# Results from Evaluation of Representative ASME AG-1 Section FK Radial Flow Dimple Pleated HEPA Filters Under Elevated Conditions - 12002

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## ABSTRACT

The American Society of Mechanical Engineers (ASME) has recently added Section FK establishing requirements for radial flow HEPA filters to the Code on Nuclear Air and Gas Treatment (AG-1). Section FK filters are expected to be a major element in the HEPA filtration systems across the US Department of Energy (DOE) complex. Radial flow filters have been used in Europe for some time, however a limited amount of performance evaluation data exists with respect to these new AG-1 Section FK units. In consultation with a technical working group, the Institute for Clean Energy Technology (ICET) at Mississippi State University (MSU)has evaluated a series of representative AG-1 Section FK dimple pleated radial flow HEPA filters. The effects of elevated relative humidity and temperature conditions on these filters are particularly concerning. Results from the evaluation of Section FK filters under ambient conditions have been presented at the 2011 waste management conference. Additions to the previous test stand to enable high temperature and high humidity testing, a review of the equipment used, the steps taken to characterize the new additions, and the filter test results are presented in this study. Test filters were evaluated at a volumetric flow rate of 56.6 $m^3$/min (2000 cfm) and were challenged under ambient conditions with Alumina, $Al(OH)_3$, until reaching a differential pressure of 1 kPa (4 in. w.c.) , at which time the filters were tested, unchallenged with aerosol, at 54ºC (130ºF) for approximately 1 hour. At the end of that hour water was sprayed near the heat source to maximize vaporization exposing the filter to an elevated relative humidity up to 95%. Collected data include differential pressure, temperature, relative humidity, and volumetric flow rate versus time.

## INTRODUCTION

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. Facilities within the DOE complex are likely to use HEPA filters to process exhaust gases prior to releasing them into the environment.

### Radial Flow HEPA Filter for Nuclear Applications

Accepted design and performance standards for nuclear air filtration has 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 Handbook [1] 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 dictate and testing criteria for air and gas treatment in nuclear applications.  The AG-1 standard requires very specific qualification procedures. Before any filter can be used within the DOE complex, it must be qualified and pass certification 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 a structural requirement inspection. More on the qualification procedures can be found in the AG-1 standard.

Currently, the primary filter of choice within the DOE complex is the AG-1 Section FC axial flow filter. The most common Section FC filter is the square, a deep pleated, axial flow filter with metal separators. While this unit provides high filtering efficiencies and dust loading capacities, it presents other issues with handling and disposal. Radial units provide benefits in remote handling, ease of sealing, disposal, compaction, reduction in sharp edges, and retention of particulates during handling [3]. Radial flow filters have been studied in the United Kingdom [3,4,5]. Based on these data, it has been determined that facilities within the DOE complex would benefit from using the new radial flow design. Section FK was added to the AG-1 standard to address special types of HEPA filters, such as the radial flow circular filter. Some European loading data for these types of filters are available [5], yet the AG-1 Section FK filters are different than their European counterparts, and therefore require further testing.

In May of 1999 the Defense Nuclear Facilities Safety Board (DNFSB) released Technical Report 23 entitled *HEPA Filters Used in the Department of Energy's Hazardous Facilities* [6]. 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 one met the required specifications, as well as the decommissioning of several testing facilities. Further points addressed in the document include the need for a qualified products list (QPL) test laboratory; the problems associated with filter wetting, aging, radiation induced degradation, and by-pass leakage consideration; and the issues associated with the HEPA filter infrastructure.

Later that same year, the DOE initiated a response to the DNFSB's Recommendation 2000-2 [7] by implementing measures with regard to 100 percent quality assurance testing of HEPA filters and a review of vital safety systems in general [8]. 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 1066 [9] 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.

**Previous Testing**

Filtration research at ICET began 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 [10], presented at numerous conferences [11,12,13], and published [14]. These details include aerosol generation, types of filters tested, and the aerosol measurement instrumentation utilized.

Testing was performed to evaluate the lifetime performance of AG-1 Section FK representative radial flow dimple pleated HEPA filters under ambient conditions. These filters are only representative AG-1 units as there are currently no qualified filters. A total of nine representative filters were challenged by one of three challenge aerosols at ambient conditions. The ambient conditions ranged from 15.6 to 26.7ºC (60 and 80ºF) and 40 to 60% Relative Humidity (RH). This information has been previously presented [15]. A major result of this testing was an observed failure in one of the representative filter designs to maintain separation between the pleats as the filter began loading to higher levels of differential pressure. The visually observed failure began early at 1.5 kPa (6 in. w.c.).

**Current Research**

This document illustrates the performance of AG-1 Section FK representative radial flow dimple pleated HEPA filters when challenged with elevated temperature and relative humidity conditions, 54ºC (130ºF) and 80+% RH. The protocol for testing dictates that the filters are first challenged under ambient conditions using Alumina ($Al(OH)_3$) as the challenge aerosol until they reach a differential pressure of 1 kPa (4.0 in. w.c.). After this initial loading, the filter will be challenged with no aerosol at an elevated temperature of 54ºC (130ºF). After approximately 1 hour and/or the filter differential pressure appears to be stabilized, a water spraying system will be initiated to increase the RH incrementally to 25%, 50%, and 75+%.All testing conditions will be monitored to record the filter's differential pressure under each stage of testing.

