Evaluating the Performance Envelope of Axial Flow HEPA Filter Designs-17466

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ABSTRACT

Nuclear grade high efficiency particulate air (HEPA) filters are routinely employed as the final control element in confinement ventilation systems. Approximately 6000 nuclear grade HEPA filters are purchased each year for use in the Department of Energy National Nuclear Security Administration (DOE/NNSA) complex. The traditional HEPA filter utilizes a pleated filter medium of fibrous glass that has been produced in a manner analogous to manufacturing paper. Containment ventilation systems are designed to condition the airstream (temperature, relative humidity, moisture, particle size distribution of aerosols, and aerosol concentration) to levels and conditions that fibrous glass HEPA filters can handle.

Axial Flow filters can be purchased with physical separators or embossed medium to maintain proper pleat geometry. Separatorless designs use media embossed with a corrugation pattern to retain pleat geometry. At least some versions of the separatorless filter packs have demonstrated unexpected and rapid failure under slightly elevated temperature and humidity conditions.

The effects of age on HEPA filter performance have been a concern for at least two decades. A combination of physical evaluation of aged filter media and a review of filter failure records resulted in Appendix C of the Nuclear Air Cleaning Handbook (NACH), Determination of HEPA Filter Life.

Mississippi State University is conducting studies to more clearly identify the operating envelope of separator and separatorless designs of ASME AG-1 Section FC axial flow HEPA filters under a set of generic design basis conditions. A parallel study is also being conducted to evaluate the effects of age on fibrous glass HEPA filters.

Activities described in this paper have been conducted under Institute for Clean Energy Technology (ICET's) NQA-1 nuclear quality assurance program approved by DOE-EM. Testing meets the requirements of EM Quality Assurance Program (QAP) EM-QA-001, Rev. 1, June 11, 2012 that includes the applicable requirements of NQA-1-2008/2009a and DOE Order 414.1D.

INTRODUCTION

The Institute for Clean Energy in the Bagley College of Engineering at Mississippi State University has extensive infrastructure for evaluating the performance envelope for HEPA filters under its NQA-1 [1] quality assurance program. ICET conducted testing of prototype AG-1 Section FK 0.9438 m^3/s (2000 cfm) radial flow filters beginning in 20-10. This testing demonstrated a weakness in the separatorless filter pack design. Pleat collapse at differential pressure (dP) less than 2490.80 Pa (10 in. w.c.) rapidly escalates to ballooning and rupture. DOE Technical Issue 2011-0001 [3] updated in March 2012 identified potential weakness of dimple pleated radial flow filter packs. This testing involved a testing sequence based on a generic design basis event (DBE). It begins with loading a test filter to 996.36 Pa (4 in. w.c.) under ambient temperature and humidity conditions followed by exposure to elevated temperature and humidity conditions of 60 °C (140 °F) and 90-95% RH for 60 minutes at rated flow.

Performance of separatorless FK filters raised questions regarding axial flow filters. Two current projects involve evaluation of axial flow ASME AG-1 Section FC [2] filters using the DBE protocol. One project determines performance capabilities of separator and separatorless designs. The other involves investigation of how age affects filter performance capabilities.

Figure 1 provides performance data from testing a U-pack separatorless axial flow 0.4719 m^3/s (1000 cfm) filter. Increasing temperature produced rapid pleat collapse and physical failure.

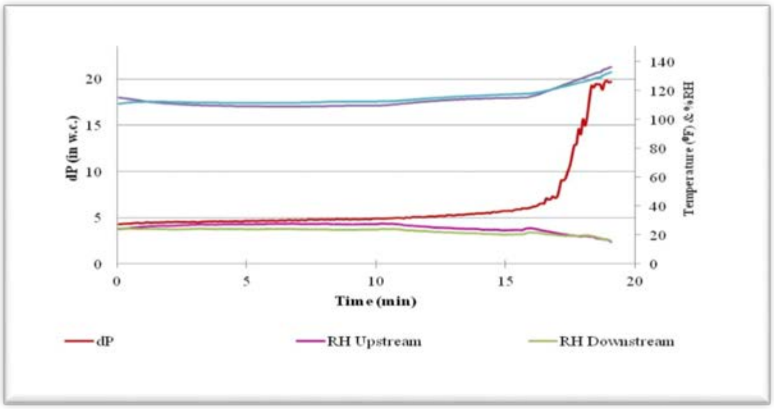

Fig. 1. Test data for a 60.96 x 60.96 x 29.21 cm (24 x 24 x 11.5 inch) Section FC Axial Flow Separatorless HEPA Filter loaded to 996.36 Pa (4 in. w.c.) dP with $Al(OH)_3$ followed by challenge at elevated temperature and relative humidity at rated flow of 0.4719 m^3/s (1000 cfm).

