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Large-scale generic test stand for testing of multiple configurations of air filters utilizing a range of particle size distributions

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The Institute for Clean Energy Technology (ICET) at Mississippi State University has developed a test stand capable of lifecycle testing of high efficiency particulate air filters and other filters specified in American Society of Mechanical Engineers Code on Nuclear Air and Gas Treatment (AG-1) filters. The test stand is currently equipped to test AG-1 Section FK radial flow filters, and expansion is currently underway to increase testing capabilities for other types of AG-1 filters. The test stand is capable of producing differential pressures of 12.45 kPa (50 in. w.c.) at volumetric air flow rates up to 113.3 m$^3$/min (4000 CFM). Testing is performed at elevated and ambient conditions for temperature and relative humidity. Current testing utilizes three challenge aerosols: carbon black, alumina, and Arizona road dust (A1-Ultrafine). Each aerosol has a different mass median diameter to test loading over a wide range of particles sizes. The test stand is designed to monitor and maintain relative humidity and temperature to required specifications. Instrumentation is implemented on the upstream and downstream sections of the test stand as well as on the filter housing itself. Representative data are presented herein illustrating the test stand’s capabilities. Digital images of the filter pack collected during and after testing is displayed after the representative data are discussed. In conclusion, the ICET test stand with AG-1 filter testing capabilities has been developed and hurdles such as test parameter stability and design flexibility overcome. © 2012 American Institute of Physics.

I. INTRODUCTION

A. Use of HEPA filters in nuclear applications

High efficiency particulate air (HEPA) filters are commonly used to control particulate matter (PM) emissions from processes that involve management or treatment of radioactive materials. For a filter to meet HEPA standards, the filter must remove at least 99.97% of particles size 0.3 μm and larger.1 Facilities within the U.S. Department of Energy (DOE) complex are likely to use HEPA filters to process exhaust gases prior to releasing them into the environment. Accepted design and performance standards for nuclear air filtration have changed from DOE or military standards to consensus or commercial standards such as those provided by ASME. Due to this shift, the DOE Nuclear Air Cleaning Handbook1 dictates that all air filtration systems for waste treatment facilities must comply with the ASME Code on Nuclear Air and Gas Treatment (AG-1).2 This standard is comprised of multiple sections that describe design and testing criteria for air and gas treatment for nuclear applications. The AG-1 standard requires very specific qualification procedures. Before filters can be used, the design must be qualified and each filter pass certification tests at a Filter Test Facility (FTF). These qualification procedures include: resistance to airflow, aerosol penetration, resistance to rough handling, resistance to pressure, resistance to heated air, spot flame test, and structural requirement inspections.

In May 1999, the Defense Nuclear Facilities Safety Board (DNFSB) released Technical Report 23 entitled HEPA Filters Used in the Department of Energy’s Hazardous Facilities.3 This report expressed concern for the potential vulnerability of HEPA filters used in vital safety systems. Several issues related to HEPA standards were addressed; including the fact that all filters did not undergo testing at FTFs to ensure each unit met standard specifications. Another issue addressed in the report was the decommissioning of testing facilities. The report also highlighted the need for a qualified products list test laboratory to resolve problems associated with filter wetting, aging, radiation induced degradation, bypass leakage consideration, and issues associated with HEPA filter infrastructure. The same year the report was released; DOE initiated a response to the DNFSB’s Recommendation 2000–20024 by implementing measures with regard to 100% quality assurance testing of HEPA filters and a review of vital safety systems in general.5 DOE’s actions also came at a time when concerns were being voiced by citizen groups over the performance of HEPA filters and how the functional status of a filter is monitored. Threats posed to HEPA filter performance by water and smoke are particularly concerning. DOE Standard 10666 titled “Fire protection Design Criteria” explains the measures and considerations to limit or prevent filter damage due to fire and smoke. Upset conditions, such as those during a fire, need to be evaluated and the performance of the HEPA filter qualified.

While radial flow filters have been used for nuclear applications in Europe, the ASME AG-1 Section-FK radial flow filters are relatively unproven and unqualified by
B. Test stand performance and data quality requirements

The ICET test stand was designed and constructed to perform lifecycle testing of AG-1 Section FK radial flow HEPA filters. The test stand is designed to that can perform lifecycle testing for multiple types of filters with multiple types of aerosols. The testing activity scope for this test stand is similar to the dust loading capacity testing performed by Loughborough at the AEA Harwell Facility.17