Two filter designs were tested, both of which are representative of an AG-1 Section FK filter. The first was the safe change filter, a filter designed to be safely removed and disposed of by hand. The second is a remote change filter, designed to be removed and replaced by a robotic arm. The media of both filters is dimple pleated, separatorless, non-woven glass paper called Boron silicate microfiber. Table I displays the filter pack design parameters.

Table I. Filter Pack Design Parameters for the Safe Change and Remote Change Filter Types.

| Filter Type | Safe Change | Remote Change |
|---|---|---|
| Number of Pleats | 345 | 330 |
| Media ($m^2$) | 29.73 | 29.17 |
| Interior Diameter (cm) | 33.02 | 27.94 |

The filters are sealed to the housing by a knife edge that fits with a neoprene gasket. Figure 1 shows the two filter designs and their respective sealing surfaces.

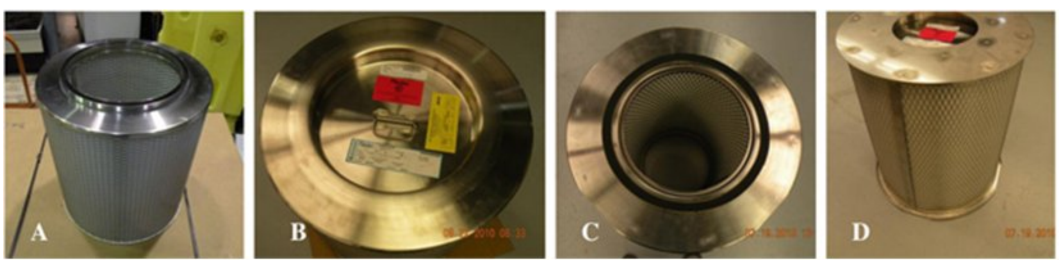


Fig. 1. Photographs of (A,B) Safe Change and (C,D) Remote Change Filters

The radial flow test stand at MSU is constructed from multiple sections of 0.61 m (24 in.) diameter, schedule 10, 304L stainless steel pipe connected with angle stubs and backing flanges. The exterior of the test stand piping is powder coated to improve durability. All sections, including the filter housing, have been electrically grounded to minimize wall deposition of aerosol particles due to electrostatic attraction. Figure 2 features an image of the test stand.

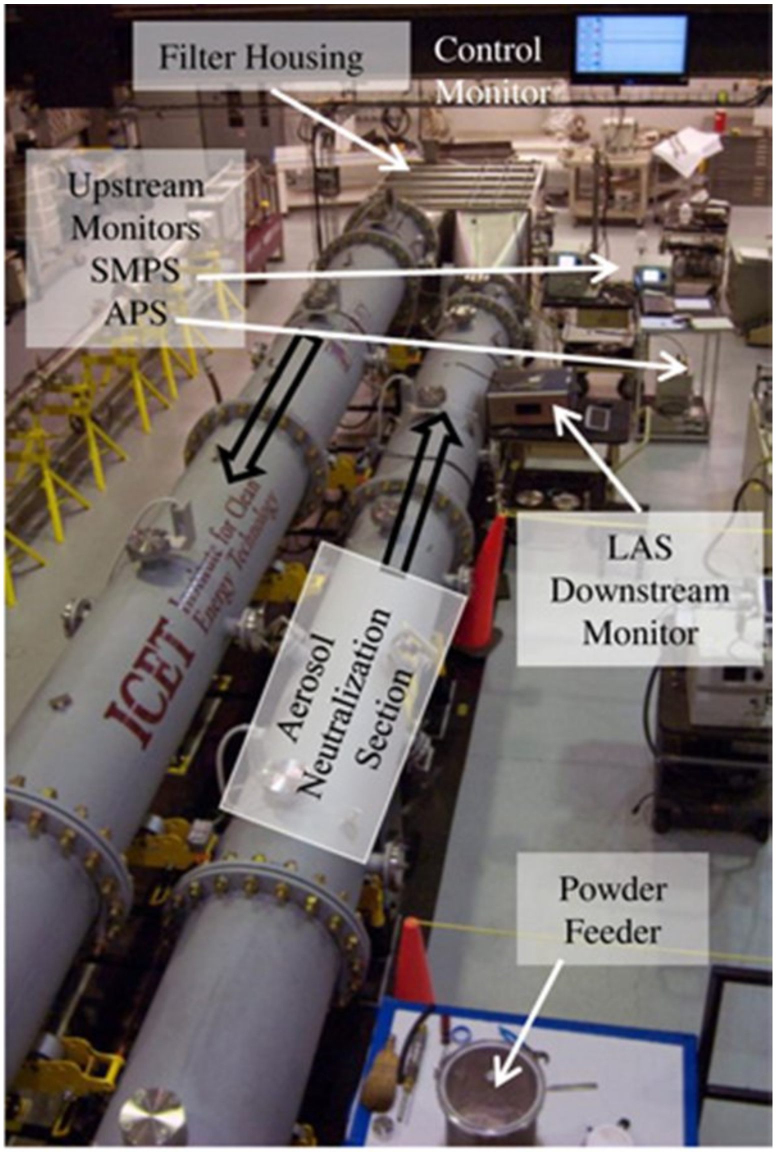


Fig. 2. Image of the Current ICET Test Stand

The test stand utilizes a fan that is capable of producing differential pressures of 12.45 kPa (50 in. w.c.) at volumetric air flow rates of 113.3 $m^3$/min (4000 cfm). The housing is capable of testing two filters at 113.3 $m^3$/min (4000 cfm) or one filter at 56.63 $m^3$/min (2000 cfm). Only one filter is used for this series of testing while a blind takes the place of the other filter, blocking airflow from the second filter port. More information about the test stand housing is available [15].