There are two versions of the separatorless filter pack design, the U-pack employing the DYN-E2 medium and W using the Pureform medium. Figure 1 provides data for testing of a U-pack filter. The rapid rise in dP shown in Figure 1 under what would be considered modest conditions demonstrates the effect of pleat collapse. The dP rapidly increases due to a loss of effective active surface area. Of particular concern is the rate at which ballooning and failure occurs within less than 20 minutes. The W-pack design does not demonstrate the same failure mode within the 60-minute test period of elevated temperature and humidity conditions. Testing has been conducted to determine performance envelope of separatorless designs (U-pack and W-pack) that demonstrate pleat collapse or failure at 60 °C

(140 °F), and 90-95% RH. Temperature and humidity conditions are increased or reduced for subsequent filters tested to identify the operating envelope. Separator-type deep-pleated Section FC filter packs are more physically robust than those of the separatorless filters. Aluminum separated Section FC filters evaluated under the generic design basis set of conditions did not demonstrate pleat collapse. These filters also demonstrated HEPA filtering efficiency at the conclusion of testing at elevated conditions.

The evaluation or testing of HEPA filters routinely uses a reduction of filtration efficiency below 99.97% for 300 nm particles as the definition of failure. However, pleat collapse should also be used as a test criterion for separatorless filter packs. Functional failure for the design basis test protocol can be defined as either demonstrating analytical evidence of filter pack instability (dP vs. time curve) or a final filter efficiency value less than 99.97% at 300 nm.

The most recent version of the Department of Energy (DOE) Nuclear Air Cleaning Handbook (NACH) [4] contains guidelines for the service life of HEPA filters. Appendix C of the NACH sets a maximum service life at ten years. However, this appendix recognizes that additional research with aged filters is needed to confirm findings of the initial testing.

A parallel study being conducted for Section FC axial flow filters investigates the effects of age on filter performance. The start of this project was timely because of concurrent actions taken within the American Society of Mechanical Engineers AG-1 Code on Nuclear Air and Gas Treatment committee (ASME AG-1). Significant dissent within the ASME AG-1 committee resulted in removal of any inclusion of service life guidelines within AG-1 due to the lack of supporting data.

The DOE Nuclear Safety Research and Development (NSR&D) program provided initial funding for the Aged Filter study. Follow-on funding for this long-term study is being provided by DOE-EM. Testing of the new filters in the separator-separatorless study is used as a baseline for comparison of aged filter performance. The Electrical Power Research Institute (EPRI) located and provided the initial group of aged filters used for testing reported in this paper.

It is important to correlate physical properties of filter pack media to full-scale performance during the generic design basis test. Both projects include disassembly and inspection of failed filter packs to determine the extent of physical failure. Media samples were removed from filters that had been tested to determine physical parameters such as tensile strength, thermal analysis, and microscopic examination. Additionally, a small set of aged filters has been disassembled prior to testing to compare to equivalent test results for new media.

Filters for the Separator-Separatorless and for the Aged Filter studies have been tested using ICET's Axial Flow Large Scale Test Stand (ALSTS). Figure 2 shows the ALSTS filter housing and aerosol measurement instrumentation.

Fig. 2. Photo of the filter housing and aerosol instrumentation of the ALSTS.

The suite of aerosol instrumentation provides particle size measurement from 0.02 um to 20 um upstream of the filter for particle concentrations up to 10^6 per cc. Downstream measurements are made using a TSI Laser Aerosol Spectrometer capable of detecting down to less than 1 particle per cc for determining filtering efficiency. Detailed description of the testing procedures with test stand measurement and test equipment can be found in papers presented in the most recent International Society for Nuclear Air Treatment Technologies Conference [5].

DESCRIPTON

Separator-Separatorless Filter Study

The separator-separatorless filter study is designed to establish the performance envelope of separatorless filters as compared to filters with separators. This study is also an extension of data collected showing pleat collapse for early prototypes of separatorless Section FK radial flow filters also performed at ICET [6]. Two new axial-flow (Section FC) separatorless, dimple-pleated filters referenced by the manufacturer as DYN-E2 U-pack and Pureform W-pack filters were tested under similar conditions and found to have the same potential for premature failure via tearing of the filter medium (see Figure 1).