The AG-1 Section FK filter housing installed in the test stand allows for testing of up to two radial flow filters at a time to accommodate scaling considerations. The goal was to develop a test stand that could adequately represent large ducting systems. The test stand housing is set up to test one filter at a flow rate of 56.63 m³/min (2000 CFM) using a blind in the second filter port to maintain proper airflow. The test stand is capable of testing two radial filters at an air flow of 113.26 m³/min (4000 CFM). Further information on the current test plan has been published.19

The two designs of AG-1 Section FK filters are tested in the ICET test stand. The first filter design is the safe change design that can be safely removed and disposed of by hand. The second filter design is a remote change design that must be removed and replaced by a robotic arm. The filter media for both designs is dimple-pleated, separatorless, non-woven glass paper called Boron silicate microfiber. The filters are sealed to the housing by a knife edge that mates with a neoprene gasket. Figure 1 shows the two filter designs and their respective sealing surfaces. The cylindrical pleated filters have an open end, or annulus, and a closed end. Air enters the annulus of the filter interior and exits around the circumference of the exterior.

The test stand can be modified to accommodate other types of filters by replacing the filter housing. Other ASME AG-1 filters planned for testing are Section FC axial flow HEPA filters and Section FM (under development) high strength media filters. An AG-1 Section FC and FM axial flow filter housing accommodates one, two, or four 61 cm by 61 by 29 cm (24 in. by 24 in. by 11.5 in) filter at an air flow of 28.32 m³/min (1000 CFM).

To maximize the flexibility of the test stand, the system was designed for a wide range of test conditions. The performance capabilities of the test stand include volumetric flow rate, temperature, relative humidity, differential pressure across the filter, aerosol count median diameter (CMD), and mass loading rate. Table I presents the performance capabilities of the test stand as configured for the testing of AG-1 Section FK radial flow HEPA filters.

Sensors are used to evaluate temperature, relative humidity, static pressure, differential pressure, and volumetric air flow rate during testing. This information is observed and recorded to monitor test conditions for post-test analysis. Aerosol measurement instruments are needed upstream and downstream of the filter to determine mass loading rate, particle size distribution, the particle concentration, and the most penetrating particle size (MPPS). The current instrumentation...
suite is able to measure the size of particles from 20 nm to 20 μm. The instruments are also able to measure the particle concentration ranges from 10⁶ particles per cm³ upstream to less than 1 particle per cm³ downstream.

Data for the evaluation of nuclear grade HEPA filters are generated under the direction of a formal test plan. The test plan is subject to a technical peer review and is subject to data quality requirements if necessary. Typical quality requirements for confinement ventilation applications are identified in the ASME NQA-1 standard. Research activities also use the ANSI/ASQ Z1.13-1000 as an equivalent to the NQA-1 standard. Research activities conducted under these standards are subject to a quality audit. A peer review panel comprised of industrial and academic experts in aerosol technology and filtration would conduct on-site review of the project at start-up, periodically during testing, and of the final results.

Specific protocols exist to ensure proper handling of the collected data. First, all computers used for data acquisition and reduction are non-networked and have no internet connections. Next, all activities are logged in lab notebooks by qualified personnel. Finally, the data are made available on a secure secondary server for the project team and peer reviewers to examine.

The following are some of the representative categories of data collected during testing. The particle size distribution (PSD) is given for the upstream challenge aerosol. During ambient testing in the downstream section of the test stand, the number concentration, geometric standard deviation (GSD), and MPPS are displayed as they change versus differential pressure. The mass loading curve and the filtering efficiency curve for the filter tested were calculated after testing. Digital images of the filter pack are also collected during and after testing. For the elevated condition tests the temperature, relative humidity, and differential pressure (dP) are presented as a function of the testing time while the challenge conditions are varied.

II. TEST STAND AND METHODOLOGY DESCRIPTION

A. Test stand layout

The ICET test stand is capable of handling many different conditions that could be required during testing. These conditions involve varying the incoming air flow rate, temperature, and relative humidity. The induced draft fan is equipped with a Dura Pulse variable frequency drive (VFD) control capable of maintaining volumetric flow within a 0%–10% variance of the set test flow rate from 0 to 113.26 m³/min (0–4000 CFM). The induced draft fan is powered by a 100 hp (75 kW) electric motor that produces a vacuum flow through the test filters. Tests at ambient condition have a range of temperatures from 15.6 to 26.7°C (60 and 80 °F) and relative humidity (RH) between 40% and 60%. Tests at elevated conditions are conducted at temperatures of 54.4°C (130 °F) and varying levels of RH up to 100%.

A photo of the test stand is shown in Figure 2. The ductwork is composed of multiple sections of 0.61m (24 in.) diameter schedule 10 304 L stainless steel pipe connected with angle stubs and backing flanges. The exterior of the test stand piping has been powder coated to improve its appearance and durability. All sections, including the filter housing, have been electrically grounded to minimize wall deposition of aerosol particles due to electrostatic attraction. It is important to note the ambient air drawn into the test stand is not filtered. Figure 3 illustrates the design schematic for the entire test stand. Table II explains the components indicated in Figure 3.