Aerosol is generated, during the ambient condition loading up to 1 kPa (4 in. w.c.), and dispersed using a powder feeder and compressed air that has been dried. The aerosol is generated by a K-TRON SODER powder feeder that deposits the aerosol powder by turning twin screw augers. The speed of these augers can be adjusted to vary the amount of aerosol that is dispensed. Dispensed powder is fed into a critical orifice (VACCON) positioned directly beneath the powder feeder. The critical orifice pulls a vacuum on the aerosol powder and ejects the aerosol into the test stand using 413.7 kPa (60 psi) of compressed air. Air supplied to the critical orifice is dried to prevent agglomeration and changes to the particle size distribution

(PSD). The pressure allows for sufficient break-up of clumps of aerosol, assuring that the resulting aerosol is uniformly dispersed. The aerosol dispersal nozzle is oriented to release the powder against the direction of airflow, i.e., countercurrent. The Alumina, $Al(OH)_3$ has an aerodynamic mass median diameter of 0.3 μm. Alumina has been previously used in other testing activities [16, 17].

To properly evaluate the HEPA filters under elevated conditions, the testing system was first characterized. Following characterization, three test filters were evaluated, one safe change design and two remote change designs. Results obtained from testing are separated into two groups; first loading up to 1 kPa (4 in. w.c.) and elevated condition testing. Several testing elements were evaluated for loading up to 1 kPa (4 in. w.c.); the overall filtering efficiency versus time, the filtering efficiency versus particle diameter at the start of testing and when the filter reached 1 kPa (4 in. w.c.), downstream geometric standard deviation (GSD) and number concentration, and the most penetrating particle size (MPPS) versus time for the filter. These results were similar to those of the already reported ambient condition testing, and therefore will not be presented in this study. The differential pressure, relative humidity, and temperature as a function of testing time will be reported.

## TEST STAND

### Physical Components

The test stand used for this study is a modified configuration of the test stand used for evaluation of the same AG-1 Section FK radial flow dimple pleated HEPA filters under ambient conditions. Figure 3 provides a schematic of the test stand illustrating its major components. The test stand additions include a natural gas HAUCK burner, a series of square ductwork, some circular ductwork, a flow straightener, a water injection system, and a removable section to allow for system changeover from ambient to elevated condition testing.

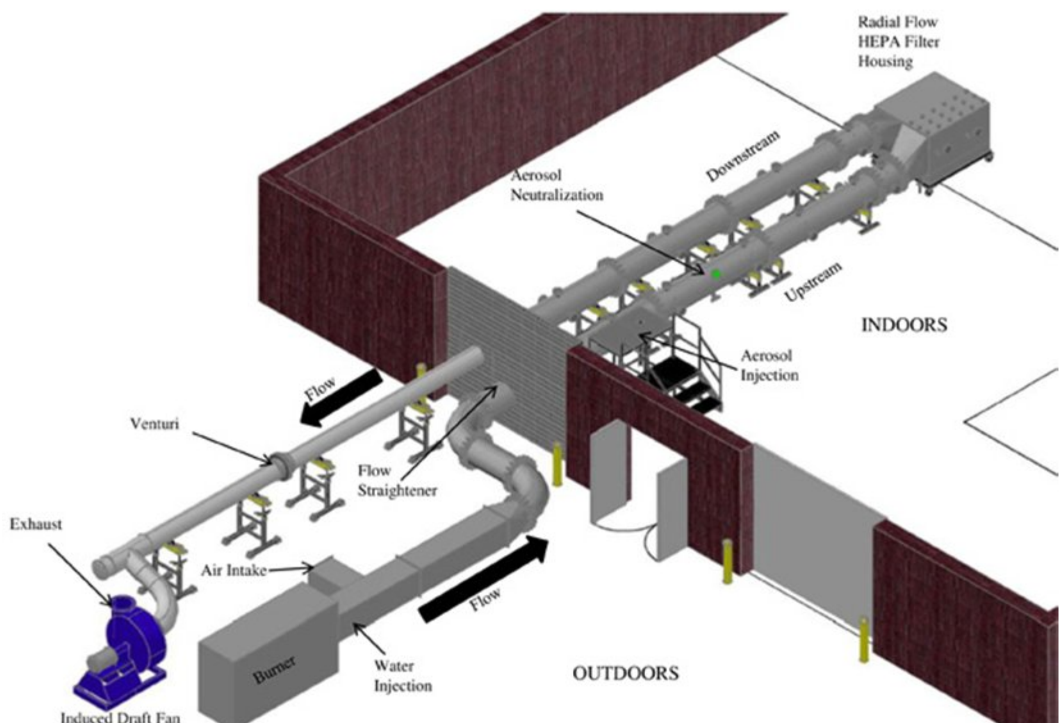

Fig. 3. Schematic of the ICET HEPA filter test stand with elevated condition section.

