evaluate advanced filter designs. The current housing is capable of testing Section FK 2000 cfm radial flow filters. The RLPTS has flow loops that allow testing a filter with air for generating dP vs. flow curves or with DOP to determine filtering efficiency. The configuration can be easily converted to use a viscous aqueous fluid (polyethylene glycol and water) to test dPs up to 225 in. w.c. The overall ensemble of RLPTS components also includes a type 2 water system for gently washing the viscous fluid from the filter. The test stand is reconfigured with the air loop after the resistance to pressure test to collect final filtering efficiency data. A drawing of the RLPTS in the liquid loop configuration and a photo of the RLPTS in the air loop configuration can be seen in Figure 18 [7].

The resistance to liquid pressure test stand consists of:

- A filter housing that serves as a test section
- Ducts and piping
- Variable flow pump and motor for liquid flows
- Variable flow fan and motor for gas flows

- Variable speed drives for flow control
- Ports for aerosol injection and aerosol measurements
- Flow and differential pressure meters and temperature sensors
- A test fluid reservoir
- Viewing ports for observation of the filter and the liquid flow
- Camera system for taking pictures and videos of the upstream and downstream sides of filter pleats

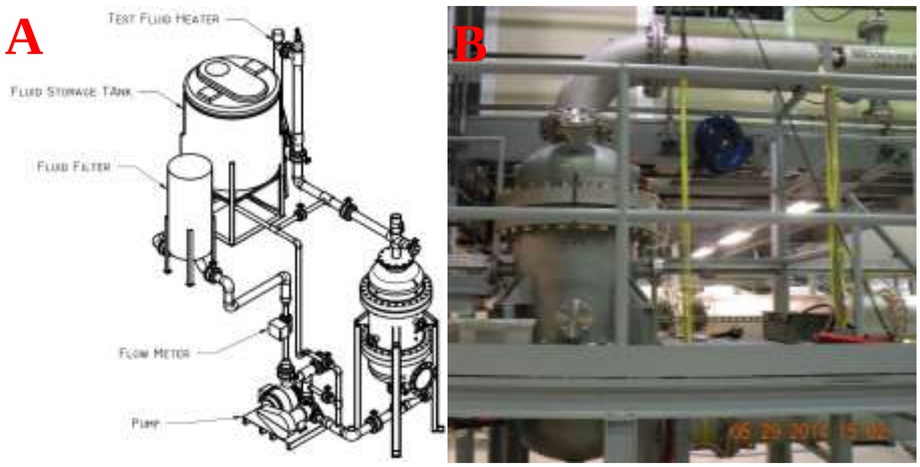

Figure 18. A.) Drawing of RLPTS liquid loop [7]. B.) Photo of air loop of the RLPTS.

Bench Scale Test Stand

A small bench scale test stand (BSTS) was developed to collect flat sheet data using air, water, and the viscous water/polyethylene glycol test fluid. The test cell for flat sheet samples is housed in a large oven to include the ability to determine the effects of exposure to test liquid and elevated temperatures on different types of media.

The BSTS has four primary components: housing, differential pressure sensors, gear pump, and air supply. The BSTS uses a flat 6.1 inch (155 mm) diameter circular coupon of filter media mounted in the filter housing. The BSTS is essentially a 1:1200 scale of the RLPTS. Transducers measure the differential pressure across the filter and the pressure within the housing relative to atmospheric pressure. All sensors can be Q calibrated to allow collection of either CM (commercial grade) or Q data. The filter medium can be evaluated for resistance to air flow using clean and dry compressed air. Equivalent flow vs. dP data are collected for water and aqueous solutions of polyethylene glycol (PEG) using a gear pump. Water flow rates of 40 ml/minute to 4 L/min are achievable. PEG solutions can be pumped at rates of 40 ml/min to 400 ml/minute at viscosities needed to test filter media to 225 in. w. c. An Anton-Parr viscometer is used to determine viscosities of test fluids used in either the RLPTS or the BSTS [7].

Data collected on the BSTS was used to size pumps, size plumbing, identify engineering challenges associated with RLPTS testing, and for the development of methods and procedures for testing full scale HEPA filters [7]. The BSTS can be seen in Figure 19.

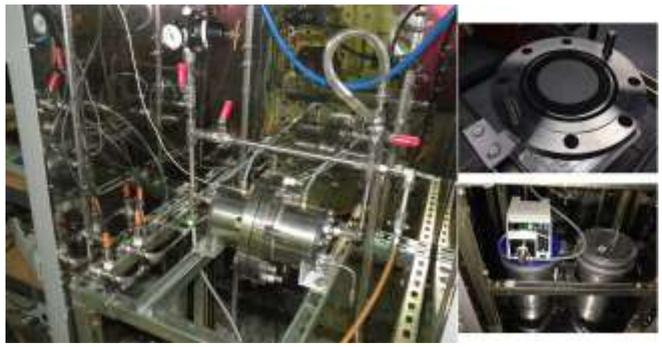

Figure 19. Photograph of BSTS, filter media coupon location, and gear pump [7].

Rough Handling Test Apparatus

ICET has the capability of conducting the rough handling qualification test as required by AG-1 section FK-5130 [1]. The rough handling machine can test the structural integrity of filters up to 225 lbs. at 200 oscillations per minute with 0.75 inch amplitudes. The rough handling machine is housed in a small sound insulated building outside the highbay in order to avoid exposure to high noise levels and to eliminate a source of vibration. The controls of the machine are located next to the door on the exterior of the building. A photograph of the rough handling machine and the building can be seen in Figure 20.

