

## **Performance Evaluation of Axial Flow AG-1 FC and Prototype FM (High Strength) HEPA Filters - 13123**

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### **ABSTRACT**

High efficiency particulate air (HEPA) filters are routinely used in DOE nuclear containment activities. The Nuclear Air Cleaning Handbook (NACH) stipulates that air cleaning devices and equipment used in DOE nuclear applications must meet the American Society of Mechanical Engineers (ASME) Code on Nuclear Air and Gas Treatment (AG-1) standard. This testing activity evaluates two different axial flow HEPA filters, those from AG-1 Sections FC and FM. Section FM is under development and has not yet been added to AG-1 due to a lack of qualification data available for these filters. Section FC filters are axial flow units that utilize a fibrous glass filtering medium. The section FM filters utilize a similar fibrous glass medium, but also have scrim backing. The scrim-backed filters have demonstrated the ability to endure pressure impulses capable of completely destroying FC filters. The testing activities presented herein will examine the total lifetime loading for both FC and FM filters under ambient conditions and at elevated conditions of temperature and relative humidity. Results will include loading curves, penetration curves, and testing condition parameters. These testing activities have been developed through collaborations with representatives from the National Nuclear Security Administration (NNSA), DOE Office of Environmental Management (DOE-EM), New Mexico State University, and Mississippi State University.

### **INTRODUCTION**

#### **HEPA Filters for Nuclear Applications**

High efficiency particulate air (HEPA) filters are routinely used in DOE nuclear containment activities. The Nuclear Air Cleaning Handbook (NACH) stipulates that air cleaning devices and equipment used in DOE nuclear applications must meet the American Society of Mechanical Engineers (ASME) Code on Nuclear Air and Gas Treatment (AG-1) standard [1,2]. Design, fabrication, performance requirements, and testing for AG-1 nuclear grade axial flow HEPA filters are set forth in Section FC of that standard. Section FC filters are axial flow units that utilize a fibrous glass filtering medium. The FC standard contains an upper limit for media velocity (volumetric flow rate per surface area of media) of 1.52 m/min (5 ft/min) to conserve filter integrity even in the event that the filter becomes wet.

The Defense Nuclear Facilities Safety Board (DNFSB) has expressed concern regarding the use of HEPA filters within the DOE complex in its Technical Report 23 [3]. Two of the issues addressed in this report were associated with the ability of HEPA filters to function under fire and smoke conditions. Upset conditions in a containment ventilation area that includes a fire poses two significant risks to HEPA filters: rapid loading leading to high levels of differential pressure across the filter, which can produce a filter rupture, and reduction of the tensile strength of filter medium due to wetting from fire suppression systems.

Smoke and soot represent a severe challenge to HEPA filter function and integrity because of both aerosol nature and particle size distribution. Smoke contains a vast range of products of incomplete combustion including solid and condensed phase particles. This mixture of large aerosols does not “build up” on and within the filter medium in the same manner as dry aerosols. Soot is an agglomerate (from 40 to 200

nanometers) comprised of individual particles of approximately 10 nanometers (nm). These small particles are prone to depth loading of filter media and can lead to 10 times the loading rate of larger particles on a per milligram (mg) basis.

DOE has taken steps to intensify scrutiny of HEPA filter usage in applications where there is the potential for fires by establishing its 1066 Fire Protection standard [4]. This guidance document is currently under review that includes compiling information on HEPA filters generated since the document was first published.

Water has long been identified as a threat to HEPA filter integrity. Filters that become wet can lose soluble material from the backside of media by the wicking of water through the media. There has also been anecdotal reporting of filters that physically fail due to repeated events where the medium has become moist. This has raised concerns of the effects of elevated relative humidity aging the medium over a long period of time and leading to reduced tensile strength.

Another reason for this testing is that much of the data describing lifetime performance of nuclear grade HEPA filters found in the literature is dated. Filter medium composition and pleating techniques for the deep pleated Section FC axial flow filters have changed over the last 30 years. Improvements in instrumentation allow close and accurate monitoring of upstream and downstream aerosol and airflow conditions throughout the duration of testing.

## **Previous Testing**

### *Axial Flow*

Filtration research at ICET began 10 years ago with its DOE sponsored HEPA Filter Monitoring Project. Studies evaluating 30.5 cm by 30.5 cm by 29.2 cm (12 in. by 12 in. by 11.5 in.) ASME AG-1 Section FC axial flow HEPA filters have tested moisture failure, source term loading, seal and pinhole leak tests, and media velocity. Details related to the design, construction, and operation of the test stand utilized in these research efforts have been reported [5], presented at numerous conferences [6, 7, 8], and published [9]. These details include aerosol generation, types of filters tested, and the aerosol measurement instrumentation utilized.

### *Radial Flow*

ICET has developed a large-scale filter test stand capable of evaluating the performance of up to two 56.63 m<sup>3</sup>/min (2000 ft<sup>3</sup>/min or CFM) (AG-1, Section FK, radial flow) filters at rated flow velocities and to differential pressure (dP) levels of 12.5 kPa (50 in. w.c.). Information concerning this test stand has been published [10]. This test stand has most recently been utilized to conduct lifecycle testing of HEPA filters under ambient and elevated conditions. Testing in 2010 and 2011 was conducted on AG-1, Section FK, prototype radial flow HEPA filters [11, 12]. These filters are intended to be a major element in the HEPA filtration systems within the DOE complex. Tests were conducted on both safe and remote change filter prototype designs at ambient and elevated conditions.