Figure 4 provides a photograph of the system used to produce elevated temperature and humidity conditions. Heat to the system is supplied by a Hauck natural gas burner. Hot air from the burner is blown into a section of 0.6 m (24 in.) square duct where a series of 12 individually controlled nozzles release a hot water spray near the burner. Hot water is used to enhance the steam generation and evaporation of the water droplets to humidify the airstream.

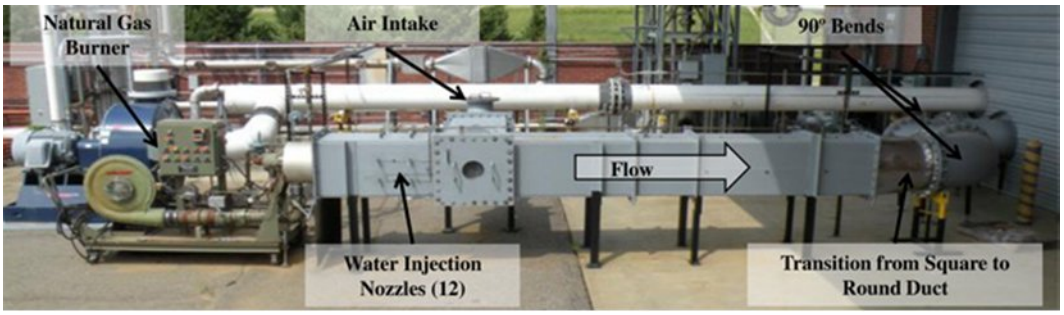


Fig. 4. ICET system utilized to produce elevated temperature and humidity conditions for testing HEPA filters

Connection of this portion of the elevated temperature and humidity system to the ICET large-scale HEPA test stand is facilitated by a section of 0.6 m (24 in.) round ductwork that uses two $90^0$ elbows as depicted in Figure 3 which also shows the transition used to connect the square duct to round duct. This configuration requires a flow straightener designed in accordance with ASME standard MFC-3M-2004 [18]. 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 penetrating the test facility wall as illustrated in Figure 4. Use of the flow straightener is necessary to ensure that cyclonic flow is not produced in the test stand due to the $90^0$ bends.

The final component of the test stand is a duct that connects the outdoor test sections with the test stand located inside the test facility. This 0.6 m (2 ft) section of pipe can be rolled into place to connect the elevated temperature and humidity system to the existing test stand. For those tests conducted at ambient temperature and humidity, the 0.6 m (2 ft) section can be disconnected to allow air intake from the room of the facility.

**Sensors and Instrumentation**

The ICET test stand is fully instrumented with sensors and controls. Installed sensors include temperature, static pressure, relative humidity, and differential pressure. Temperature and static pressure sensors are installed on all 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. Data from all sensors and controls are continuously logged by a central test stand control computer.

Control of the volumetric flow rate of the test stand is fully automated. Airflow through the test stand is produced using an induced draft fan (Spencer Turbine Co.) and controlled by a venturi airflow meter installed in the downstream section of the test stand. The frequency of the fan motor is automatically adjusted by means of the variable frequency drive to ensure the measured airflow rate matches the volumetric airflow set point.

The primary instrumentation used on the large-scale test stand includes the aerodynamic particle sizer (APS), scanning mobility particle sizer (SMPS), and the 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. 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.

## TEST STAND CHARACTERIZATION

### Burner Characterization

The HAUCK natural gas burner was the first item that required characterization. Testing was performed to determine the flame temperature, aerosol generation, and CO emissions at varying air and fuel input levels. The different operational set points were varied by manipulating the natural gas limiting valve and the primary air controller which allowed the test team to control the amount of fuel and air fed into the combustor. Before filter testing began the natural gas burner performance and particle size distribution (PSD) data were collected for various burner operation set points.  This revealed that the aerosols produced by the burner were relatively 10% or less than those measured when loading with alumina and should not be problematic to testing.

### Initial Filter Test

After burner characterization was complete, a series of initial filter tests were performed. The first test was performed on a safe change filter loaded with alumina as the challenge aerosol. Once the filter reached a differential pressure of 1 kPa (4 in. w.c.) across the element, the alumina was discontinued and the test stand was prepared for testing at elevated conditions. To prepare for elevated conditions testing, a 0.6 m (2 ft) segment of ductwork was inserted in the test stand to connect the indoor section to the outdoor sections. The radiological sources were then removed from the test stand to prevent damage or contamination from the elevated temperature or humidity. Only once these steps were completed could the burner be ignited. During the changeover the test stand flow remained at 56.63 $m^3$/min (2000 cfm). Once the burner was ignited, the temperature inside the test stand began to rise, approaching the testing temperature of 54 ºC (130 ºF). While the test plan design stated to wait one hour before adding the water spray, the filter quickly began increasing in differential pressure before even reaching the target test temperature. As shown in Figure 5, the first elevated condition test filter ruptured 22 minutes after burner ignition, much sooner than anticipated.