Elevated temperature and humidity conditions are achieved using the test stand components illustrated in Figure 3. A natural gas burner, capable of 88 MW (3 MBTU), provides the thermal input, and a water spray injection system, spraying water at 60°C (140 °F) and 0.015 m³/min (4 GPM).
A major component of the test stand is the filter housing. The current housing was designed and fabricated by Flanders CSC. Modifications to the housing were made at the time of construction to allow for testing of remote or safe change radial flow filters. Figure 4 illustrates the housing configuration utilized to test one filter at 56.63 m³/min (2000 CFM). For single filter testing, the radial flow filter is positioned in the upstream position to avoid dead end effects on the flow and particle size distribution. A blind filter is used to seal the second housing filter position. The radial filter is pushed with the open end, into the housing to form a seal with a mating plate that defines the inlet to the filter.

Modifications were made to the filters and housing to accommodate both safe and remote change filter designs. Photographs of the modified filters are shown in Figure 1. The two filter designs differ in the location of sealing surface. Remote change radial flow filters are designed to be remotely installed vertically into the housing using a crane. Safe change radial flow filters are designed for bag-in/bag-out horizontal installation into the housing. The gels seals in the original designs were replaced with neoprene gaskets for testing at ICET.

The large-scale HEPA test stand currently employs a safe change radial flow filter housing. Testing of remote change filters required a modification to the safe change housing, as well as, to the remote change test filters themselves. In order to accommodate the slightly longer length of the remote change design, two all-thread rods were welded to the filter installation guide bars of the housing by Flanders Inc. A metal bar can then be placed across the end of the filter to secure the remote change radial flow filter in the housing as illustrated in Figure 4.

Because the remote change radial flow filter has a different diameter than a safe change filter, its endcaps must be modified to fit the guide bars of the safe change housing. This diameter difference was corrected by welding a flat metal plate of correct diameter to the closed end of the remote change test filters, which can be seen in Figure 1(d). The endcap at the annulus of the remote change filter is slightly larger in diameter than a safe change filter. This was corrected on test filters by cutting away portions of the endcap to accommodate the filter guide bars within the safe change housing.

### TABLE II. Test stand components.

<table>
<thead>
<tr>
<th>Component number</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Induced draft fan</td>
</tr>
<tr>
<td>2</td>
<td>Venturi flow meter</td>
</tr>
<tr>
<td>3</td>
<td>Radial flow housing</td>
</tr>
<tr>
<td>4</td>
<td>Aerosol neutralization section</td>
</tr>
<tr>
<td>5</td>
<td>Aerosol sampling locations</td>
</tr>
<tr>
<td>6</td>
<td>Powder feeder</td>
</tr>
<tr>
<td>7</td>
<td>Flow straightener (in duct)</td>
</tr>
<tr>
<td>8</td>
<td>Water nozzles</td>
</tr>
<tr>
<td>9</td>
<td>Air intake</td>
</tr>
<tr>
<td>10</td>
<td>Natural gas burner</td>
</tr>
</tbody>
</table>

B. Physical test parameter sensors

The ICET test stand is fully instrumented with sensors and controls to monitor the test stand environment. Control of the volumetric flow rate of the test stand is fully automated to maintain the test air flow rate to within 0%–10% of the set point. Installed sensors measure temperature, static pressure, relative humidity, and differential pressure. Temperature and static pressure sensors are installed on appropriate upstream and downstream sections of the test stand. A relative humidity sensor is installed on the upstream section. Differential pressure sensors are installed for measurement across the filter (or filters) tested, as well as, across the upstream and downstream sections of the test stand. Data from all sensors and controls are continuously logged by a central test stand control computer. An analytical balance is used to determine filter mass.

C. System control and data acquisition

Airflow through the test stand is produced by an induced draft fan and is measured by a venturi airflow meter installed...
in the downstream section of the test stand. This airflow meter measures volumetric air flow by examining the differential pressure between the entrance and the throat of the venturi. Using the differential pressure measurement, the frequency of the fan motor is automatically adjusted by means of the VFD, ensuring the measured airflow rate matches the volumetric airflow set point. All other physical test parameters are recorded for data analysis after the test is completed.