A prescriptive test matrix is not used to direct testing activities for this study. Such methodology calls for complete enumeration including all possible combinations of temperature and humidity. Instead, logic-based guidelines are used to select test parameters based on performance results from the last filter tested. This allows completely mapping the performance capabilities of the two separatorless style HEPA filter packs, (DYN-E2 U and the Pureform W filters [8]) in a minimum number of tests. The starting conditions for testing new separatorless filters include loading to 996.36 Pa (4 in. w.c.) under ambient conditions. The initial test filter is loaded to the target dP and then challenged at elevated conditions of 60 °C (140 °F), and 60–70% RH for at least one hour. This intermediate set of temperature and humidity conditions was selected as being close to failure conditions from previous tests.

Filter failure at a given set of test conditions causes the next filter to be tested under less challenging conditions. If a filter passes under a given set of conditions, an additional filter is tested under the same conditions. Two filters must pass the test conditions in order to confirm acceptable performance for a given combination of filter loading, temperature, and humidity.

The following outline is used to describe the test protocol for both studies. An initial dry mass of the filters is determined by drying the filter in an oven at 48.8 °C (120 °F) for four hours before weighing. The filter is then installed into the ALSTS and subjected to design flow at ambient air conditions (15.5 – 26.6 °C (60–80 °F), 40–60% RH) for one hour. The conditioning phase is followed by a determination of an initial FE. The filter is removed from the filter housing and weighed to determine the filter tare-weight.

The ICET determined FE is compared to FE results determined by the ATI Filter Test Facility (FTF) [7] in Baltimore, MD. The filter is reinstalled in the test stand and subjected to rated flow at ambient test conditions (T and RH) and loaded with aluminum trihydroxide [Al(OH)3] to the target dP. It is then removed while the air temperature within the test stand is adjusted to upset conditions. The filter is reinstalled and allowed to stabilize with respect to the elevated temperature at rated flow. Relative humidity is then ramped up to the test target value. Test stand conditions for all sensor locations (temperature, relative humidity, differential pressure and volumetric flow rate) are continuously recorded by the test stand system control and data acquisition system.

The filter is exposed to the target test conditions of T and RH for a period of one hour with close monitoring of the filter dP. Test stand parameters are returned to ambient conditions upon completion of the one-hour test period. The filter is allowed to dry under airflow until its dP returns to the target dP or until the relative humidity and temperature readings upstream and downstream of the filter are equal.

Final FE measurements are made with the test stand operating under ambient conditions. The filter is then removed from the test stand its mass is determined. The filter is dried at 48.8 °C (120 °F) for four hours, removed from the test stand and weighed to obtain the final dry mass.

Failure of a filter leads to testing a second filter under the same set of conditions. Testing a second filter provides insight into variability of results between filters. This also allows collecting a different set of data if the second filter demonstrates pleat collapse. Pleat collapse in the second filter implements a modified test procedure to identify the reduced flow rate necessary to stabilize increase and/or reduction of dP. Operational failure of ventilation systems can occur if airflow drops below thresholds, even if physical integrity of the HEPA filters has not been breached. Standard operating procedures implemented in the event of high-high alarms for elevated filter dP may require limits to be set for reducing airflow. It is important to know the extent to which airflow will need to be reduced in order to stabilize pleat ballooning.

Data collected during this scoping study will expeditiously provide practical estimates for the following variables:

- o Temperature and relative humidity thresholds for pleat ballooning with respect to the extent of filter loading.
- o Post-rupture filtration efficiencies for the test conditions.
- o Extent to which volumetric flow rates need to be reduced to stabilize ballooning of pleats in order to prevent filter medium rupture.

Separator and separatorless Section FC Filters purchased from three manufacturers (American Air, Camfil, and Flanders) are used in this study. Filter categories reflect the three media pack designs: separator, DYN-E2 U-Pack, and Pureform W-Pack.

An initial filter from each category and manufacturer is tested under the most aggressive conditions. A second filter is tested under those same parameters to confirm a passing result. If the first filter fails, a second is tested with a single test variable to better define the operating envelope. If both filters fail, testing proceeds under less aggressive test conditions. Figure 3 shows the rapid dP increase (green line) during exposure to humidity (blue line) conditions conditions for a U-pack filter that failed. Notice how rapidly pleat collapse and ballooning occurs. Filter dP goes from less than five inches to greater than 30 inches in just a few minutes. The relatively stable dP above 30 inches is a result of physical failure of the filter pack.