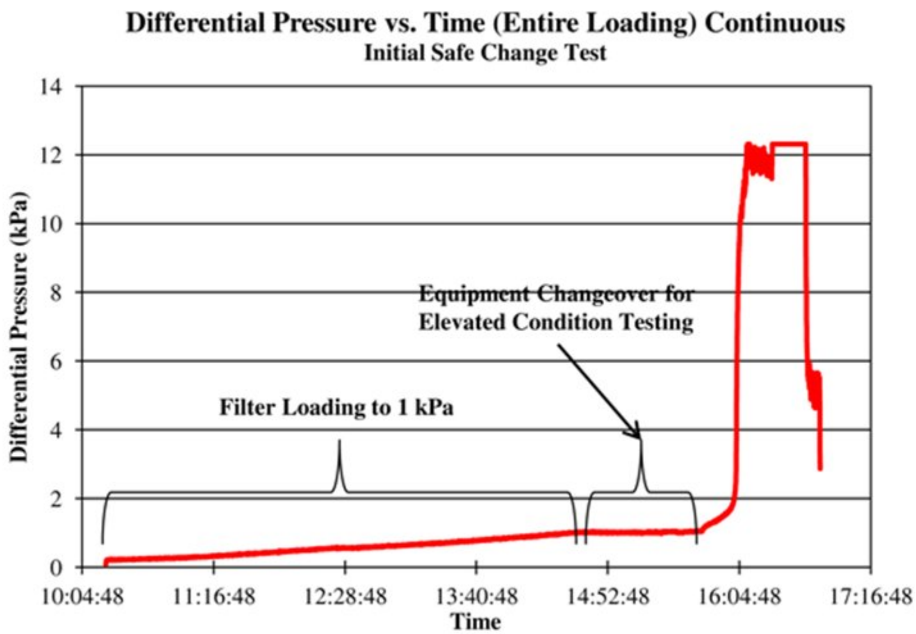


Fig. 5. Loading curve for initial elevated temperature and humidity shakedown filter.

Because the first test revealed a major issue with either the filter or with testing apparatus, the next test included a few changes. First, a remote change filter was tested rather than a safe change filter due to its superior performance exhibited during the ambient condition testing. Next, the filter was removed during preheating of the test stand to 54 ºC (130ºF). This second change ensures that any products of incomplete combustion generated during burner ignition would not affect testing.

The first part of this test proceeded as originally planned. The filter was loaded with alumina until a differential pressure across the filter of 1 kPa (4 in. w.c.) was reached. Next, the volumetric airflow was reduced to 14.3 $m^3$/min (500 cfm) and the filter was removed from the housing. The radiological sources were also removed during this time, and the outside and inside portions of the test stand were joined. Then the burner was ignited and allowed to operate for a sufficient time to burn cleanly, confirmed by the particle counting instrumentation. Once the test stand reached 54 ºC (130ºF), the filter was reinserted.

Following filter reinsertion, the volumetric air flow was increased to 56.63 $m^3$/min (2000 cfm). Figure 6 illustrates the differential pressure, temperature, and relative humidity from this test. It can be seen from the figure that for approximately 40 minutes the filter was challenged with elevated temperature without any water spray. During that time there was only a negligible increase in the differential pressure. The filter finally ruptured once the water spray was turned on and increased to a level that allowed for 80% relative humidity in the airstream. Because this filter performed so differently from the first, further testing was needed to determine the cause for the poor performance of the first filter.

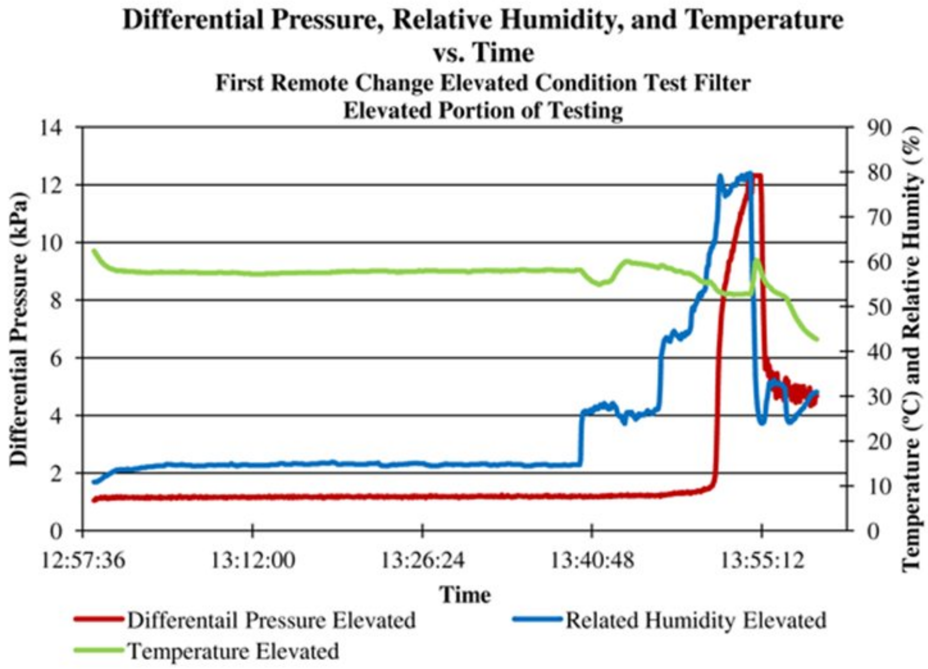


Fig. 6. Evaluation of a remote change filter at elevated temperature and humidity.