D. Aerosol generation

Three different aerosols are currently being used to simulate loading of differently sized particles. The first aerosol is carbon black (N991) manufactured by Cancarb Inc. represents soot loading. Loughborough at AEA Harwell Laboratory in the UK has conducted tests using this aerosol. The second aerosol is alumina, Al(OH)₃, Spacerite S-11 manufactured by Almatis, Inc. This aerosol is used to represent loading by small particles. Alumina has previously been used in filter loading tests. The final aerosol used is Arizona road dust (A1 Ultrafine) manufactured by Powder Technology Inc. This test dust is used to represent loading by larger particles. While these aerosols are the only ones currently in use, the test stand is capable of making use of a wide variety of other aerosol powders.

An aerosol is generated and dispersed using a powder feeder and dried compressed air. A powder feeder deposits aerosol powder by turning twin screw augers. The speed of these augers can be changed to vary the amount of aerosol that is dispensed. Dispensed powder is fed into a critical orifice 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 with an air dryer to prevent agglomeration and changes to the PSD. The pressure allows for sufficient break-up of the powder, resulting in a uniformly dispersed aerosol. The aerosol injection nozzle is oriented so that it injects the powder against the direction of airflow inside the test stand: i.e., countercurrent.

The powder feeder can be adjusted to obtain a mass loading rate sufficient to cause failure (rupture) of a radial filter within 24 h. This yields a target mass loading rate for the alumina and carbon black aerosols of 30 mg/m³, and for the Arizona road dust of 100 mg/m³. Current testing has shown rupture of Section FK filters to occur on average at 7.5 kPa (30 in. w.c.) of differential pressure.

Another aerosol generation system is currently under development to generate smoke and soot in a burn box. In this box, different combustibles will be burned to provide the test stand with smoke and soot at much higher temperatures than the filter would normally encounter, thereby simulating a loading scenario during upset fire conditions.

E. Aerosol neutralization

The aerosols dispersed in the test stand can be highly charged by triboelectric processes during the generation process. These charges must be neutralized to maintain a steady morphology of particle deposit on the filter. The test stand is equipped with four Strontium-90/Yttrium-90 (Sr-90/Y-90) beta radiation sources to effectively neutralize the triboelectric charging of the aerosol particles. The four sources are oriented 90° from each other and are located immediately downstream of the aerosol injection site and upstream of the particle measurement instruments.

Sr-90/Y-90 produces two energetic beta particles from the decay of Sr-90 to Y-90 and from Y-90 to Zirconium-90. As the beta particles traverse the test stand, some of their kinetic energy is deposited in the surrounding air, effectively producing ion-pairs. The ion-pairs bond with the charged aerosols to neutralize them. For proper neutralization, 6 × 10⁶ ion-pairs per second per cubic centimeter need to be produced. To ensure this value is reached or exceeded, four 1.48 × 10⁹ Bq (40 mCi) sources were used. It is estimated that the four sources together will generate 2.5 × 10⁷ ion-pairs per cubic centimeter with a 1 s residence time, which is well above the minimum requirement. A report relating the neutralizer design and performance is in preparation.

F. Aerosol measurement

The current suite of aerosol measurement instruments used on the large-scale test stand is the aerodynamic particle spectrometer (APS), the scanning mobility particle sizer (SMPS), the laser aerosol spectrometer (LAS), and the electrical low pressure impactor (ELPI). The APS is a time-of-flight measurement device that measures the aerodynamic diameter and light-scattering intensity of aerosol particles and has been extensively studied. The SMPS consists of a 95 cm long differential mobility analyzer, and a condensation particle counter. The LAS operates based on the principle that the degree of light scattering is dependent on the size of the aerosol particle. The ELPI is capable of sizing and counting aerosol particles by charging them electrically, sizing them by inertial impaction, and counting them utilizing internal electrometers for each impactor stage. More information on these instruments is available. When these instruments are used a PSD from 0.01 μm to 20 μm upstream and 0.09 μm downstream can be measured. The concentration range upstream is from 1 particle per cm³ to 1 × 10⁷ particles per cm³ and downstream from less than 0.02 particles per cm³ to 1.8 × 10⁶ particles per cm³.

III. TEST STAND CHARACTERIZATION

A. Ambient condition testing characterization

1. Flow characterization

Before testing began, the ICET large-scale test stand was fully characterized by conducting a series of shakedown tests. Characterization includes operation and control of the induced draft fan and VFD used to produce desired test flow rates. Fan start-up was optimized to prevent the VFD from overshooting the desired flow rate. Figure 5(a) provides an example of the flow rate exceeding the desired flow rate of 56.63 m³/min (2000 CFM) by nearly 50%.
Parameters established for testing called for no more than a 10% deviation in flow rate, yet the flow rate would exceed the desired set point by more than 10% on startup. This issue of overshooting the set volumetric flow rate was corrected by dampening the voltage applied to the VFD to provide a slower increase up to the desired set point. Another issue, displayed in Figure 5(b), is the VFD control during the latter stages of filter testing when the fan speed is unable to keep pace with the rise in differential pressure.