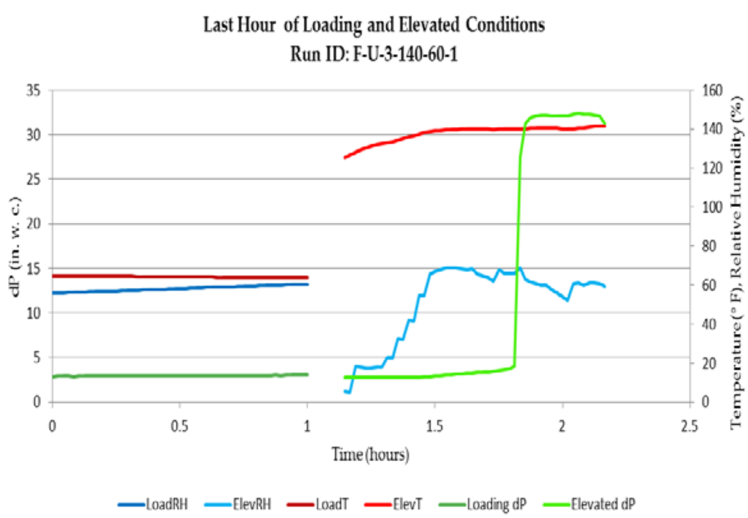

Fig. 3. U-Pack Filter loaded to 747.26 Pa (3 in. w.c.) tested at 60 °C (140 °F) and 60% RH.

Figure 4 provides test curves for a W-pack separatorless filter that did not fail and Figure 5 provides test curves for a separator style filter that also passed the test.

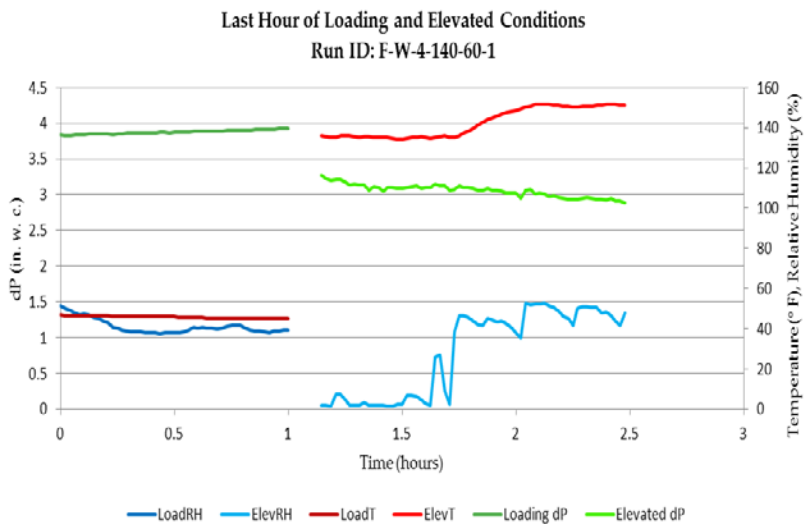

Fig. 4. W-Pack Filter loaded to 996.36 Pa (4 in w.c.), tested at 60 °C (140 °F) and 60% RH

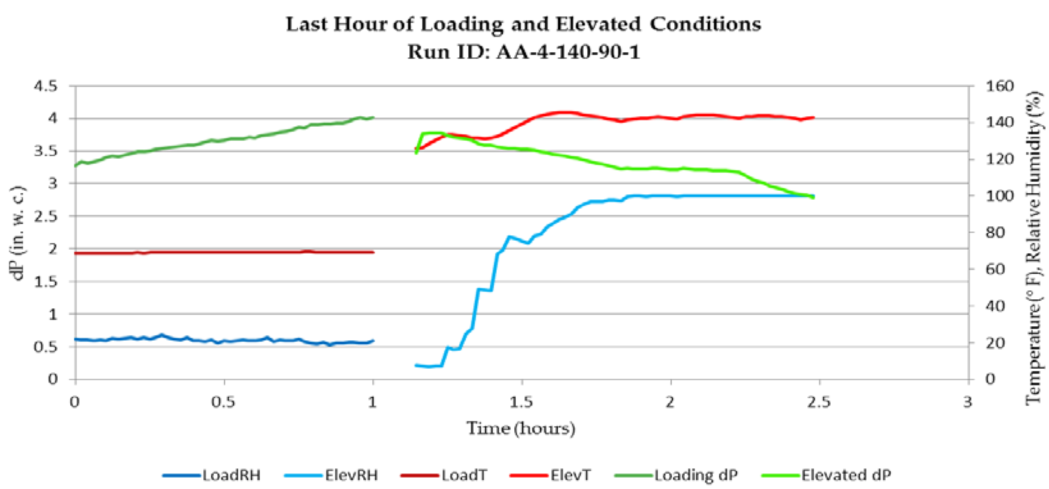

Fig. 5. Separator Style Filter loaded to 996.36 Pa (4 in. w.c.) at 60 °C (140 °F) and 90% RH

To date there have been six (6) new separator style filters tested. This includes representative filters of two of the three manufacturers -- four (4) separator style filters from one manufacturer and two (2) from the second manufacturer. All six of these filters demonstrated less than maximum percent penetration criteria of 0.03% for 300 nm particles with a calculated filtering efficiency greater than 99.97% at the stated conditions.

