A Summary of the Effects of Aging on Nuclear Grade High Efficiency Particulate Air Filter Media

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ABSTRACT

The shelf and service life of High Efficiency Particulate Air (HEPA) filters is discussed in Appendix C of the Department of Energy (DOE) Nuclear Air Cleaning Handbook (NACH), DOE-HDBK-1169-2003. This appendix became a topic of serious discussion starting in the late 2000s after the American Society of Mechanical Engineers Code on Nuclear Air and Gas Treatment (AG-1) added a non-mandatory appendix (AG-1-2009 FK-A "Determination of HEPA Filter Service Life") based on the NACH information. A proposal was submitted to convert the same information to a mandatory AG-1 appendix (FC-B). According to the NACH, HEPA filter life can be determined based on decreases in tensile strength of dry filter media with age and exposure to water and decreases in water repellency with age. Additionally, HEPA filter life is defined as beginning on the date the filter is manufactured due to the decrease in tensile strength associated with folded media. A new definition inserted into the debate lobbied for the separation of storage time from in service time when determining the HEPA filter life. Balloting of the new code section (FC-B) failed after multiple iterations and was therefore never included in AG-1; however, the service life non-mandatory appendix was retained. The Effects of Aging on Nuclear Grade HEPA Media and Filters Study performed at the Institute for Clean Energy Technology (ICET) at Mississippi State University included evaluating the physical parameters of media. Testing was performed with media from AG-1 section FC HEPA filters ranging in ages from new to 48 years-old and media from rolls. Test methods for the ICET study include duplication of work done by Bergman that established the current service life guidance. Test methodologies were based on available AG-1, American Society for Testing and Materials (ASTM), Technical Association of the Pulp and Paper Industry (TAPPI), and other standards.

INTRODUCTION

High Efficiency Particulate Air (HEPA) filters are defined as having a minimum filtering efficiency (FE) of 99.97% of airborne particles of 0.3 micrometers in diameter. HEPA filters are credited as the final barrier against the release of radioactive aerosol contamination in nearly every operating U. S. Department of Energy (DOE) and National Nuclear Security Administration (NNSA) nuclear facility. Approximately 3000 nuclear grade HEPA filters are purchased each year for use in the DOE/NNSA complex. Each of these filters is tested, inspected, and stored under special environmental conditions until needed. Then, through a set of rigorous procedures designed to ensure the physical integrity and thereby the functional reliability of these crucial, yet fragile components, the filters are installed, tested post-installation, in-place leak tested on a periodic basis, removed, and disposed of.

The American Society of Mechanical Engineers AG-1 Code on Nuclear Air and Gas Treatment (AG-1) contains code sections specifying design, performance parameters, and operational envelope for fibrous glass media HEPA filters used in nuclear containment ventilation systems. The DOE Nuclear Air Cleaning Handbook (NACH), DOE-HDBK-1169-2003, provides guidance regarding the use of HEPA filters in nuclear facility ventilation systems. The NACH and AG-1 both contain an equivalent statement of service life for AG-1 fibrous glass media HEPA filters. Basic points of the HEPA filter life guidance are included below [1–2].

- Service life of a fibrous glass media HEPA filter used in containment ventilation systems begins on the date of manufacture.
- Maximum service life of fibrous glass media HEPA filters used in containment ventilation systems is ten years.
- Maximum service life of fibrous glass media HEPA filters used in containment ventilation systems in which the filters may become wet is five years.
- Fibrous glass media HEPA filters used in nuclear applications are to be removed from service quickly if it is discovered that they have become wet.

The existing HEPA filter service life guidelines were developed using the analysis of results from joint research projects between the Lawrence Livermore National Laboratory (LLNL) and the Filter Test Facility (FTF), previously located at the DOE Rocky Flats facility [3-5]. LLNL conducted advanced laboratory testing to determine the amount of binder on aged samples of media. An acrylic binder is used to unify the glass fibers in HEPA filter media to increase the tensile strength of the media. Tensile strength of the filter medium is reduced when it gets wet, so medium is also coated with a water repellent compound [5]. The Rocky Flats effort included putting aged media through a series of qualification tests to determine changes in the media's physical parameters. These parameters include determination of tensile strength in both the machine and cross direction, determination of elongation under tension, determination of water repellency, and determination of percent penetration [4].

The Effects of Aging on Nuclear Grade HEPA Media and Filters Study conducted at the Institute for Clean Energy Technology (ICET) incorporates testing methods employed in the earlier studies reported by Fretthold and Gilbert [4–5].