Optimization of the flow rate over the full test range requires damping of the increase in VFD frequency during startup to prevent overshoot while keeping up with the exponential rise in differential pressure when the filter approaches rupture. This situation is handled by stair-stepping the differential pressure to the desired flow rate during start-up. Figure 6 illustrates the performance of the control system in maintaining the rated flow over the full range of filter testing.

2. Parameter stability

Further shakedown tests were conducted to ensure the stability of flow, temperature, and relative humidity over time.

A flow straightener designed according to requirements of ASME standard MFC-3M-2004 (Ref. 26) has been used. The flow straightener is fabricated from 76.2 mm (3 in.) steel pipes which are 0.9 m (3 ft) in length and inserted into the section upstream of the flow measurement venturi as illustrated in Figure 3 penetrating the test facility wall. This flow straightener is necessary to ensure that cyclonic flow in the test stand due to the 90° bends in the test stand duct work does not affect the venturi flow measurement and fan speed control.

To ensure that samples taken for aerosol measurement are representative of the entire duct, flow traverses were taken. Flow traverses also enabled the assessment of swirl of the airflow inside the test stand. Horizontal and vertical velocity profiles of the test stand were obtained by performing velocity traverses of the test stand duct. EPA standard test methods 1 and 2 (Refs. 27 and 28) were used to determine sampling location and a number of traverse points for these tests. The horizontal and vertical velocity profiles of the test stand duct obtained from these tests are illustrated in Figure 7. The velocity profiles were obtained with no filter installed in the test stand housing. The plots indicate that the flow stays relatively uniform everywhere except the top and back sides of the duct. Figure 7 reveals that when the burner is operating, the flow averages more than the set point. Since the differential pressure for the venturi meter is proportional to the product of air density and volumetric flow squared, the decreasing air density at high temperature is responsible for the higher flow. The average volumetric flow rate when the burner is operating is 66.5 m³/min (2350 ACFM).

3. Differential pressure correction and leak testing

Because the filter housing used in the ICET test stand has a slight differential pressure across it with no filter installed, a tare dP for the housing was determined. This was accomplished by measuring the dP across the housing at 7.08 m³/min (250 CFM) increments from 28.3 to 113.3 m³/min (1000–4000 CFM). When this tare dP is subtracted from the measured dP, the differential pressure...
FIG. 7. Test stand ductwork volumetric air flow traverses.

reading for HEPA filters is equivalent to that measured at the FTF. The results of the tare dP measurements plotted, using Eq. (1), where the “K” constant is calculated to equal $1.3979 \times 10^{-7}$. Figure 8 shows the results of the tare dP correction

$$dP = KQ^2.$$  \hspace{1cm} (1)

The test stand leak testing is governed by ASME N509-2002 and N510-2007 standards.\(^29,30\) These standards allow for 0.1% infiltration in duct and 0.1% in housing during leak testing for a type 1 facility. The volume of the ICET large-scale HEPA test stand that must undergo leak testing is 8.32 m$^3$ (293.9 ft$^3$), with 2.45 m$^3$ (86.6 ft$^3$) from the filter box and 5.87 m$^3$ (207.3 ft$^3$) from the inlet and outlet ducts. For a nominal flow of 113.27 m$^3$/min (4000 CFM), the allowable infiltration during leak testing is 0.113 m$^3$/min (4 CFM). The ICET test stand had a leak of $\sim$0.028 m$^3$/min (1 CFM).

4. Aerosol PSD and number density

The three challenge aerosols used in the ICET test stand have different PSD and display different number concentrations flowing upstream. The PSD of each aerosol is presented in Figure 9. In Figure 9, we see the PSD for each aerosol. The data were generated by collecting the submicron aerosol concentration with the SMPS unit and the larger particles with the APS unit. The APS characterizes the aerosol size based on an aerodynamic diameter and was converted over to an equivalent diameter using the particle density of the aerosol and assuming the aerosol shape is a sphere.

In Figure 9, it appears the carbon black and alumina aerosol might be slightly bimodal. This appearance is due to the reduction in counting efficiency of the APS instrument as it measures particles less than 1 $\mu$m in size. To minimize

FIG. 8. Tare dP for the ICET large-scale HEPA test stand housing without a filter.

FIG. 9. PSD of the challenge aerosols.
this error the transition point from SMPS to APS was set at 0.85 μm. Taking this into consideration the challenge aerosols have only one mode. The number concentration, CMD, GSD, and mass median diameter (MMD) for each aerosol is presented in Table III.