A total of six (6) Pureform W-pack and fourteen (14) U-pack separatorless filters have been tested to date. The test results indicate that all Pureform W-pack separatorless filters passed posttest penetration criteria/filtering efficiency requirements for the most aggressive test conditions (249.08 Pa and 996.36 Pa (1 and 4 in. w.c.) at 60 °C (140 °F) and 60-80% RH).

A summary of the test results for the separator and separatorless filters is shown in Table I.

TABLE I. Summary of Test Results from Separator vs. Separatorless Axial Flow Filters to Date

Manufacturer	Pack Type	Loaded dP Pa (in. w. c.)	Temp °C (°F)	% RH	Failure (Yes/No) & time to failure after reaching conditions
Mfgr. 1	Separator	249 (1)	60 (140)	90	No
Mfgr. 1	Separator	996 (4)	60 (140)	90	No
Mfgr.2	Separator	249 (1)	60 (140)	90	No
Mfgr.2	Separator	996 (4)	60 (140)	90	No
Mfgr.2	Separator	996 (4)	60 (140)	90	No
Mfgr.2	Separator	996 (4)	60 (140)	90	No
Mfgr.2	U	249 (1)	60 (140)	60	No
Mfgr.2	U	498 (2)	60 (140)	60	No
Mfgr.2	U	498 (2)	60 (140)	60	No
Mfgr.2	U	498 (2)	60 (140)	80	No
Mfgr.2	U	498 (2)	60 (140)	80	No
Mfgr.2	U	498 (2)	60 (140)	90	Yes, 31 min
Mfgr.2	U	747 (3)	54 (130)	60	No
Mfgr.2	U	747 (3)	54 (130)	60	Failed, but T and RH unstable/ out of range
Mfgr.2	U	747 (3)	54 (130)	60	No
Mfgr.2	U	747 (3)	54 (130)	80	No
Mfgr.2	U	747 (3)	54 (130)	80	No

Mfgr.2	U	747 (3)	54 (130)	90	Yes, 7 min
Mfgr.2	U	747 (3)	60 (140)	60	Yes, 19 min
Mfgr.2	U	996 (4)	60 (140)	60	Yes, failed before hour started at 136 °F and 55% RH
Mfgr.2	W	249 (1)	60 (140)	60	No
Mfgr.2	W	996 (4)	60 (140)	60	No
Mfgr.2	W	996 (4)	60 (140)	60	No
Mfgr.2	W	996 (4)	60 (140)	80	No
Mfgr.2	W	996 (4)	60 (140)	80	No, but required third test since elevated conditions were unstable
Mfgr.2	W	996 (4)	60 (140)	80	No

Aged Filter Testing

The primary aim of the Aged Filter research is to correlate mechanical properties of the media with performance capabilities of individual filters demonstrated during full scale testing. Filter packs are removed from both tested and untested filters to compare their media to new media from. Methodology has been developed to systematically section filter packs and collect samples for physical examination. This includes determining of the degradation of fiber bindings and coatings to explain loss of mechanical properties or water repellency.

Thermogravimetric Analysis (TGA) and Differential Thermal Analysis (DTA) provide a quantitative measure of coating degradation for each component of the filter media when compared to a thermograph for new media. Degradation of the acrylic binder has previously been correlated with decreased tensile strength of the media and is an important factor in life-cycle limitations of filters.

A total number of eleven (14) aged Section FC separator axial flow HEPA filters have been used in a study funded by NSR&D [9]. The Electric Power Research Institute (EPRI) located and facilitated provision of these units from the Duke Energy Crystal River Nuclear Power Plant #3.

Six of the 14 had been used in clean ambient environments. Three of the six were manufactured in 1992 and the other three a second group of three were manufacture in 2009. Five of the 14 were manufactured in 2009 had been stored in a warehouse under level B conditions. The final three were autopsied without testing under the DBE scenario.