## **Current Research**

Current research is concerned with the performance evaluation of ASME AG-1 Section FC axial flow HEPA filters and AG-1 Section FM prototype high strength axial flow HEPA filters. These testing activities are intended to demonstrate the effectiveness of an improved version of Section FC axial flow HEPA filters using the scrim backing. AG-1 Section FM has been under development for some time

establishing a standard for filters that use high strength medium. This section has been developed to facilitate use of a fiberglass scrim-backed conventional HEPA filter medium. The scrim backing dramatically increases the tensile strength of the medium and adds a marginal increase in differential pressure. Initial tests have been conducted with small 20.3 cm by 20.3 cm by 29.2 cm (8 in. by 8 in. by 11.5 in.) axial flow filters comparing the performance of FM filters to equivalent FC units at New Mexico State University. The scrim-backed filters demonstrated the ability to endure pressure impulses capable of completely destroying FC filters.

Two initial tasks need to be completed in order to move the current draft version of Section FM to a point where it can be balloted and approved. The first task is to develop a functioning test stand and set of test procedures for qualifying FM filters. Secondly, high quality data necessary for establishing performance requirements for FM filters must be generated. Additionally, lifetime performance data are needed for the development of loading models and for direct comparison of FC and FM filter performance under upset conditions.

Both FC and FM filters will be tested. Both types of filters will be evaluated under ambient and elevated conditions of temperature and relative humidity. Two different types of FC filters are examined: aluminum separator filters and dimple pleat separator filters. FC filters from three different manufacturers are tested. Results will include mass loading curves, penetration curves, and plots of the testing airflow conditions.

## **TEST STAND**

The majority of the test stand used for evaluation of the AG-1 FC and prototype FM filters was used for the testing of radial flow HEPA filters previously discussed. Minor modifications were made to the test stand to allow for evaluation of axial flow filters. The modified test stand is displayed in Figure 1. The test stand consists of both indoor and outdoor portions.

### **Test Stand Components**

Multiple components of the test stand can be seen in Figure 1. The components, beginning with the outdoor upstream section, include the natural gas burner, water injection, and air intake. These three components are used when the system is needed to operate at elevated temperature and relative humidity of the airflow. An image of the elevated conditions equipment is presented in Figure 2.

Following the outdoor upstream components, the test stand has a removable section of duct to allow for testing at ambient conditions by drawing in room temperature air. The next components are the aerosol injection and neutralization system, which will be discussed later in the aerosol generation and neutralization section. Immediately before the filter housing are the upstream aerosol concentration measurement ports.

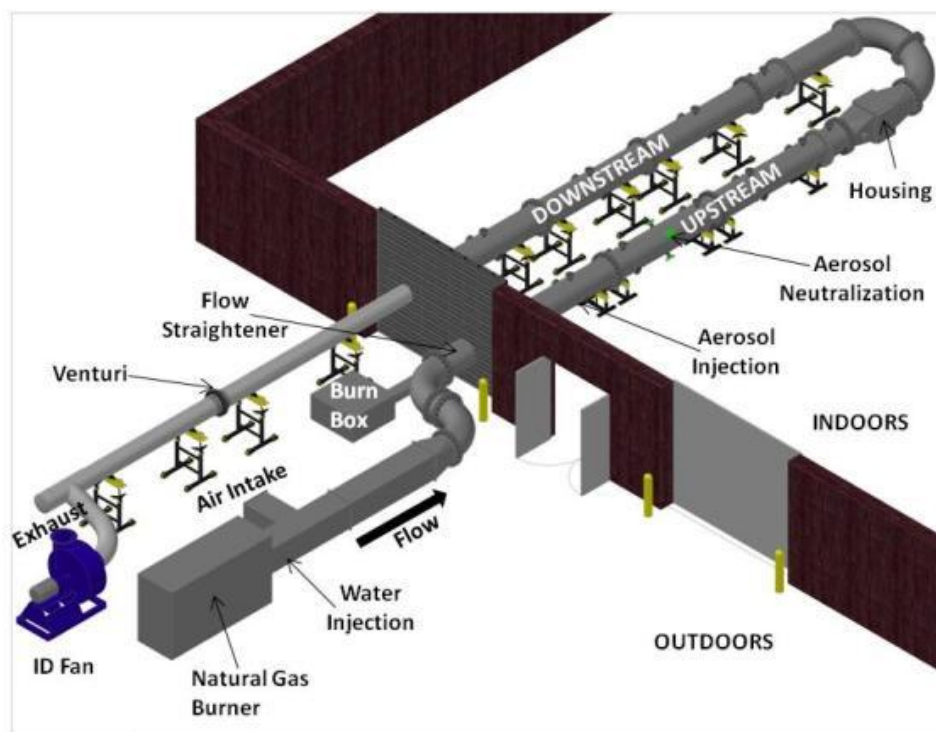


Fig. 1. Detailed drawing of the ICET large scale filter test stand.