Figure 20. Photograph of rough handling machine, building, and control panel.

MEASURING AND TEST EQUIPMENT

ICET has an extensive set of instrumentation equipment on hand for measuring HEPA filter test stand parameters such as volumetric flow, test fluid velocity, air relative humidity, temperature, and differential pressure. Isokinetic in-duct samplers, inertial impactors, and EPA stack sampling equipment are also used for gravimetric determination of particulate matter (PM) in gas streams. Additionally, a basic set of particle counting instruments is available to evaluate both PM concentration and particle size distribution (PSD) of aerosols used to challenge filters for loading studies or filtering efficiency determinations. Table 1 provides a generalized listing of the types of measuring and test equipment (M&TE) available.

Table 1. Categories of ICET M&TE available for use on test stands used to evaluate radial flow filters.

Instrument Type	**Instrument Scale and Accuracy**	**Units**	**Process Measurement Accuracy**
Temperature (Upstream and Downstream Instruments)	-40 to 256 ± 0.72°F	Degrees Fahrenheit	171 ± 0.72°F
Relative Humility (Upstream and Downstream Instruments)	0 to 95 ± 2%	% Relative Humidity	50 ± 2%
Air Flow (Venturi type instrument used to measure air flow through the Test HEPA Filter)	0 to 5,000 ± 5% ACFM	ACFM	100 to 3,000 ± 5% ACFM
Air Flow (Mass Flow Meter for Isokinetic Sampling)	0 to 0.5 ± (0.4% of span + 1.6% of reading)	SCFM	0.3 ± 0.004 SCFM
Differential Pressure (Test HEPA Filter)	0 to 60 ± 0.15 inches w.c.	Inches w. c.	0 to 20 ± 0.15 inches w.c.
Differential Pressure (Vertical Flat Sheet Test Stand)	0 to 10 ± 0.025 inches w.c.	Inches w. c.	0 to 5 ± 0.026 inches w.c.
Differential Pressure (**In-duct coupon Flat Sheet Sampling)**	0 to 60 ± 0.15 inches w.c.	Inches w. c.	0 to 20 ± 0.15 inches w.c.
Weight (Full Scale HEPA Filter)	150 kilograms with 1 gram resolution	Kilograms	70 kilograms with 1 gram resolution
Weight (Vertical Flat Sheet Samples)	2,100 ± 0.20 milligrams Linearity	Grams	2,100 ± 0.20 milligrams Linearity
Weight (Flat Sheet and ELPI Samples)	205 ± 0.03 milligrams Linearity	Grams	205 ± 0.03 milligrams Linearity
Caliper (Filter Dimensions)	± 1/32 inch	Inches	Length ± 1/8 inch
			Inside diameter ± 1/16 inch
			Outside diameter ± 1/8 inch
			Circular runout not to Exceed 3/32 inch
			Parallel not to exceed 1/8 inch
			Minimum medium to faceguard gap of 1/8 inch
			All other dimension ± 1/16 inch
Laser Aerosol Spectrometer	0.09 to 7.5 micrometer	Penetration	0.1 to 0.5 micrometer
Aerosol Diluter	100 to 1		100 to 1
Aerosol Diluter	20 to 1		20 to 1
Aerosol Generator	10 to 100 microgram per liter at air flows from 50 to 8,100 CFM and 20 psig	Penetration	10 to 100 microgram per liter at air flows from 400 to 3,000 CFM and 20 psig
Scanning Mobility Particle Sizer (SMPS)	10 to 1,000 nanometers or 0.024 to 1 micrometers		24 to 1,000 nanometers or 0.024 to 1 micrometers
Aerodynamic Particle Sizer (APS)	0.3 to 20 micrometers	#/cc	0.3 to 20 micrometers
Dekati ELPI Model 3935-30	0.03 to 20 micrometers	g/cc	0.03 to 20 micrometers

Traditional Aerosol Characterization Infrastructure

Current generations of aerosol measurement instrumentation began to enter the marketplace within the last 30 years. However, conventional methods of determining particle size distributions have been widely used for a much longer period. ICET filter testing frequently uses a variety of gravimetric methods in conjunction with current instrumentation. Impactors and isokinetic sampling efforts generate gravimetric data for total catch of particulate matter or size segregated samples. The following list identifies equipment and accessories used to make gravimetric determinations.

1. Two *APEX* 522 metering consoles with associated EPA stack sampling accessories
2. *Mettler Toledo* AT-261 electronic microbalance
3. *Denver Instruments Company* TR-4102 top loading balance
4. Class U masses
5. *Mitutoyo* digital calipers
6. NIST traceable critical orifices
7. Dehumidifier for maintaining laboratory conditions
8. Ionizing unit for static control inside microbalance
9. Spot ionizer for static control on filter assemblies

Additional Test Equipment

1. *Mettler Toledo* Model SB32001 top-loading balance
2. *Lindberg/Blue* Model M01440A-1 oven
3. *Sheldon Manufacturing, Inc.* Model FS28-2 oven
4. Sr-90 neutralizer designed by ICET for neutralizing particle charge
5. Kr-85 neutralizer (*TSI*) for neutralizing PSL spheres
6. Anton-Parr SVM 3000 Stabinger Viscometer
7. Scanning electron microscope for characterizing test aerosols and particle deposits on filters

Software

A variety of software is used for development of test stand control systems, reduction of data, and preparation of plots. ICET maintains a master listing of software along with automated calculational application (ACA) packages that are required for individual pieces of software [8]. The listing of software includes documenting the versions of software and is maintained by the ICET software custodian to ensure current software versions are used for each instrument or intended purpose. A generalized list of software can be seen in Table 2.