Results listed in Table II represent two of the three primary suppliers AG-1 Section FC filters. Only ten (10) filters were tested using the previously discussed testing protocol at elevated conditions of 60 °C (140 °F) and 90% RH. The data indicate that all eight (8) aged (Mfgr. 2) filters (6.5 years from the manufacturing date) passed with initial FE of 99.98% - 100% and all final FE at 100%. One (1) of the Mfgr. 1 filters failed the initial FE with $Al(OH)_3$ and was used for autopsy data without further testing. The other two (2) Mfgr. 1 filters (24.5 years from manufacturing date) passed the efficiency criteria and elevated conditions testing.

This initial study has included a limited number of filters. However, the range of ages and methods of manufacture provided an ideal population for validating testing and autopsy procedures under NQA-1. Autopsy and analysis results for a representative filter are recorded in Table II.

TABLE II. Summation of Test Results for Filter A-EP-F-C-4-140-90-3

Property	Test Result (SI Units)	Test Result (Industry Units)
Average Tensile Strength in Cross Direction	356.04 (N/m)	2.03 (lbf/in)
Average Tensile Strength in Machine Direction	1275.41 (N/m)	7.28 (lbf/in)
Average Percent Elongation in Cross Direction	2.52%	2.52%
Average Percent Elongation in Machine Direction	1.11%	1.11%
Average Tensile Absorption Energy in Cross	6.34 (J/m^2)	3.02×10^{-3} ($ft*lbf/in^2$)
Average Tensile Absorption Energy in Machine	9.55 (J/m^2)	45.4×10^{-3} ($ft*lbf/in^2$)
Adsorbed Moisture	0.1605%	0.009809 mg
Component 1	4.258%	0.2603 mg
Component 2	3.656%	0.2235 mg
Component 3	1.727%	0.1056 mg

Data contained in Table II were generated from the axial flow filter pack shown following Figure 6.

Fig. 6. Photo of the filter pack for test filter A-EP-F-C-4-140-90-3.

The filter pack is divided into three sections. Each section has a combination of specific pleats removed along with additional pleats identified using a random number generator. The selected pleats are then sectioned to produce strips for determination of tensile strength, thermal analysis, and microscopic analysis. Figure 7 provides a rendering of the specimen-sampling scheme for each pleat.

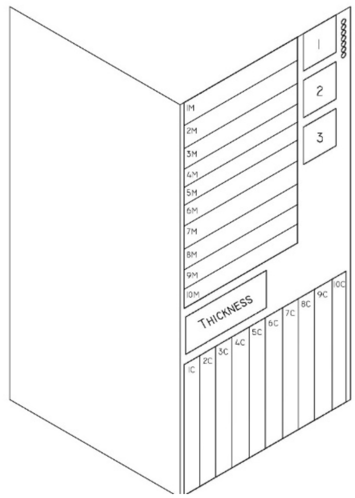

Fig. 7. Rendering of the specimen sampling scheme for pleats.

Instruments used to collect tensile strength and thermal analysis data are provided in Table III. This table also includes standard methods used for data collection. TGA and DTA data are collected using the 2014 update of ASTM E1131-08. The ICET procedure does not include the last portion of the ASTM standard calling for use of a reactive gas.

TABLE III. Instrumentation and Standards used for Analytical Techniques

Technique	**Instrument**	**Manufacturer**	**International Standard Used**
Thermogravimetric Analysis (TGA and DTA)	SDT Q600	TA Instruments	ASTM E1131-08 2014 update
Tensile Strength Testing	Vantage NX Universal Tester	Thwing-Albert	AG-1 FC-I-4000 TAPPI T 494 TAPPI T 402

Tensile strength of media samples was determined using a Vantage NX Universal Tester equipped with TA 149 grips as shown in Figure 8.

Fig. 8. Photo of the Vantage NX Universal Tester and TA 149 Grips (right inset).