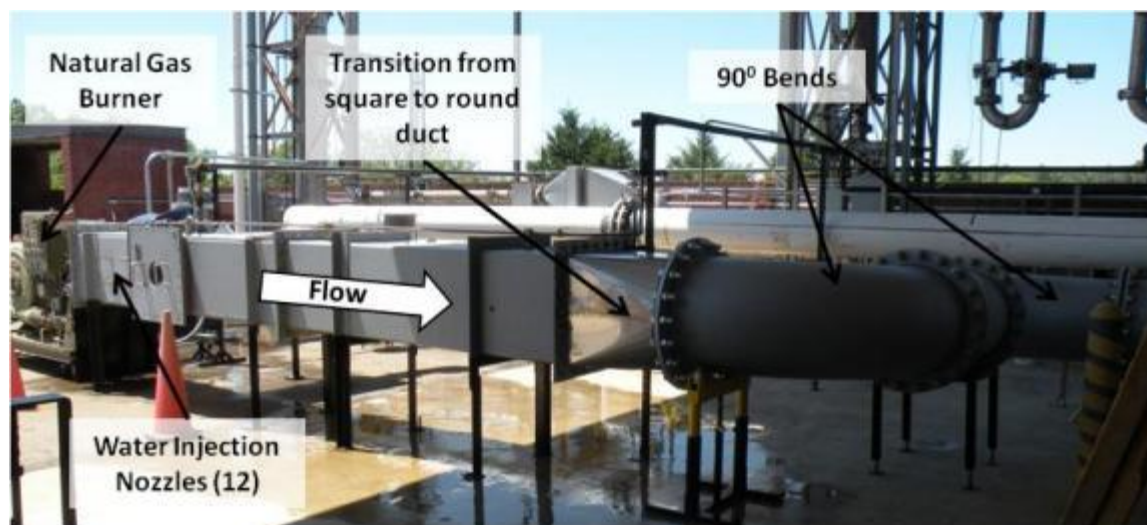


Fig. 2. Elevated temperature and humidity generation system of ICET filter test stand.

The test housing, manufactured by Flanders, is designed to hold one axial flow HEPA filter. The housing is reinforced to allow testing of filters up to 25 kPa (100 in w.c.) of differential pressure. At the request of MSU, additional ports were added upstream and downstream of the filter bay for additional sampling ports, camera placement, and/or sensor placement.

The first downstream components are the downstream aerosol measurement ports. The venturi lies further downstream and evaluates the airflow rate. The last component is the 74.5 kW (100 hp) fan. This fan is controlled by a variable frequency drive and can operate based on actual or standard flow.

The ICET test stand is fully instrumented with sensors and controls. Data from all sensors and controls are continuously logged by a central test stand control computer equipped with a touch screen display. Digital images of test filters may be collected at any point during testing. Digital images collected during testing provide important data related to the filter pack during loading. A digital camera can be inserted upstream of the filter through a 7.62 cm (3 in.) port. This camera may be used to collect initial images of the filter media before loading, at specified intervals of dP when aerosol injection is off, and after completion of testing before removal of the filter from the filter housing.

## Aerosol Generation and Neutralization

### *Dry Powder Aerosols*

Multiple aerosols are capable of being used as challenges in the ICET test stand, including Carbon black, Alumina(  $\text{Al}(\text{OH})_3$ ), and Arizona road dust. The first aerosol, Carbon black (N991), is provided by CANCARB Limited in Medicine Hat, Alberta, Canada. This powder has a mass median diameter (MMD) of 1.2 - 2.0  $\mu\text{m}$  and represents loading by soot. D. Loughborough at the AEA Harwell Laboratory in the UK has conducted tests using this aerosol [13]. The next aerosol is Alumina,  $\text{Al}(\text{OH})_3$ , (Almatis Spacerite S-11) purchased from Brenntag Specialties, Inc., in South Plainfield, NJ. This aerosol has an MMD of 0.8  $\mu\text{m}$  and is used to represent loading by small particles.  $\text{Al}(\text{OH})_3$  has previously been used in filter loading tests [14, 15]. The final aerosol used is Arizona Road Dust (A1 Ultrafine, ISO 12103-1) purchased from Powder Technology, Inc, of Burnsville, MN. This test dust is used to represent loading by large particles as it has a MMD of 5.0  $\mu\text{m}$ . The particle size distributions (PSD) of the three challenge aerosols are presented in Figure 3. The average number concentration, count median diameter (CMD), geometric standard deviation (GSD), and MMD is presented in Table 1.

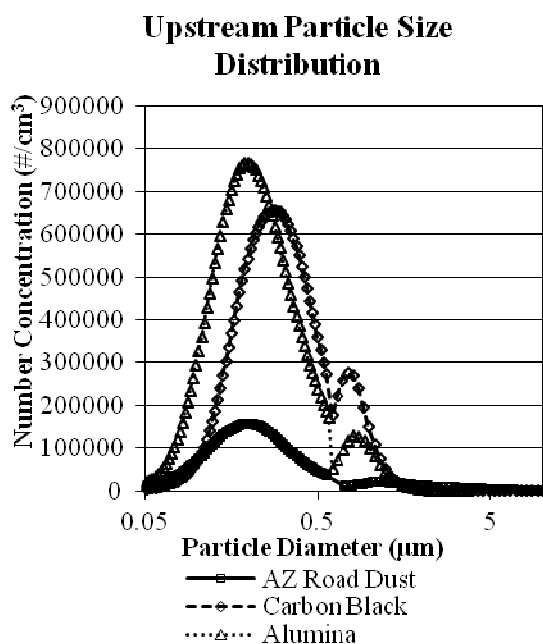


Fig. 3. Challenge aerosol particle size distribution.