### TABLE III. Measured aerosol parameters.

<table>
<thead>
<tr>
<th>Aerosol</th>
<th>Number concentration</th>
<th>CMD</th>
<th>GSD</th>
<th>MMD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina</td>
<td>650 000 #/cc</td>
<td>0.185 μm</td>
<td>2.17</td>
<td>0.8 μm</td>
</tr>
<tr>
<td>AZ road dust</td>
<td>100 000 #/cc</td>
<td>0.186 μm</td>
<td>1.86</td>
<td>5 μm</td>
</tr>
<tr>
<td>Carbon black</td>
<td>450 000 #/cc</td>
<td>0.250 μm</td>
<td>2.21</td>
<td>1.2 μm</td>
</tr>
</tbody>
</table>

B. Elevated conditions characterization

1. Burner aerosol issue characterization

The first issue to resolve for elevated condition testing was to characterize the burner emissions. The test team theorized that the burner emissions had a PSD with a very high concentration of ultrafine particles during ignition. This theory was confirmed by examining the burner start up PSD, as shown in Figure 10.

Figure 10 shows that the number concentration of burner emissions rivals that of the alumina powder, yet the burner emission particles are ∼150 nm smaller than the alumina, thus increasing their filter plugging potential. However, the burner ran significantly cleaner very quickly after start-up, generating fewer aerosols as seen in Figure 10. Figure 10 also shows the warmed up burner generates a similar PSD and number concentrations as ambient room air. Therefore, the filter must be removed from the test stand when starting the burner to avoid the initial aerosols it generates. This protocol was validated in a preliminary test. The use of this method as opposed to venting the burner gas was used due to safety limitations.

2. Volumetric flow rate characterization

After resolution of the burner emission issues, the test team examined the parameters affecting the volumetric flow rate. The system is intended to operate at a constant flow rate independent of changing temperature, while the actual flow rate rises with increasing temperature. To evaluate this flow increase, the research team first performed pitot traverses through the test stand ducts to determine the volumetric flow rate through the horizontal and vertical axis under elevated conditions, as shown in Figure 7. The traverses revealed the flow was averaging a difference of 7.1 m³/min (250 CFM) higher than the setting of 56.63 m³/min (2000 CFM) at ambient conditions and a difference of more than 14.3 m³/min (500 CFM) higher in some places at elevated temperature.

To further examine this the research team tested a filter pre-loaded with alumina to a differential pressure of 1 kPa (4 in. w.c.) at elevated standard flow rates. The test stand remained at ambient temperature and relative humidity in order to further evaluate the specific influence of elevated flow rate. Figure 11 presents the results from this test, illustrating how differential pressure of the filter increases as the volumetric air flow rate is increased first to 65 m³/min (2300 SCFM), then to 71 m³/min (2500 SCFM), and back to 56.63 m³/min (2000 SCFM). Figure 11 shows that the greater the flow rate deviates from 56.63 m³/min (2000 SCFM), the greater the slope of the differential pressure increase across of the filter, which indicates that the increase in volumetric flow impacts filter life.

3. Elevated temperature characterization

The next test performed by the test team was designed to evaluate the impact of temperature alone, negating the
increase in flow rate associated with operating according to standard flow (SCFM in English units). For this test, a new filter was pre-loaded with alumina to 1 kPa (4 in. w.c.), then removed from the test stand housing. The burner was then ignited and the system allowed to reach a stable 54 °C (130 °F) before the filter was reinstalled, this action was taken to avoid the burner ignition aerosols. The filter was exposed to a flow of 56.63 m³/min (2000 ACFM) at a temperature at 54 °C (130 °F). After 1 h of exposure, the filter showed very little change in differential pressure, 0.125 kPa (0.5 in. w.c.), indicating that temperature has a minor influence on the performance of the filter, less than the influence of the elevated flow rate.

C. Data quality control measures

Evaluation of filters using the large-scale test stand is conducted in accordance with a rigorous quality program from the initial purchase of test filters to quality assurance checks for all instrumentation utilized. The process begins by ordering filters that meet test design specifications. The filters are then shipped from the manufacturer to the FTF at Air Techniques International (ATI) in Baltimore, MD for inspection and testing prior to shipment to ICET. Upon receipt at ICET, all documentation accompanying the shipment is checked to ensure that all filters have been received and all inspection/testing documentation from the FTF is included. Shipping containers and filters are inspected for damage immediately upon receipt. Any damage noted is recorded on an inspection document and digital photographs of the shipping containers and filters are collected. Filter serial numbers are checked against the shipping documentation to verify that the order is complete. Shipping documents, FTF inspection/testing results, ICET inspection results, and photographs are catalogued in a central database.