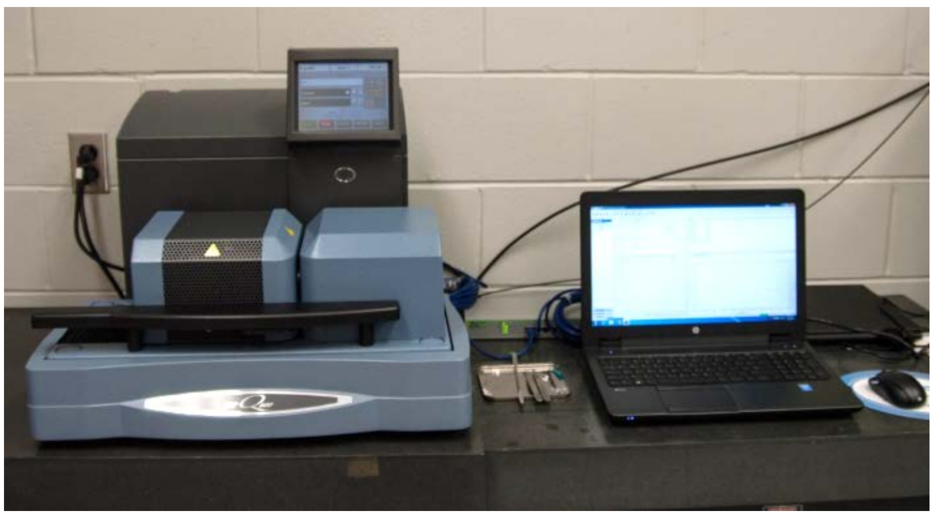

Fig. 9. Photo of the SDT Q600 Thermal Analysis Instrument.

Figure 9 provides a photo of the SDT Q600 thermal analysis instrument capable of collecting thermal gravimetric analysis (TGA), differential scanning calorimetry (DSC), and differential thermal analysis (DTA) data.

Two trends have emerged as a result of current tests. Figure 10 shows a comparison of average tensile strength for aged filter sets subject to different treatment and to aging.

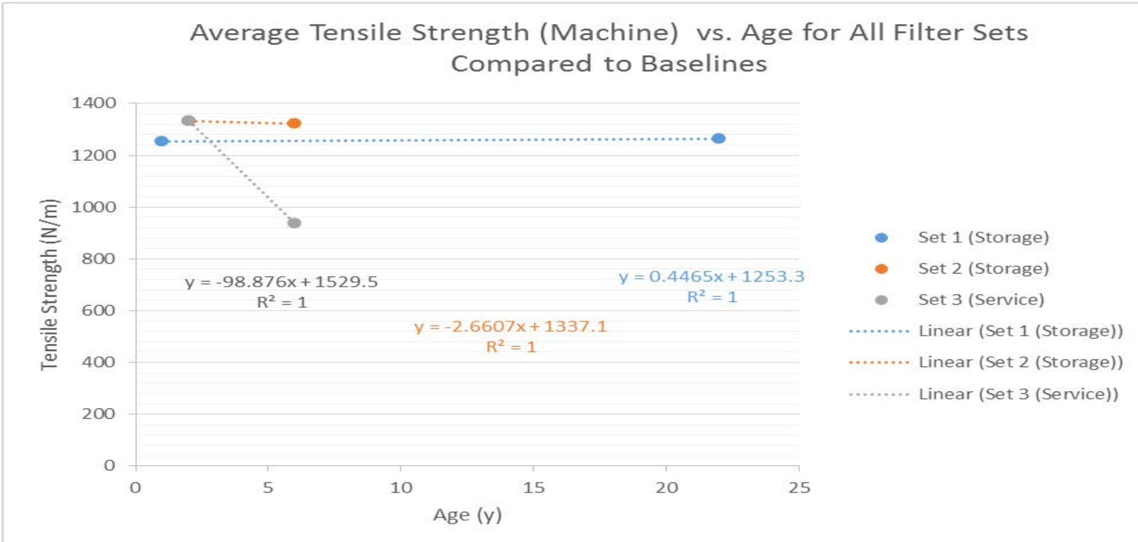

Fig. 10. Plot of the average tensile strength vs. age for aged filter sets.

The preliminary trend from tensile strength data may indicate an unsurprising difference associated with storage conditions and use.

Figure 11 shows mass percent moisture for each filter set as a function of age. Adsorbed water on pretreated media specimens is a marker of functionality for water repellent fiber coatings. The mass percent loss for moisture for all filter sets is compared to the new baseline filters from each manufacturer. Analysis was performed after conditioning to TAPPI T 402 standard method.