Table 1. Challenge Aerosol Parameters

Aerosol	Upstream			
	Number Concentration	CMD	GSD	MMD
Al(OH) <sub>3</sub>	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

Aerosols for challenging filters will be generated from bulk material using a powder feeder delivering material to a sonic nozzle. Figure 4 provides photos showing the assembly of powder feeder, sonic nozzle, and injection nozzle used for generating the aerosol challenge. Dispensed powder is received by a critical orifice nozzle positioned directly beneath the powder feeder. The critical orifice is maintained at 413.7 kPa (60 psi) with dry, compressed air. Air supplied to the critical orifice is dried to prevent agglomeration and changes to the PSD. The pressure allows for sufficient break-up of aerosol clumps ensuring the resulting aerosol is uniformly dispersed. The aerosol dispersal nozzle is oriented so that it injects the powder against the direction of airflow.



Fig. 4. Generation of aerosol and injection into the ICET large scale filter test stand.

### *Aerosol Neutralization*

Aerosol generation using this technique tends to produce particles more highly charged than under equilibrium conditions. This can lead to increased uncertainty associated with both aerosol particle size distribution measurements and with mass loading capacity of filters. General target values for neutralizing surface charges on particles are to expose them to an ion pair concentration of  $6 \times 10^6$  per cubic centimeter for one second. The ICET test stand has been equipped with an aerosol neutralization section using Sr-90/Y-90 sources to achieve the necessary concentration of ion pairs over 5.5 m (18 ft) of the test stand ductwork.

### **Aerosol Measurement Instrumentation**

The primary aerosol measurement instruments used on the large-scale test stand are the aerodynamic particle spectrometer (APS), scanning mobility particle sizer (SMPS), and a laser aerosol spectrometer



(LAS). The APS, SMPS, and LAS are products of TSI, Inc., of Shoreview, MN. The APS is a time of flight measurement device that measures the aerodynamic diameter and light-scattering intensity of aerosol particles [16, 17]. The SMPS consists of a TSI Model 3080 electrostatic classifier (EC), a TSI Model 3081 differential mobility analyzer (DMA), and a TSI Model 3775 condensation particle counter (CPC). The LAS operates based on the principle that the degree of light scattering is dependent on the size of the aerosol particle. More information on the above instruments is available [18]. Table 2 presents the concentration and size capabilities for the instruments listed above.

Table 2. Size and Concentration Capacity for Aerosol Measuring Instruments

Instrument	#/cc (min)	#/cc (max)	PSD ( $\mu\text{m}$ )
TSI SMPS with Model 3775 CPC	1	$1 \times 10^7$	0.004 - 3
TSI Model 3321 APS	1	$1 \times 10^3$	0.5 - 20
TSI Model 3340 LAS	<0.02	$1.8 \times 10^4$	0.09 - 7.5

## TEST PLAN

Multiple FC and prototype FM filters will be evaluated under ambient and elevated conditions. The ambient conditions testing will occur at 21-27°C (70 to 80°F) and 40-60% RH. The challenge at elevated conditions testing will be at 54.4°C (130°F) and 50% RH or greater. The ambient condition testing will consist of loading the filter at the aforementioned conditions with one of the three challenge aerosols until the filter ruptures or reaches a very high differential pressure, such as 10 kPa (40 in. w.c.).

As previously mentioned, filters from three different manufacturers are tested. The three manufacturers are American Air Filters, CamFil Farr, and Flanders. All three manufacturers make FC filters, but only CamFil Farr makes the FM filters with the scrim backing. Flanders manufactures the majority of filter medium used in their filters while CamFil Farr and American Air Filters use media from Hollingsworth and Vose or from Lydall. Lydall is the manufacturer that provides the scrim-backed high strength medium. Figure 5 features an image of an FC axial flow HEPA filter.



Fig. 5. Image of an AG-1 Section FC axial flow filter.

Most of the filters are deep pleated and use metal separators, while one set has dimple pleat separators. Testing includes Aluminum separated filters for all three manufacturers, but the only filter manufacturer

for testing of the dimple pleat filters is Flanders. The prototype FM filters also use the Aluminum separators. Table 3 displays the test matrix for the FC and prototype FM filter testing activity.