Prior to testing a filter, a series of quality control steps is carried out to ensure the test stand is suitably configured for testing. Each step is documented by the responsible person or persons. This process begins with verification by the testing supervisor of all test stand sensors (flow, temperature, static pressure, differential pressure, and temperature) to ensure they are properly installed and calibrated. Any sensor not within calibration is calibrated, and the “as found” data and calibration data are catalogued.

Once the testing supervisor has verified and documented that all test stand sensors are within calibration, he organizes a pre-test conference with the project principal investigator, the quality control supervisor, ICET’s health and safety officer, and all test personnel to review the test stand configuration, the type of filter to be tested, and test parameters (temperature, humidity, flow rate, aerosol challenge conditions, etc.). The health and safety officer is also responsible for assuring that any aerosol emissions, from the test stand meet any environmental compliance requirements. The pre-test conference is documented and any comments by the principal investigator, quality assurance supervisor, and health and safety officer are recorded and signed by each individual. Only after completion of this conference and signing of the pre-test conference document can testing begin.

Testing procedures and control documents are used for each aspect of testing. Test procedures include: installation and removal of test filter, test stand startup and shutdown, readiness and operation of aerosol generation equipment, readiness and operation of aerosol measurement instrumentation, and test data archiving information. The test control document records all aspects of the testing performed utilizing the specific filter. Some of the information included in the test control documents are: the test control number, lab notebook page numbers, test time and date, type and design of filter tested, filter serial number, testing flow rate, initial differential pressure, and aerosol challenge information, and a check list for each test procedure completed during the course of testing. A record of the file names for all data files generated during testing is recorded in the lab notebooks. All of these measures ensure testing activities are performed and recorded in a complete and accurate manner.

IV. REPRESENTATIVE TEST RESULTS

A. Ambient condition testing

The FK prototype filter data sets discussed below were obtained from the evaluation of a remote change filter designed to meet AG-1 Section FK requirements manufactured by Flanders Inc. Discussion of remote change filter data sets will be followed by a set of loading curves for both safe and remote change filters loaded with each of the three test aerosols. All filters were inspected by the Air Techniques International (ATI) FTF in Baltimore, MD, prior to testing to verify production quality.

The remote change test filter was evaluated by loading the filter with the carbon black aerosol from its initial dp of 348.7 Pa (1.4 in. w.c.) until failure. Loading of the filter was performed at rated flow of 56.63 m³/min (2000 CFM), a temperature range of 21.1–26.7 °C (70–80 °F), and a RH of 40%–60%. The filter was conditioned for 1 h at rated flow in the absence of challenge aerosol, removed from the test stand, and weighed to determine the tare mass of the filter.

1. Upstream number density, PSD, GSD, and mass loading

The upstream data recorded are the size and concentration of the aerosols generated from the aerosol generation system. This information is typically recorded using the APS and SMPS, for large and small particles, respectively, although other instruments are available for use to vary the range of particles to be detected. The information can be used to present the upstream PSD, CMD, and GSD, fully characterizing the upstream challenge aerosol. The mass loading rate is also obtained from the information recorded by the upstream instrumentation.

2. Downstream number density, MPPS, and GSD

The downstream aerosol PSD is characterized by measuring the variability of aerosol size distribution and concentration as the differential pressure changes. The data are
presented as number concentration, GSD, and MPPS. These results are illustrated as Figures 12(a)–12(c). Figure 12(a) shows the downstream concentration drops to virtually 0 as the differential pressure across the filter rises due to dust loading on the filter. This drop occurs before the differential pressure rises just 0.25 kPa (1 in. w.c.) above its initial differential pressure. Increases in the downstream concentration begin to rise at above 3.75 kPa (15 in. w.c.) and structural failure of the filter occurs at 7.2 kPa (29 in. w.c.).

Particle count/size data are used to calculate the MPPS and GSD. Downstream particle measurements are made continuously using a TSI model 3340 LAS. These data are used to correlate particle size and number concentration as the filter loads, as indicated by increasing dP. Although the data are scattered, the results yield an approximate MPPS less than 150 nm and the GSD to be less than 1.3.

3. Filtering efficiency

One of the most important characteristics of a filter is its filtering efficiency. As previously mentioned, HEPA filters are required to be at least 99.97% efficient at removing particulate matter greater than 0.3 μm from an airstream. This calculation was performed by examining the total concentrations upstream and downstream, as well as, examination of the PSD upstream and downstream to determine the MPPS. From testing of these filters we found that the FE at the MPPS was greater than 99.97%; therefore, we can assume that the FE for particles 0.3 μm and larger is also greater than 99.97%. The total filtering efficiency for all particles measured and differential pressure as a function of time for the test filter is displayed in Figure 13. As illustrated, the filtering efficiency was always above the HEPA requirement and very quickly approached greater than 99.9999%. This high value of FE was maintained until just before filter rupture.