Table 2. Software List.

Instrument/Test Stand	**Software**
APS	Aerosol Instrument Manager Software
SMPS	Aerosol Instrument Manager Software
EC	Electrostatic Classifier Software
LAS	LAS Software
RLSTS Control	Wonderware Intouch Window Maker Automationdirect Productivity Suite Wonderware Intouch Window Viewer Wonderware Histdata Server Wonderware MBTCP DAServer
RLSTS Data Reduction Computer	Microsoft Excel 2013

AEROSOL AND AEROSOL PARTICLE GENERATION

Particle Generation

ICET has secured or fabricated numerous particle generators for introduction of challenge agents into test stand fluid flows. The variety of particle generators has been assembled in order to have the ability to vary particle size distribution, the chemical matrix of the particles generated, and number density concentrations of PM used as challenge agents in the ICET HEPA test stands. ICET has the following means for introducing PM into the test stand:

1. *TSI* 9306A polydisperse PM generator
2. *TSI* 3475 monodisperse PM generator
3. *ATI* PSL (polystyrene latex) generator
4. *ATI* DOP (dioctyl phthalate) generator
5. ICET large-scale PM generator
6. *Laskin* nozzles
7. Powder feeders with venturi pump

Test Aerosol

ICET is capable of generating several different types of aerosols with a wide variety of compositions. Aerosols used at ICET include but are not limited to the following: dioctyl phthalate, powdered aluminum trihydroxide, NIST A1 ultrafine Arizona Test Dust, and acetylene soot.

Dioctyl phthalate – DOP – Aerodynamic mass median diameter, 0.546 µm, From Acros Organics, New Jersey USA, 1-800-ACROS-01. This test aerosol has been traditionally specified as a test aerosol for determination of filter efficiency in AG-1 Section FC-5120 and Section FK-5120 [1].

Aluminum Trihydroxide – SpaceRite S-3 $Al(OH)_3$ from J.M. Huber Corporation is used as a loading aerosol to simulate particles found in the WTP.

Arizona Test Dust – A1 Ultrafine Arizona Test Dust from Powder Technology Incorporated is used to represent large particles loaded onto filters.

Acetylene Soot – Produced from an oxygen starved acetylene flame that is immediately injected into the test stand. This aerosol is used to simulate very small particles loading under accident fire conditions.

CONTROL OF TESTING AND TEST PROCEDURES

ICET has developed extensive infrastructure and therefore requires an extensive set of procedures for testing HEPA filters for a variety of parameters including meeting the requirements of ASME AG-1 Section FK-5110, FK-5120, and FK-5130 [1]. Procedures are used to control every aspect of the life of a filter being tested at ICET. This includes from delivery to ICET until testing is completed and filter is autopsied, disposed of, or placed in storage. Procedures are developed, reviewed, controlled, and implemented under ICET's NQA-1 qualified quality assurance program. A generalized listing of procedures includes:

- Filter Inspections
- Control of Testing
- Resistance to Air Flow (FK-5110)
- Filter Efficiency/Penetration (FK-5120)
- Rough Handling (FK-5130)
- Loading
- Mass Determination
- Resistance to Liquid Pressure (RLPTS testing)
- Seal Leak Test (RLPTS testing)
- Filter Autopsy

All items received at ICET must undergo a thorough inspection upon arrival. Shipping containers and items are first visually inspected and documentation examined to ensure the appropriate item has been received. All items received at ICET are assigned a unique ID that is permanently marked on the item to ensure control of the item.

After initial general receipt inspection of a filter, it undergoes ICET procedure HEPA-015, *Radial Flow Filter As- Received Inspection* that includes marking sections on the filter, identifying and documenting damage or deficiencies to the filter and medium, collecting photographs of each section, and marking filter orientation for installation into test stand. Once the as received inspection is completed, filters undergo tolerance measurements in accordance with ICET procedures HEPA-010, *Measurement of Filter Fabrication Tolerances for Safe Change Radial Flow HEPA Filters Test Procedure* or HEPA-011, *Measurement of Filter Fabrication Tolerances for Remote Change Radial Flow HEPA Filters Test Procedure*. Tolerance measurement procedures ensure filters conform to AG-1 Section FK requirements for 2000 cfm radial flow filters as well as manufacturer specified drawings [1].

Radial flow filters undergo resistance to airflow in accordance with ASME AG-1 Section FK-5110 and ICET procedures HEPA-RLSTS-009, *Resistance to Air Flow* or HEPA-RLPTS-007, *Filter dP for Air Flow*. In addition to meeting the requirements of FK-5110, the differential pressure of radial flow filters is measured at incremental steps of rated flow from 5% of rated flow to 100% of rated flow [1].