Table 3. Test Matrix for FC/FM Testing

Filters Tested	Filter Type	Separator	Manufacturer	Test Type	Challenge Aerosol	Airflow Rate
1	FC	Aluminum	American Air	Ambient	Alumina	28.3m <sup>3</sup> /min
1	FC	Aluminum	Flanders	Ambient	Alumina	28.3m <sup>3</sup> /min
1	FC	Aluminum	Camfill Farr	Ambient	Alumina	28.3m <sup>3</sup> /min
1	FM	Aluminum	Camfill Farr	Ambient	Alumina	28.3m <sup>3</sup> /min
1	FC	Aluminum	American Air	Elevated	Alumina	28.3m <sup>3</sup> /min
1	FC	Aluminum	Flanders	Elevated	Alumina	28.3m <sup>3</sup> /min
1	FC	Aluminum	Camfill Farr	Elevated	Alumina	28.3m <sup>3</sup> /min
1	FC	Dimple	Flanders	Elevated	Alumina	28.3m <sup>3</sup> /min
1	FC	Dimple	Flanders	Elevated	Alumina	42.5m <sup>3</sup> /min
3	FM	Aluminum	Camfill Farr	Elevated	Alumina	28.3m <sup>3</sup> /min

## TEST RESULTS

### Ambient Condition Testing Results

Ambient condition testing consisted of evaluating three FC filters with aluminum separators and one FM filter. The first of the testing results presented is the differential pressure versus time plot displayed in Figure 6. This plot indicates the increase in pressure drop across the filters as they are loaded. Note the loading times of up to 100 hours. The FC filters began to leak to the point that they were no longer HEPA efficient somewhere between 50 and 60 hours. The FM filter stayed HEPA efficient. Figure 7 displays the mass loading curves for the four filters tested under ambient conditions. Figure 6 indicates that the FM is able to hold much more material than the FC filters because they never leaked during the testing. The test was only stopped due to the fluctuations in the differential pressure, which will be addressed in the conclusion of this paper.

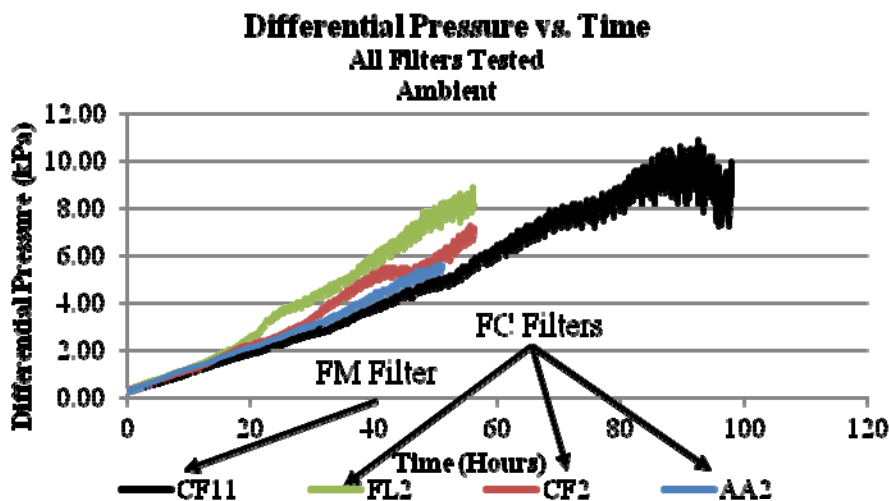


Fig. 6. Differential pressure versus time for all filters tested under ambient conditions until failure.



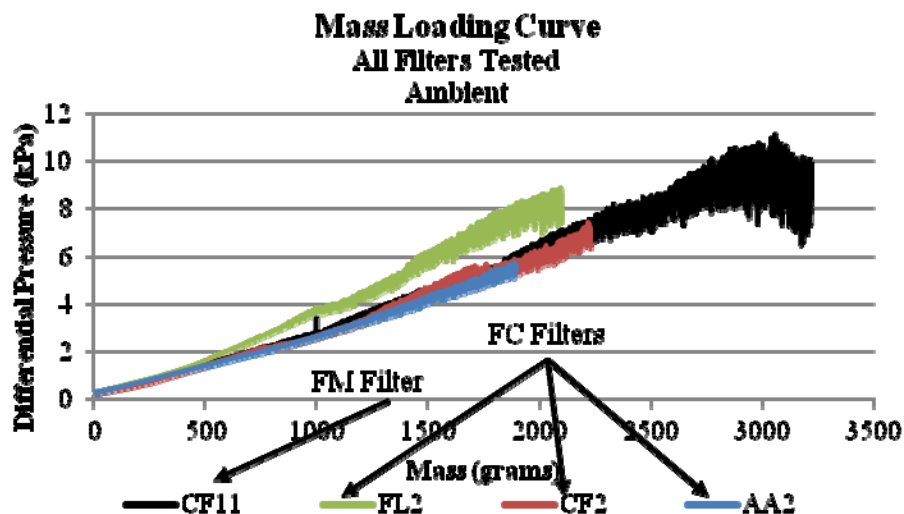


Fig. 7. Mass loading curves for all filters tested under ambient conditions until failure.

The next parameter of interest is the filtering efficiency of the filters. All filters were at or above HEPA efficiency. Figure 8 indicates that all filters were above 99.97% efficient until, in the FC filters' case, they began to leak. The FM filter never dropped below HEPA efficiency during testing.