4. Mass loading curves for the different filters and aerosols tested

The filter mass loading curve is a very significant component in filter lifecycle performance data. The mass loading curves for different filter types and challenge aerosols are presented in Figure 14. The graph in Figure 14 indicates the impact that the PSD has on the total mass loading on these HEPA filters. These loading curves all show a more abrupt rate of change in dP above 2 kPa (8 in. w.c.). This is representative of a change in the filter pack geometry due to pleat collapse as shown in Figure 15.
5. In-testing images

The test stand is equipped with a digital camera in the filter housing to monitor record changes in the filter pack during loading. The camera is located at the area postulated to undergo the highest amount of stress and thus deemed most likely to observe failure, near the seam in the filter media. Digital images collected during testing provide important evidence related to the filter pack during loading. Time-stamped images of the filter pack exterior are collected during testing at specific dP intervals (initial up to failure). Images collected by this camera allow observation of filter pack behavior during testing as well as post-test review of either the series of still images or a compilation of the images into a “video” of filter pack behavior.

![Image](FIG. 15. In-testing images (a): 1 kPa (4 in. w.c.), (b): 2.5 kPa (10 in. w.c.), (c): 5 kPa (20 in. w.c.), (d): Failure due to pleat collapse 7.2 kPa (29 in. w.c.).)

Figure 15 displays the filter pack at 1 kPa (4 in. w.c.), 1.5 kPa (10 in. w.c.), and 5 kPa (20 in. w.c.) of differential pressure, and filter failure, which for the test filter was 7.2 kPa (29 in. w.c.) In Figure 15(a), the gaps between the filter media pleats can be seen. These pleats allow for maximum filter surface area. Figures 15(b) and 15(c) show gaps starting to close, and 15(d) shows that the pleats have collapsed, leading to failure.

A second removable digital camera is used to capture still images of the interior of the filter. Collecting images of the filter pack interior can only occur in the absence of a challenge aerosol. Typically, this camera collects images at full test flow rate prior to testing and after failure. Images after failure, sometimes referred to as post-rupture, are also collected. Figure 16 displays these images at the filter pack – potting material interface (a), the filter interior (b), and the filter exterior (c). These images show that approaching and during filter rupture there is a significant change in the filter geometry.

![Image](FIG. 16. Filter rupture images.)

B. Elevated condition testing

The following results examine only the elevated temperature and relative humidity portions of the test. The filters were loaded with alumina until they reached 1 kPa (4 in. w.c.) of differential pressure across the filter. The filter was then removed, while the burner was ignited to prevent soot loading of the filter. Once the test stand was pre-heated, and the burner PSD stabilized, the filters were reinstalled and the flow rate increased to a standard flow rate of 56.63 m³/min (2000 SCFM). All filters responded similarly, therefore the results for one remote change filter will be examined here. In this test, the alumina loaded filter was exposed to elevated temperature 54 °C (130 °F) for 1 h, while the RH remained low. Figure 17 illustrates that during that time there was little to no increase in the differential pressure across the filter. After 1 h, the water spray was initiated to elevate the RH. The RH was incrementally increased to 80% before the filter ruptured. No additional aerosol challenge was added during the high temperature and high humidity test. The data suggest that high...
humidity can greatly increase the filter dP of partially loaded filters.

V. CONCLUSIONS

A versatile test stand has been designed and constructed by ICET at Mississippi State University that is capable of lifecycle testing for a range of filter types by housing replacement. Testing conditions can be varied by challenge aerosol, testing flow rate, temperature, and relative humidity. The test stand is designed to be as adaptable as possible to meet many particular testing requirements and will continually undergo upgrades to enhance the versatility of the test stand and capabilities of the facility. The data generated by the test stand will meet NQA-1 quality standards if requested by the customer. Planned upgrades include installation of an AG-1 Section FC housing to allow performance testing for Section FC and FM filters. This testing will also utilize a burn box where different combustibles will be burned to generate varying soot and smoke challenges. Future enhancements may include filter housings to accommodate different filter types/designs, use of a broader range of aerosols and sizes, and additional sensor and monitoring instrumentation.

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24. EPA Standard Test Method 2—Determination of Stack Gas Velocity and Volumetric Flow Rate (Type S Pitot Tube), U.S. Environmental Protection Agency, 2/2000; 40 CFR 60 Appendix A.