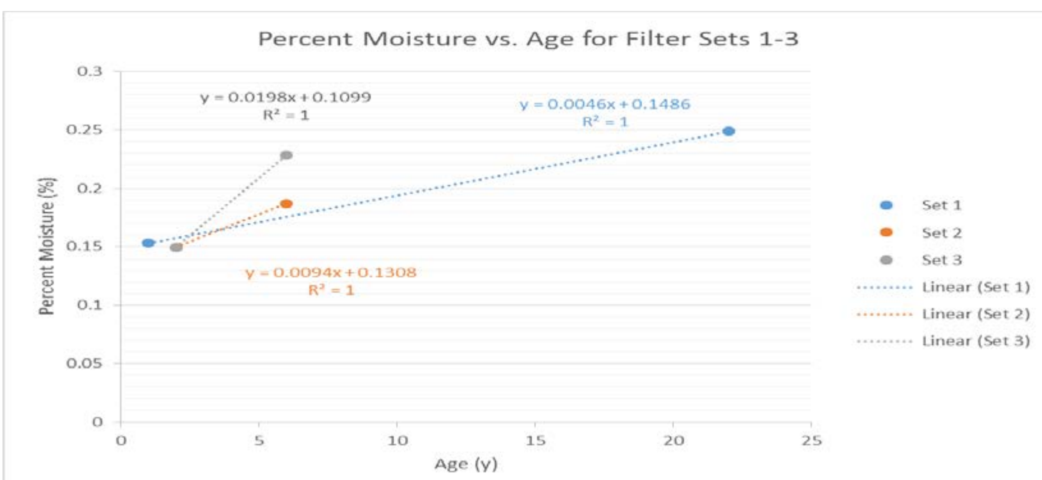

Fig. 11. Plot of percent moisture loss vs. age for aged and new filter sets.

Figure 11 presents the results of thermal analysis data in the region of interest for acrylic binder coatings, listed as “Component 2.”

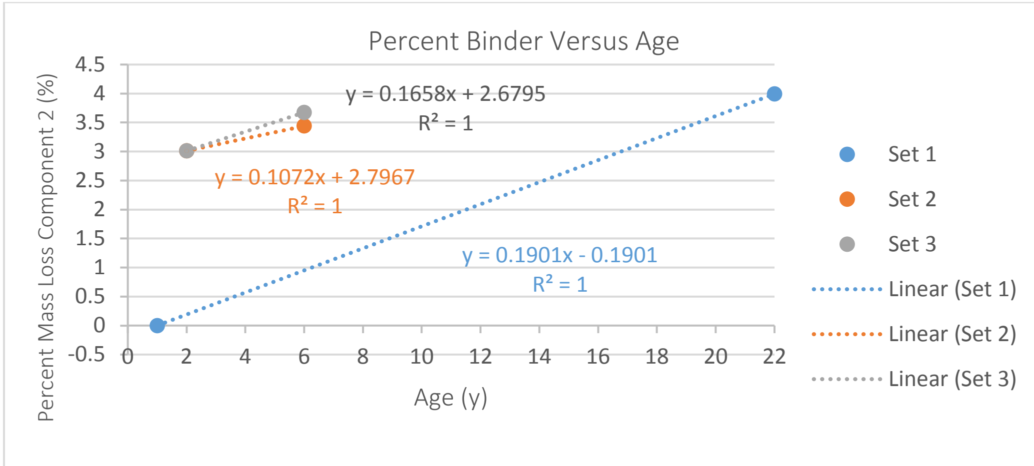

Fig. 12. Percent binder vs. age for all filter sets as compared to new filters.

No trend is directly evident, and the absence of Component 2 at the target temperature in the 1 year old baseline filter is noted. This comparison assumes the media types are similar in composition.

CONCLUSIONS

Separator and Separatorless Filter Study

Testing conducted to date show indicate that the conventional ASME AG-1 Section FC axial flow separator-type HEPA filters that have been loaded to four inches of water column differential pressure with aluminum trihydroxide are capable of enduring one hour of elevated temperature and relative humidity conditions (60 °C (140 °F) and 90% RH) for one hour without failing. W-pack separatorless filters loaded to 996 Pa (4 in. w.c.) differential pressure followed by exposure to 60 °C and 80% relative humidity also survived 60 minutes of testing.

However, U-pack separatorless filters have failed when loaded to 298 Pa (2 in. w.c.) under temperature and humidity combinations as low as 60 °C (140 °F) and 90% RH. Testing is continuing and statistically meaningful guidance with respect to the U-pack performance envelope as a function of loading, temperature, and humidity will be available in 2017.

Aged Filter Study

A limited number of aged filters have been tested, far fewer than required for drawing conclusions. Additional aged filters have been located and testing will be conducted during 2017. The number of filters needed to adequately represent manufacturers, designs, media, use, and storage conditions is large. However, most of the filters can be autopsied for physical evaluation of media without undergoing full scale testing. A large library of physical effects of aging on media will facilitate interpretation of full-scale test results. ICET is developing methodology to conduct accelerated aging of media to further correlate results with temperature, humidity, and oxidizing gases such as ozone.

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