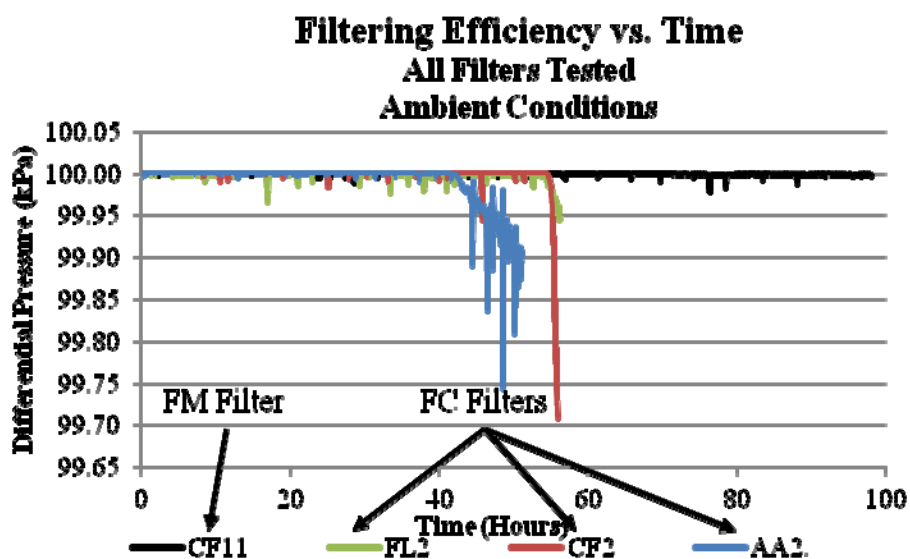


Fig. 8. Filtering efficiency versus time for all filters tested under ambient conditions until failure.

The filtering efficiency versus particle diameter, or penetration curve, for an FC axial flow HEPA filter is displayed in Figure 9. Multiple penetration curves are shown in Figure 9. After the initial samples, the filter was loaded with material and the filtering efficiency rose to greater than 99.998%. This very high efficiency was maintained until the filter began to leak because a high differential pressure was reached..

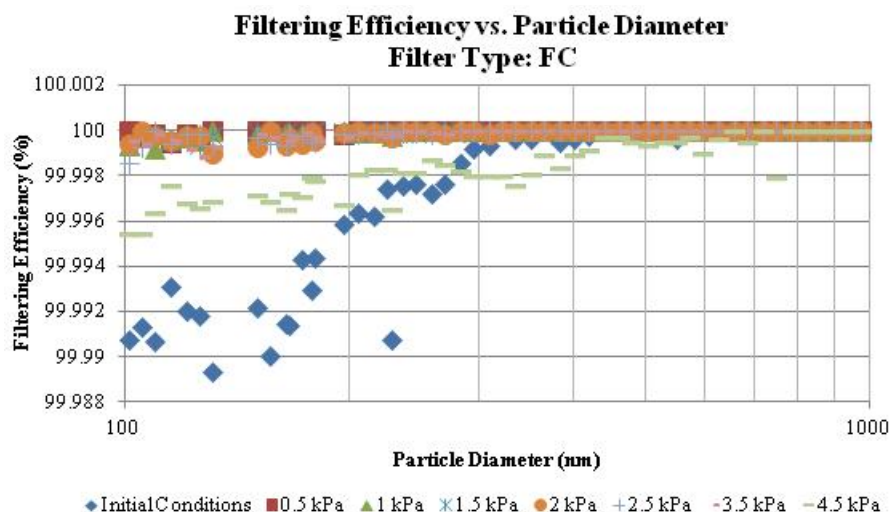


Fig. 9. Filtering efficiency versus particle diameter, or penetration curve, for an FC axial flow test filter.

### Elevated Condition Testing Results

To compare the performance of the test filters under elevated conditions, the mass loading of the filters up to 1 kPa (4 in. w.c.) under ambient conditions and their performance when subjected to elevated levels of temperature and relative humidity was examined. The first parameter, mass loading, is displayed in Figure 10. Figure 10(A) displays the mass loading curves for all 8 filters tested at elevated conditions. Three FC filters with Aluminum separators were tested, two FC filters with dimple pleat separators, and three FM filters. The two dimple pleat separator filters were tested at two different airflow rates. By examining all components of Figure 10, it can be seen that the dimple pleat filters were able to load the most material of all the filters. It can also be seen in Figure 10 that the Aluminum separator FC filters and the FM filters load approximately the same amount of material.