Radial flow filters undergo test aerosol penetration in accordance with FK-5120 and ICET procedures *HEPA-RLSTS-012, RLSTS Filtering Efficiency* or HEPA-RLPTS-003, *RLPTS Filtering Efficiency* [1]. ICET procedures for measuring filter efficiency (FE)/penetration have been developed to ensure consistent measurements of filter FE/penetration. When measuring aerosol concentrations it is important to account for any differences in measurement methods of different types of instruments. In particular, optical particle sizers can introduce sizing error due to the characteristics of the aerosol. To limit bias introduced from using multiple instruments to calculate the FE/penetration a LAS and a SMPS are each used to measure the upstream and downstream concentration of DOP aerosol. A set of valves is used to swap between upstream and downstream ducting for measurements. Due to limitations of the LAS, a set of diluters is used for measuring the upstream concentration of particles in the air stream. The system of valves and diluters can be seen in Figure 16 [9]. To ensure a sufficient challenge of aerosol, the total count is measured upstream of the filter before beginning the aerosol penetration test. Performing the penetration test includes recording background data and instruments zero readings. Penetration of filters is measured using DOP and loading test aerosols depending on the type of test the filter is undergoing. Penetration is measured at 100% rated flow, 20% rated flow, 5% of rated flow and at any additional test plan specified designated flow rate.

Radial flow filters that are to undergo rough handling are attached to the rough handling machine and tested for 15 minutes in accordance with ASME AG-1 Section FK-5130 and ICET procedure *HEPA-025, Rough Handling Procedure* [1]. Photographic evidence is collected of any damage incurred to filters during the rough handling procedure.

ICET has a developed procedures for loading filters up to 50 in. w. c. with a variety of aerosols. Aerosols used in loading studies include powdered aluminum trihydroxide, Arizona Test Dust A-1 ultrafine powder, and acetylene soot. Additional powdered aerosols are capable of being used. Powdered aerosols are dispersed into the test stand using a powder feeder and venturi nozzle for atomization. Acetylene soot is generated using burners mounted on open ports of the test stand allowing the acetylene gas to burn and the airflow to suck the soot into the test stand.

Filter mass is measured when the filter is first received as well as at intervals during testing according to test plan specifications. Filter mass is determined using a calibrated balance according to ICET procedure *HEPA-014, Filter Mass Determination.*

DATA MANAGEMENT AND REDUCTION

Large amounts of data are collected during the testing of each filter. Data sets include but are not limited to:

- Filter dimension measurements
- Filter mass
- Flow rates
- Temperature, pressure, and relative humidity

- LAS sizing and counts (upstream and downstream)
- SMPS sizing and counts (upstream and downstream)
- APS sizing and counts (upstream)

Tolerance measurements are accomplished using calibrated calipers that display to four decimal places. All tolerance measurements are recorded on the attachment to the tolerance procedure.

Filters for loading studies that are received with gel seals have the seals replaced with gaskets to ensure changes in filter mass are not due the gel seal adhering to the knife edge sealing surface of the filter housing. Filter mass is recorded during receipt inspection, before initial installation in test stand, after filter conditioning, and at specified increments during loading. Typically the filter is weighed at 10 in. w. c. of loading and 50 in. w. c. of loading but can be done more often.

The flow rate is measured using a venturi in the downstream duct of the test stand. The differential pressure across the venturi as well as the static pressure, temperature, and humidity at the venturi are used to calculate the mass flow rate throughout the test stand. The density upstream of the filter is then used to determine the volumetric flow rate upstream of the filter. Based upon this determination the fan speed is controlled by the PLC to achieve the target flow rate at the filter inlet. Additionally the differential pressure across the venturi is stored in the data acquisition system and converted to flow rate during post test data reduction.

Static pressure, differential pressure, temperature, and relative humidity are all recorded at several locations on the test stand. Test conditions are recorded in in. w. c. for pressure, degrees Fahrenheit for temperature, and percent for relative humidity.

Aerosol instrumentation data is recorded in normalized concentration to ensure comparability between instruments. The concentration is reported as a function of particle size. SMPS records particle sizing and counts from 0.024 µm to 1.0 µm. The LAS records particle sizing and counts from 0.09 µm up to 7.5 µm. The APS records particle sizing and counts from 0.5 µm to 20 µm.

REPORTING OF RESULTS

Data collected during tested is compiled into individual test reports and distributed to the customer in a timely fashion. Intermittent reports can be provided to customers after stages of testing as well as after the completion of testing an individual filter, if needed. Cumulative results of testing a group of filters is compiled into a final test report as a deliverable at the completion of a project.

Filter tolerance measurements are rounded to two decimal places for reporting purposes. Table 3 shows how tolerance data is reported for 2000 cfm radial flow HEPA filters.