To determine the causes for the performance of the first test filter, multiple possibilities were considered and evaluated. The first possible cause was the emissions produced by the burner, particularly those produced immediately after ignition. The volumetric flow rate influence due to the differences in standard flow versus actual flow (SCFM versus ACFM in English units) and the effect of elevated temperature were also investigated.

**Burner Aerosol Issue Resolution**

The burner emission issue was the first to be addressed. It was suspected that during ignition the burner emissions had a PSD with a very high concentration of ultrafine particles. That is why during the second filter test the remote change filter was removed from the test stand during burner ignition and reinstalled after the PSD had dropped to levels consistent with room air. The burner startup and 'clean operation' PSD needed to be examined. The burner start up PSD can be seen in Figure 7 (A) compared to the PSD of Alumina.

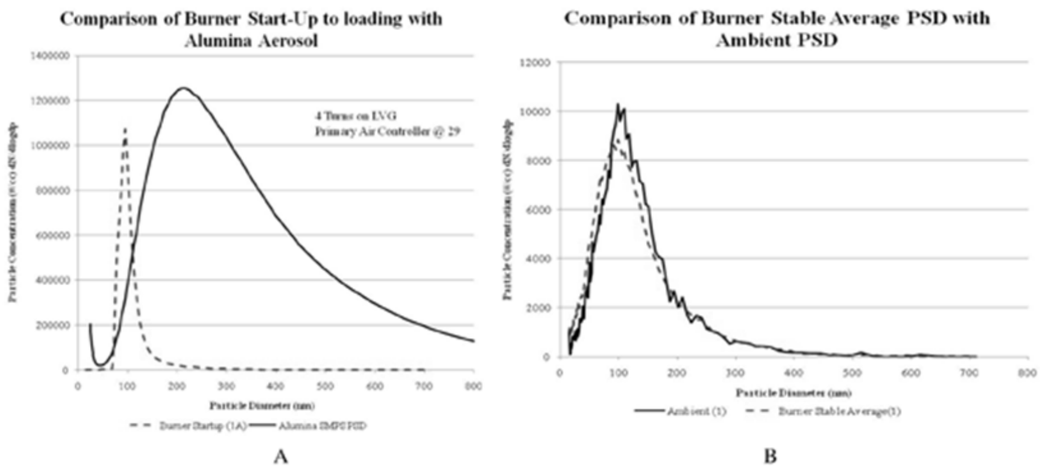


Fig. 7. (A) Burner ignition particle size distribution compared with alumina. (B)Comparison of burner stable average particle size distribution with ambient particle size distribution

In Figure 7 (A), the number concentration of burner emissions rival that of the alumina powder, yet are approximately 150 nm smaller, thus increasing their filter plugging potential. This information directly conflicts with the previously collected data that examined burner emissions at different set-points. Further investigation revealed that the burner ran significantly cleaner very quickly after start-up, generating fewer aerosols. Figure 7 (B) displays a middle set point for the burner in which the PSD and number concentrations produced compares very closely with an ambient room air PSD. Thus, it was determined to remove the filter from the test stand during burner startup to avoid loading the filter with the initial generated aerosols.

**Volumetric Flow Rate Issue Resolution**

After resolution of the burner emission issues, the test team examined the influence of the volumetric flow rate on the filter life. The test stand operates according to standard flow rate, which remains the same independent of temperature, while the actual flow rate rises with increasing temperature, resulting in a higher media velocity through the filter. To evaluate this effect the research team first performed pitot traverses through the test stand ducting to evaluate the volumetric flow rate through the horizontal and vertical axis. The traverses revealed the flow was averaging 7.1 $m^3$/min (250 cfm) higher than the setting of 56.63 $m^3$/min (2000 cfm) at ambient conditions and more than 14.3 $m^3$/min (500 cfm) higher in some places at elevated temperature.

The research team then tested a filter preloaded to a differential pressure of 1 kPa (4 in. w.c.) at elevated standard flow rates, but only at ambient temperature and relative humidity to further evaluate the influence of elevated flow rate. Figure 8 illustrates how the differential pressure of the filter increases as the volumetric air flow rate is increased first to 65 $m^3$/min (2300 SCFM) and then to 71 $m^3$/min (2500 SCFM) and back to 56.63 $m^3$/min (2000 SCFM). As indicated in Figure 8, the greater the flow rate deviates from 56.63 $m^3$/min (2000 SCFM), the greater the slope of the differential pressure increase across of the filter, showing that the increase in volumetric flow impacts filter life.