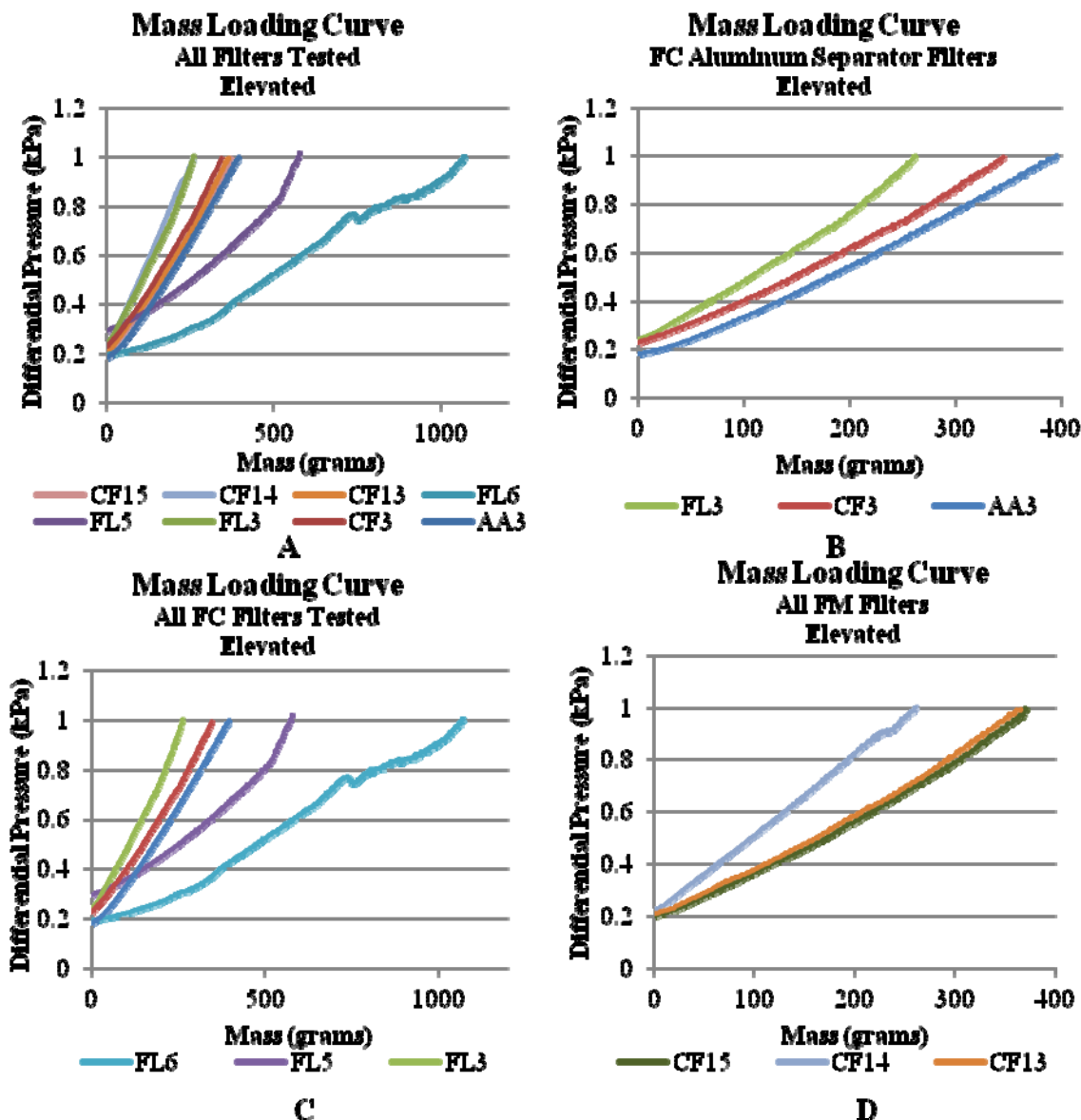


Fig. 10. Mass Loading curves for all filters used for elevated condition testing.

The remaining test parameter to examine the test filters performance at elevated temperature and relative humidity. Figure 11 displays the results of one FC Aluminum separator filter (A), one FC dimple separator (B), and one FM filter (C). These plots display the differential pressure for the filter and the up and downstream relative humidity and temperature. Figure 11 (B) displays the FC dimple separator filter experiencing a rapid increase in differential pressure due to 10 minutes of elevated temperature. The other filters tested decreased in differential pressure after the elevated relative humidity portion of the test.