Table 3. Tolerances

Measurement	As Measured	Accepted Tolerance	Pass/Fail
Outer diameter of filter, inlet flange facing down	20.37 in. 20.36 in. 20.37 in. 20.37 in.	20 3/8 ± 1/16 in. (20.31–20.44in.)	Pass
Diameter of filter, inlet flange facing down	Largest Difference .005 in.	within 3/32 in. (0.09 in.)	Pass
Outer diameter of filter, inlet flange facing up	20.37 in. 20.36 in. 20.37 in. 20.36 in.	20 3/8 ± 1/16 in. (20.31–20.44 in.)	Pass
Diameter of filter, inlet flange facing up	Greatest Difference 0.009 in.	within 3/32 in. (0.09 in.)	Pass
Gasket Channel Depth	0.78 in. 0.79 in. 0.78 in. 0.79 in.	0.825 (+0, -1/16 in.) (0.76–0.83 in.)	Pass
Inner throat diameter, inlet flange facing up	12.99 in. 13.00 in. 13.00 in. 12.99 in.	13 ± 1/16 in. (12.94–13.06 in.)	Pass
Length of filter	Flange Cap 23.86 in. 23.08 in. 23.88 in. 23.09 in. 23.86 in. 23.07 in. 23.85 in. 23.07 in.	23 7/8 (+0, -1/8 in.) (23.75–23.88 in.)	Fail Accepted value 23.8750 in. rounds to 23.88 in. Measured value 23.8795 in. rounds to 23.88 in. (Rounded into tolerance)
Flange and end cap, parallel	Greatest Differences 0.02 in. 0.03 in.	within 1/8 in. (0.13 in.)	Pass
Deviations in flatness, filter throat and end cap	0.02 in. 0.01 in.	within 1/16 in. (0.06 in.)	Pass
Filter top and bottom end caps to reference edge	Top Bottom 2.98 in. 3.00 in. 3.01 in. 3.00 in. 3.03 in. 3.00 in. 2.96 in. 3.00 in.	within 3/32 in. (0.09 in.)	Pass
Outer and inner diameter to reference edge	Outer Inner 5.89 in. 6.65 in. 5.90 in. 6.67 in. 5.95 in. 6.70 in. 5.96 in. 6.73 in.	within 3/32 in. (0.09 in.)	Pass

Plots of data or results such as dP versus volumetric flow rate are generally used to summarize behavior of individual filter test results. The resistance to air flow plot can reveal pleat collapse or ballooning if the differential pressure versus flow rate is not linear. Figure 21 shows the dP vs. flow curve for data collected between 400 and 2000 cfm.

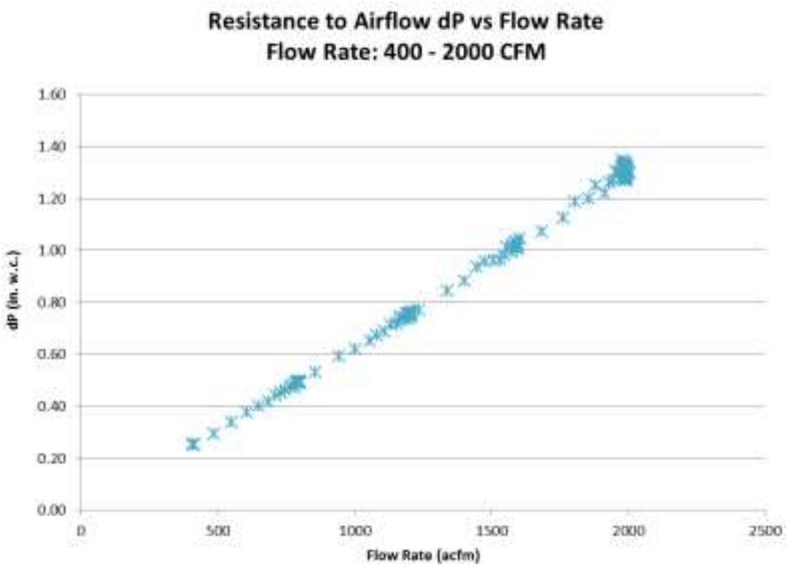

Figure 21. Resistance to air flow curve.

Particle size distributions (PSD) are critical parameters when discussing filter loading tests. Accurate determination of particle size distributions and number densities of aerosol particles upstream and downstream of a filter are essential for determining filtering efficiency. Figures 22 and 23 show PSDs for a filter being tested with DOP for determination of filtering efficiency. Low counts can occur downstream of the filter that result in a scatter of data. The SMPS data in Figures 23, 24, and 25 has scattered results due to low downstream counts. Comparison of the downstream curves generated with the LAS and SMPS shows the difference between LAS and SMPS minimum detection limits and why the SMPS is not ideal for determining filtering efficiencies for high efficiency filters.

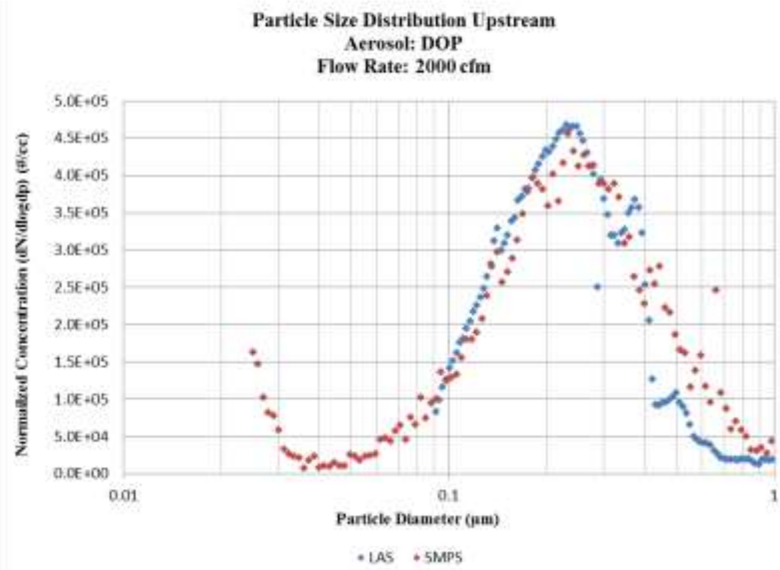

Figure 22. Upstream particle size distribution plot.