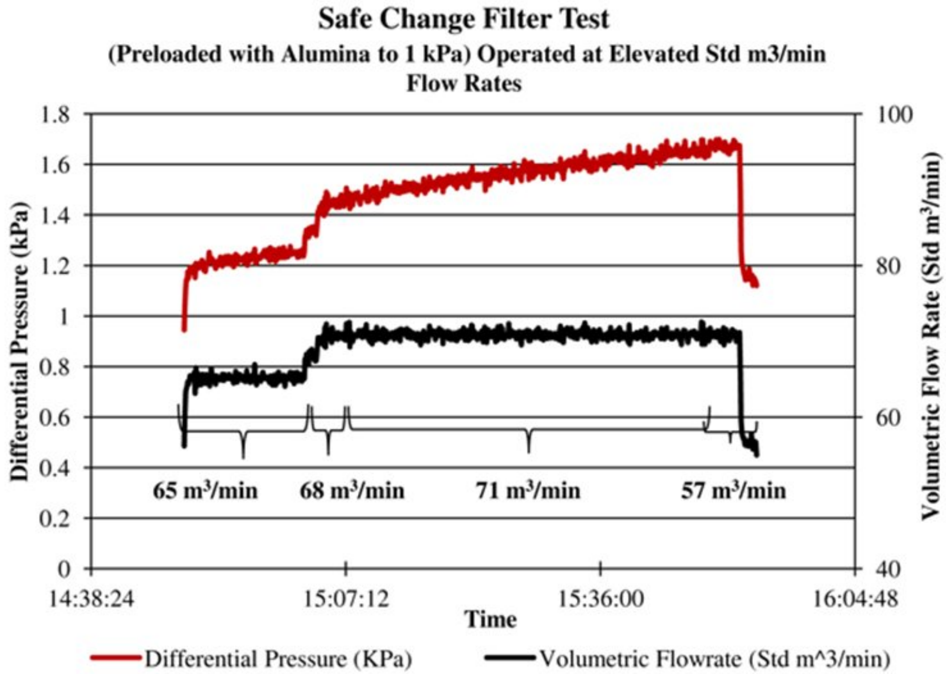


Fig. 8. Effect of increased volumetric flow rate on filter differential pressure

**Elevated Temperature Issue Resolution**

The next test was designed to evaluate the impact of temperature and RH alone, negating the increase in flow rate associated with operating according to standard flow (SCFM in English units). The remote change filter was pre-loaded with alumina to 1 kPa (4 in. w.c.) and then removed from the test stand housing. The burner was ignited and the system allowed to attain a stable 54 ºC (130ºF), after which the filter was reinstalled and the test begun. The filter was exposed to an actual flow of 56.63 m3/min (2000 ACFM) and a temperature of 54 ºC (130ºF). After 1 hour the filter showed very little change in differential pressure, approximately 0.125 kPa (.5 in. w.c.).This small change in differential pressure indicates that temperature has only a minor influence on the performance of a filter, less than the influence of the elevated flow rate.

**TEST PLAN TESTING RESULTS**

The test matrix for elevated condition testing used two remote change filters and one safe change filter. 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 test continued by filter removal, test stand interior and exterior connection, radiological source removal, and burner ignition. Once the test stand was pre-heated and the burner PSD stabilized, the test filter was then reinstalled and the flow rate increased to a standard flow rate of 56.63 m3/min (2000 SCFM).

**Remote Change Test Filter Results**

The first remote change filter test began with elevated temperature at 54 ºC (130ºF) for 45 minutes without adding any water spray. Figure 6 shows that during that time there is little to no increase in the differential pressure across the filter. After 45 minutes of exposure to elevated temperature, the water spray was initiated to elevate the RH. First the RH was raised to approximately 25%, and the differential pressure increased slightly across the filter. After 7 minutes, the water spray was increased to 45% RH and the differential pressure began to rise a little faster. Once the water spray was increased to 80% RH, the filter ruptured.

The second remote change filter test proceeded as the first; the filter was initially challenged with elevated temperature then increasing RH at intervals until rupture. In this test the elevated temperature challenge took1 hour while the remainder of the test took 25 minutes. As with the first remote change filter test, the filter began to rupture when the RH was increased to 80%.These test results can be observed in Figure 9. The two remote change filters both reacted very similarly to challenge at elevated conditions, as illustrated in Figures 6 and 9,. Only after the relative humidity reached approximately 80% did the filters fail.