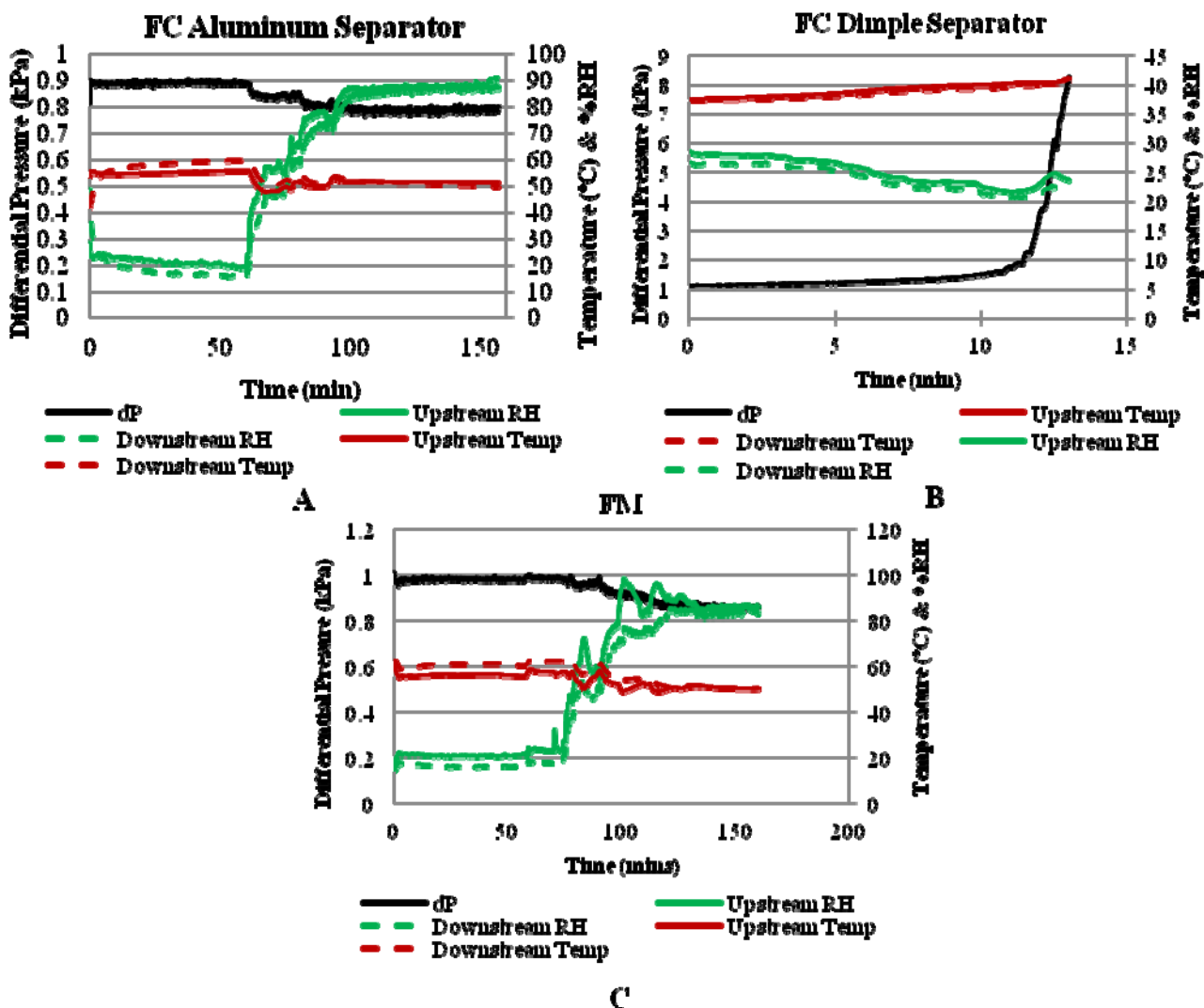


Fig. 11. Elevated condition testing results for (A) an FC filter with aluminum separators, (B) an FC filter with dimple separators, and (C) an FM, high strength filter.

## CONCLUSIONS

The purpose of this testing activity was to compare the performance of the prototype FM HEPA filters to the standard FC axial flow filters. The first performance criterion is nominal filtering efficiency. All filters tested exceeded the HEPA requirement of 99.97%. Once the filters were loaded with a small amount of aerosol, their efficiency increased to greater than 99.99%. Despite this high filtering efficiency, the FC filters began to leak once they reached a differential pressure of 5 to 8 kPa (20 to 32 in. w.c.).

The second parameter for comparison is the mass loading for the filters. As shown in Figures 7 and 10, the FC filters with aluminum separators and FM high-strength filters held a similar amount of material versus their corresponding pressure drop. The dimple pleat FC filters were able to hold much more material than the other filters tested. Ultimately, the FM filters held more material because they did not leak at higher levels of loading.

The Aluminum separated FC filters and the FM filters also did not fail during the elevated conditions testing. From Figure 11 (B) it can be seen that there is some issue with the dimple pleat separators as they began to rise quickly in differential pressure. After the elevated condition testing was completed all filters were dried overnight in an oven to remove any remaining water entrained in the media. These filters were then challenged with aerosol again to determine a final filtering efficiency. The aluminum separated FC and FM filters displayed comparable filtering efficiencies to what was measured prior to elevated condition testing. The dimple pleat FC filters saw a reduction in filtering efficiency but were very close to HEPA standard, at 99.969%.

A fluctuation in differential pressure and airflow rate was noticed during the testing of the prototype FM filters. Initially, it was suspected that this fluctuation was due to issues with the control system for the fan operation. After some assessment of the control system, it was determined that this was not the cause of the airflow fluctuations. Using the ICET camera probe, the test team captured images of the filter while still under airflow and found that it was the filter pack that was moving. The filter pack of the prototype FM filters was not as rigid as needed and was determined to be the cause of the airflow fluctuations. The next phase of testing will include evaluation of a redesigned prototype FM filter with additional pleats to stiffen the filter pack. Additional future work will include the addition of a burn box to allow for testing of filters with post combustion productions including smoke and soot. Future work is contingent upon receipt of funding.

## **PROJECT TEAM**

The Institute for Clean Energy Technology (ICET) at Mississippi State University (MSU) was established in 1979 to support the Department of Energy's (DOE) Magnetohydrodynamic (MHD) power program. From its inception, the mission of ICET has been to develop advanced instrumentation and use that instrumentation to characterize processes and equipment. ICET's testing capability and its ability to rapidly deploy very sophisticated instrumentation in the field have been important components of its success. ICET has recently become part of the newly formed Energy Institute at MSU.

ICET has a multidisciplinary staff of 20 full-time employees that include chemists, physicists, computer scientists, and chemical, electrical, and mechanical engineers. ICET scientists have leading-edge expertise in the application of lasers to energy and environmental cleanup. ICET's staff is a unique blend of measurement specialists, control specialists, and an experienced engineering and operations staff primed to carry out its mission. ICET also employs graduate and undergraduate students who further support research operations. ICET also employs a Certified Industrial Hygienist (CIH) and a Certified Hazardous Materials Manager (CHMM). These individuals ensure all activities conducted by ICET adhere to applicable environmental, safety, and health practices.

This testing activity has been developed through collaborations with representatives from the National Nuclear Security Administration (NNSA), DOE Office of Environmental Management (DOE-EM), New Mexico State University, and Mississippi State University.

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