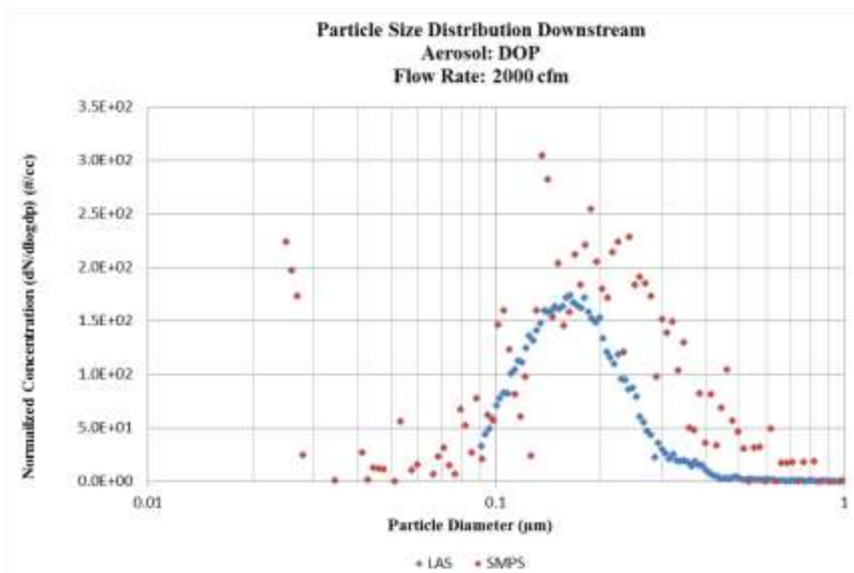

Figure 23. Downstream particle size distribution plot.

Filter penetration and efficiency over the whole particle size range are reported as shown in Figure 24 and Figure 25.

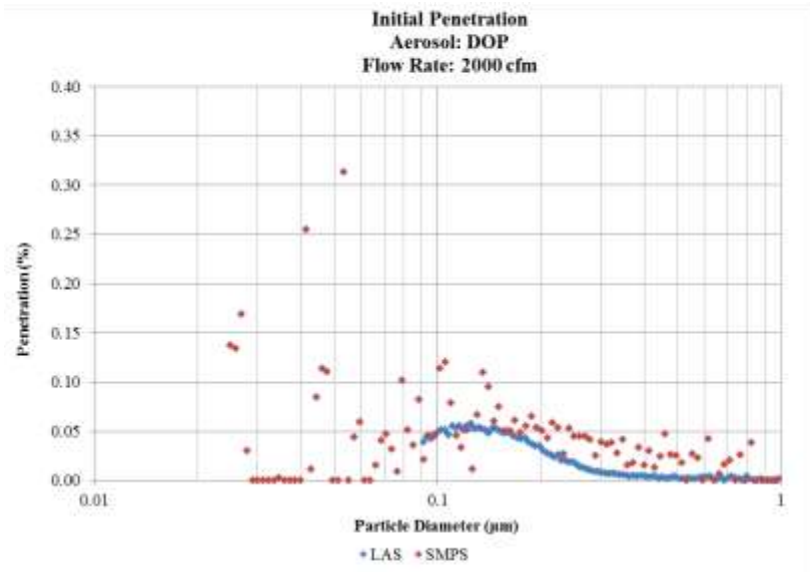

Figure 24. Filter penetration plot.

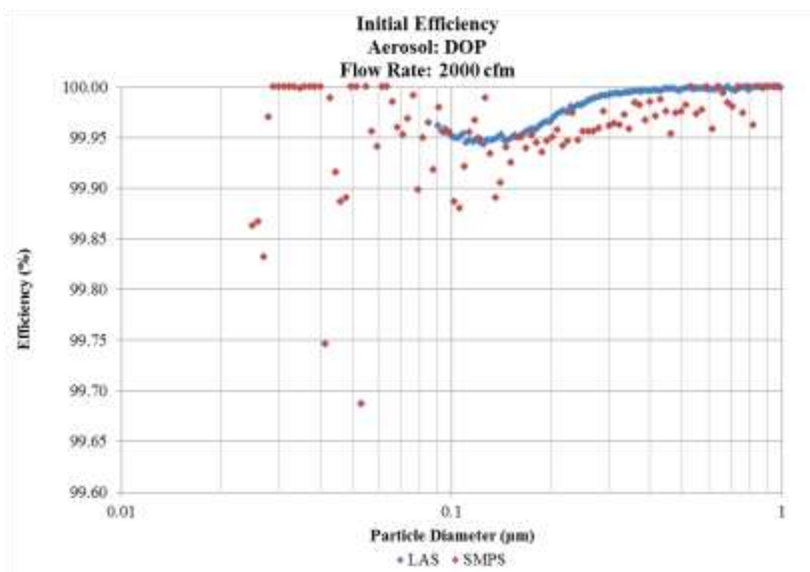

Figure 25. Filter efficiency plot.

Stability of testing conditions is critical to ensure that filter testing is performed consistently. A plot of testing conditions versus time is shown in Figure 26. This plot is used to document the adherence of test conditions to those called for in the project test plan and the test control document for a specific filter. Large changes in flow rate, temperature, and relative humidity for the filter test shown in Figure 26 are the result of changing test conditions for performing FE/penetration measurements at specified intervals during loading.