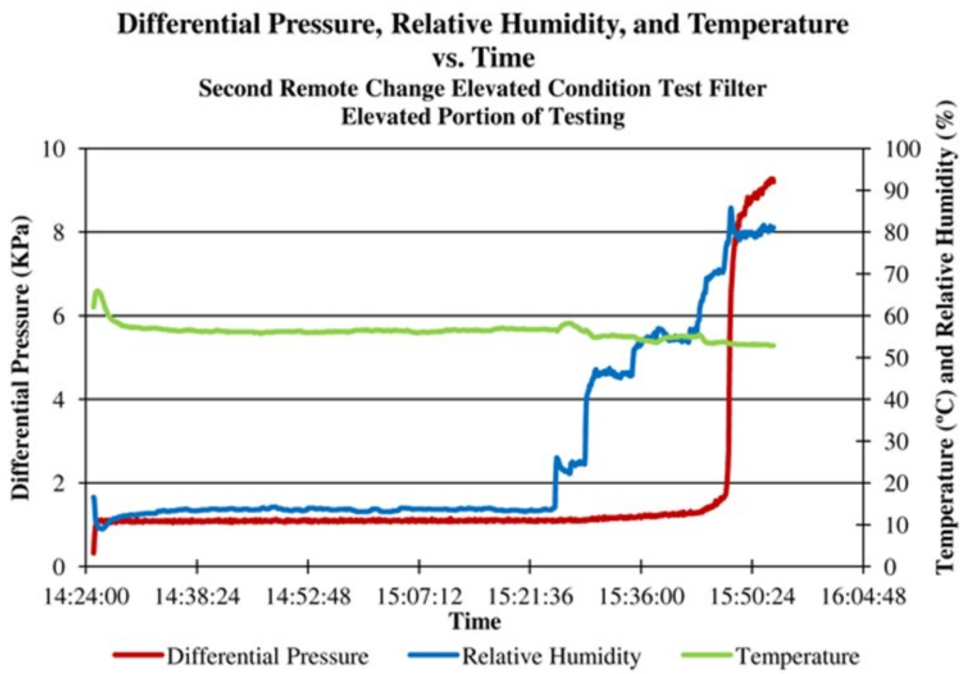


Fig. 9. Differential pressure, humidity, and temperature versus time for remote change filter tested under elevated conditions.

**Safe Change Test Filters Results**

Figure 10 examines the elevated condition testing of a safe change filter. The safe change filter test was tested just as the remote change designs. The figure shows that the safe change design ruptured before the water spray was initiated. The filter lasted 44 minutes until rupture. This information is consistent with the results displayed during shakedown activities and previous testing of this filter design under ambient conditions and points to the fact that the safe change filter is an inferior design relative to the remote change filter design.

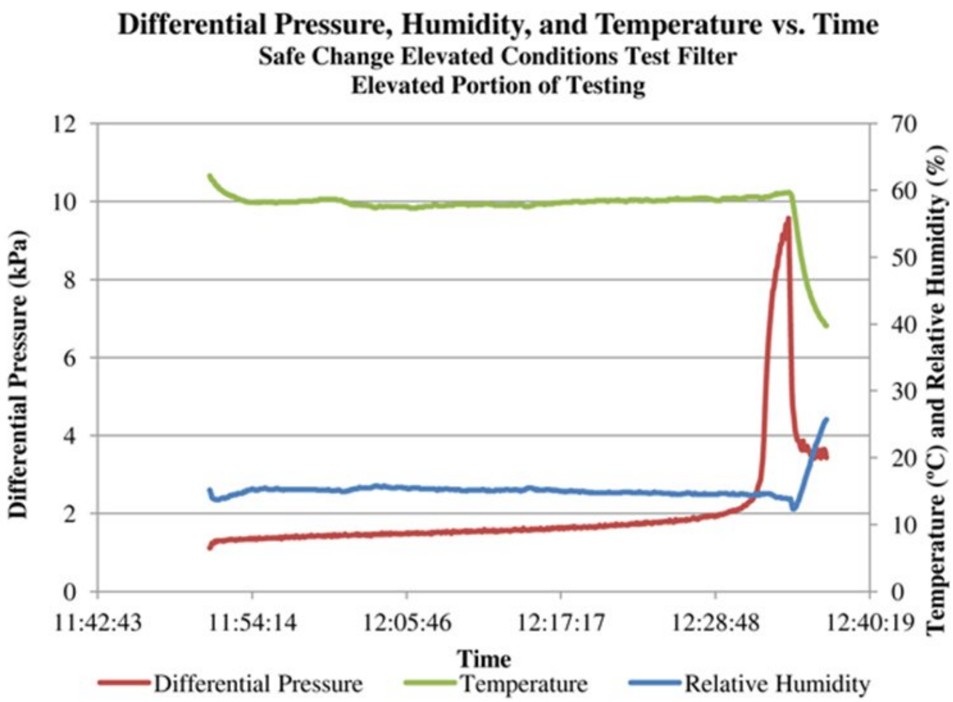


Fig. 10. Differential pressure, humidity, and temperature versus time for safe change filter tested under elevated conditions with run ID: SC-DS1-004.

**CONCLUSIONS**

The evaluation of the dimple pleated radial flow HEPA filters was directed toward the examination of performance during upset or accident conditions. The results display a significant difference in the performance under elevated conditions for the two filter designs. The results present multiple factors that can influence the performance of either design: actual flow (ACFM) increase due to elevated temperature standard flow (SCFM), airflow temperature, and airflow humidity.

The operating conditions for an airflow system are important. The results display that a operating based on standard flow (SCFM), as the test system does, with an air stream at an elevated temperature will correspond to a higher media velocity through the filter, thus increasing the differential pressure across the filter. Due to this correlation, flow operation should either use actual flow (ACFM) or correct the standard flow for temperature only and not the other variables in standard flow calculation.

It is evident that elevated humidity is most challenging to filter performance. In every remote change filter design test, the filter only began to fail after the water spray was initiated to elevate the relative humidity of the airstream. The remote change filters typically failed after a relative humidity greater than 75%. This failure is caused in part by the dimple pleats of the media. As the pleats absorb moisture they begin to lose their rigidity, leading to a failure to keep the media folds separated. It is possible that if a physical separator, such as a string separator, was incorporated in the design, the filter could experience a longer service life in both ambient and elevated conditions.

**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.

**ACKNOWLEDGEMENTS**

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