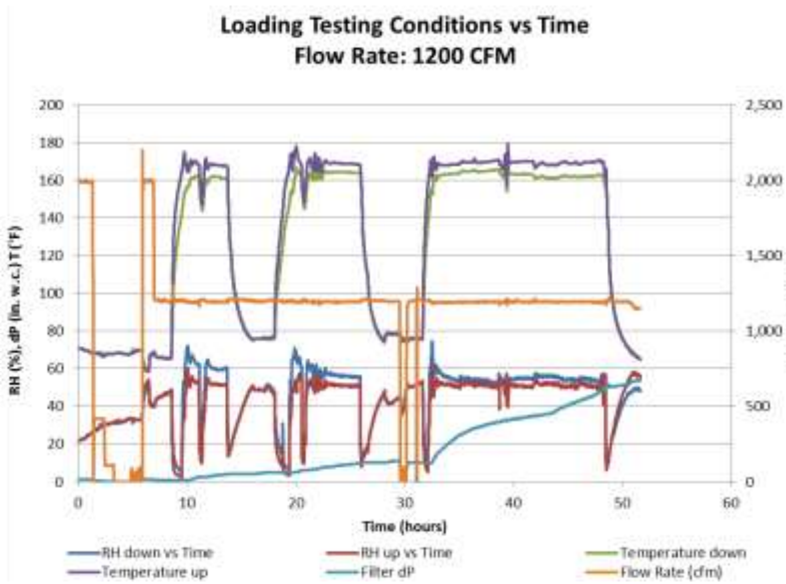

Figure 26. Testing conditions versus time.

There is not a single aerosol measurement instrument that is capable of measuring particle size distributions of particles over the range of interest (greater than 10 micrometers down to 10 nanometers). Upstream particle size distributions are made using the APS and LAS to do an optimum job of describing the PSD. These are important data for loading studies. The SMPS is the most capable instrument for making particle size distribution measurements for particle sizes below one micrometer. However, its inability to generate dependable data for low particle concentrations makes it less suitable for measurements downstream of a functioning HEPA filter. The PSD plot created from LAS and APS data is shown in Figure 27.

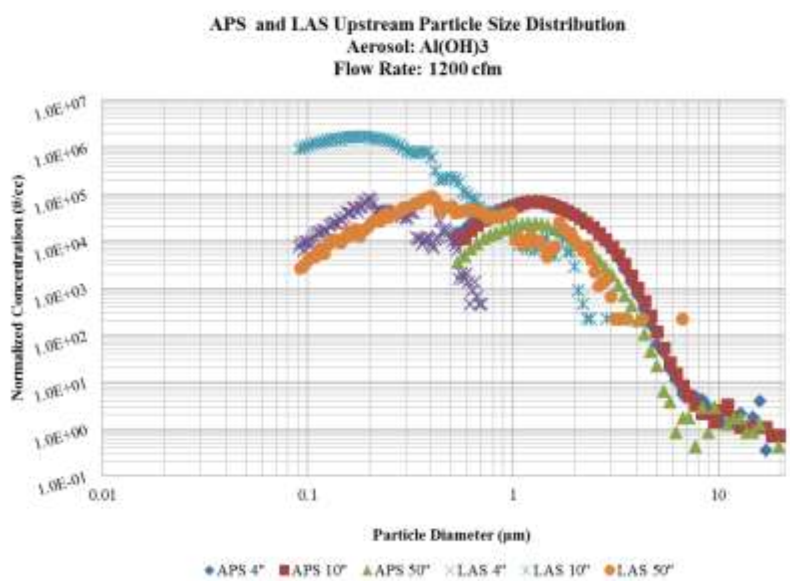

Figure 27. PSD for APS and LAS with test aerosol.

Several sets of data are reported in tabular form to give specific values for critical numbers. The initial dP, penetration/filtering efficiency at 0.3 µm, geometric mean diameter, geometric standard distribution, and most penetrating particle size are all reported in tabular format for each interval at which the filter penetration test was completed. Table 4 shows tabular data reported for FE/penetration testing.

Table 4. Summation of Penetration, FE, and Particle Statistical Data

FE Condition	Penetration @ 0.3µm SMPS/LAS	FE @ 0.3µm (%) SMPS/LAS	MPPS (µm) SMPS/LAS	GSD Upstream/ Downstream	GMD (µm) Upstream/ Downstream
Initial 2000 cfm	5.0E-05 3.3E-05	99.995 99.997	0.095 0.138	1.96/1.53 1.60/1.34	0.160/0.148 0.193/0.156
Initial 400 cfm	9.2E-06 1.5E-05	99.999 99.998	0.661 1.469 0.687*	1.87/2.17 1.60/1.34	0.174/0.158 0.200/0.198
Initial 100 cfm	2.3E-04 2.2E-04	99.977 99.978	0.026 1.124 0.575*	1.79/1.73 1.59/1.59	0.222/0.197 0.242/0.240
Post Rough Handling, 2000 cfm,DOP	9.2E-05 6.0E-05	99.991 99.994	0.027 0.144	1.87/1.66 1.60/1.36	0.168/0.149 0.193/0.160
Post Rough Handling, 2000 cfm, Test Aerosol	0.0E+00 1.1E-05	100.000 99.999	0.594 0.120	1.94/2.11 1.66/1.47	0.217/0.183 0.227/0.187
4 in w. c., 2000 cfm, DOP	1.2E-05 2.1E-06	99.999 100.000	0.082 0.120	1.86/1.44 1.58/1.42	0.174/0.137 0.200/0.155
4 in. w. c., 2000 cfm, Test Aerosol	0.0E+00 0.0E+00	100.000 100.000	0.496 0.101	1.89/1.53 1.66/1.24	0.229/0.375 0.232/0.182
10 in. w. c., 2000 cfm, DOP	1.7E-05 1.0E-05	99.998 99.999	0.055 2.296 0.165*	1.91/1.84 1.60/1.52	0.162/0.153 0.193/0.179
10 in .w. c., 2000 cfm, Test Aerosol	0.0E+00 1.3E-06	100.000 100.000	0.334 0.092	1.92/1.00 1.66/1.30	0.218/0.334 0.236/0.212
28 in. w. c., 2000 cfm, DOP	5.8E-03 5.5E-03	99.419 99.447	0.046 0.197	2.22/1.83 1.59/1.48	0.157/0.155 0.192/0.186
28 in. w. c., 2000 cfm, Test Aerosol	1.1E-03 2.2E-03	99.888 99.778	0.057 0.235	2.71/2.21 1.71/1.56	0.154/0.190 0.244/0.226

* Secondary most penetrating particle size where larger particles are very low in concentration causing a skewed MPPS.

The initial dP, initial mass of the filter, interval mass of filter, and mass of test aerosol loaded on the filter is reported in tabular form. A table of mass loading data for a filter test is shown in Table 5.

Table 5. Summation of loading test results

Initial Mass (without gasket)	33842 g
Initial Mass (with gasket)	33910 g
Initial dP	1.31 in. w. c.
Tare Mass	33971 g
Mass at 10 in. w. c.	36102 g
Mass Loaded at 10 in. w. c.	2131 g
Final Mass at 50 in. w. c.	39197 g
Dry Mass at 50 in. w. c.	39173 g
Total Mass Loaded	5202 g

When testing with the RLPTS, the resistance to liquid pressure test is performed in place of the loading test. Data for the RLPTS test will include an initial and final FE/penetration and PSD curves as well as conditions during the liquid pressure test.

CONCLUSION

The infrastructure developed at ICET is capable of assisting in the development, characterization and qualification of ASME AG-1 Section FK radial flow filters. Performance of these test stands covers a wide range of testing parameters including nontraditional performance requirements. Test stands, M&TE, control of testing, and procedures used in ICET filter testing activities are consistent with ICET's NQA-1 quality assurance program. Performance capability of each test stand and all procedures have been verified to ensure that Q testing of Section FK 2000 cfm radial flow filters can be completed at ICET.

ACKNOWLEDGEMENT:

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REFERENCES

[1] American Society of Mechanical Engineers (ASME). *Code on Nuclear Air and Gas Treatment (ASME AG-1)*. [Standard]. New York: ASME, (2013).

[2] Giffin, Paxton K. et. al. *Performance Comparison of Dimple Pleat and Ribbon Separated Radial Flow HEPA Filters*, Proceedings of the International Society for Nuclear Air Treatment Technologies 32nd Nuclear Air Cleaning Conference. June 17-19, 2012. Institute for Clean Energy Technology. Mississippi State University.

[3] American Society of Mechanical Engineers (ASME), *Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi (ASME MFC-3M-004)*, [Standard], New York: ASME, (2005).

[4] Wong, Matthew, et. al. *Design and Performance of an In-Place Flat Media Particle Loading Testing System*. Proceedings of the International Society for Nuclear Air Treatment Technologies 34th Nuclear Air Cleaning Conference. June 5-7, 2016. Institute for Clean Energy Technology. Mississippi State University.

[5] TSI. *Laser Aerosol Spectrometer Model 3340 Operation and Service Manual*. Rev. D. TSI. [2012].

[6] Phillips, Spencer, et. al. *Design and Performance of a Flat Media Filtering Efficiency Test Stand*, Proceedings of the International Society for Nuclear Air Treatment Technologies 34th Nuclear Air Cleaning Conference. June 5-7, 2016. Institute for Clean Energy Technology. Mississippi State University.

[7] Unz, Ron. et. al. *Infrastructure for Testing and Qualifying Robust Radial Flow HEPA Filters*. Proceedings of the International Society for Nuclear Air Treatment Technologies 33rd Nuclear Air Cleaning Conference. June 22-24, 2015. Institute for Clean Energy Technology. Mississippi State University.

[8] Phillips, Kate, et. al. *Verification, Validation and Control of Automated Calculation Applications Subject to ASME NQA-1 Quality Assurance Requirements*. Proceedings of the International Society for Nuclear Air Treatment Technologies 34th Nuclear Air Cleaning Conference. June 5-7, 2016. Institute for Clean Energy Technology. Mississippi State University.

[9] Jacks, Robert. Charles Waggoner. *Institute for Clean Energy Technology Radial Flow HEPA Filter Test Stand Sampling Configuration*. Proceedings of the International Society for Nuclear Air Treatment Technologies 34th Nuclear Air Cleaning Conference. June 5-7, 2016. Institute for Clean Energy Technology. Mississippi State University.