This study involved a Technical Working Group (TWG) that provided guidance in testing protocols and assisted in identifying and obtaining AG-1 section FC HEPA filters from the commercial nuclear power industry, Electric Power Research Institute (EPRI), and DOE complex sites. TWG members played a vital role in identifying and securing filters beyond the ten-year service life that have been stored or in service in non-radiological applications. Filters selected for evaluation were put into distinct categories that were based on operational history, design, and age. Filters were first categorized based on service or storage history. Filters were then categorized into sets based on filter design and age at the beginning of testing.

SOURCES OF MEDIA TESTED

The Nuclear Safety Research and Development (NSR&D) Program provided initial funding for the Effects of Aging on Nuclear Grade HEPA Media and Filters Study. EPRI facilitated the provision of thirteen filters from the Crystal River Plant Site that were used to develop autopsy and media testing methodology. EPRI has continued to aid in securing non-radiologically contaminated filters that have been stored or in service. Filters provided from EPRI members also included a statement of service conditions, if available, to help correlate filter autopsy and filter testing results.

EPRI and DOE have facilitated the donation of more than 200 aged filters that were either in service or in storage at seven different sites to ICET. Diablo Canyon Power Plant supplied four filters, Enrico Fermi Nuclear Generating Station supplied four filters, and Prairie Island Nuclear Generating Plant supplied five filters, all of which were removed from service. DOE Richland Operations Office (DOE RL) and the DOE Office of River Protection (DOE ORP) from Hanford provided numerous filters that have been in storage. The Air Techniques International (ATI) FTF, LLNL, and Energy Northwest also supplied aged filters that were maintained in storage.

Media Types

Media for this study were manufactured by three media manufacturers and included both flat sheet media and ridged media. Discussions regarding qualification testing methods for the ridged designs indicate that in the past media may have been sent for qualification testing prior to ridge forming. The testing in this study was performed after the ridge forming of the media, which could have impacted the testing results. Qualification testing performed prior to ridge formation may not yield the same results as testing after formation.

Numerous filters evaluated were separatorless filters with ridged media. Most of these samples were either the Dyne-E2 media of current Flanders U-packs or the Pureform media of current Flanders W-packs; however, there were two 33-year-old filters that had a highly ridged pleat face. The amplitude of the ridges was much higher than the current U-pack and W-pack filters, as shown in Figure 1. The high amplitude ridges caused some testing difficulties. Gently stretching the media was required to perform select qualification tests.

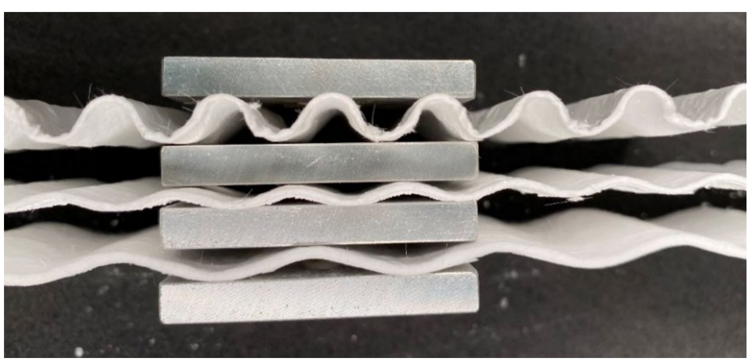

Figure 1. Photograph of highly ridged media (top) compared to current media from U-packs (middle) and from W-packs (bottom).

MEDIA TESTING BACKGROUND

ICET was tasked by DOE to perform autopsies of aged filters to help better understand HEPA filter life. Evaluation of degradation in physical properties and functionality requires a high population of aged filters of different ages, designs, manufacturers, and operational histories. Due to the limited availability of this population and the impropriety of looking solely at formulations and components from past years, this undertaking also involved not only analysis of the physical properties of aged media, but also evaluation of current media properties and functionalities.

Qualification tests report on the properties of medium and serve as a benchmark to aged filter medium testing. Each media type from nuclear grade filters had previously undergone qualification testing and therefore met thresholds for specific physical properties and functionalities. In autopsy of HEPA filter media from aged filters, qualification testing can be performed on the extracted media to gauge the degree of deterioration in functionality based on the ability to meet or not meet AG-1 requirements for each test. These sets of tests have been performed at ICET in the same manner, where possible, as original qualification tests undergone by each media type.

TEST METHODS

Method and procedure development for autopsy and analysis activities drew from a wide variety of international standards and codes. Testing procedures were developed using standards cited from AG-1 mandatory appendix FC-I.

Samples were generated from rolls of media and generated using simple random sampling to select areas of media from filters for specimen generation and analytical testing. AG-1 mandatory appendix FC-I includes references to Technical Association of the Pulp and Paper Industry (TAPPI) T 402 for pretreatment of specimens, TAPPI T 494 for tensile testing, ASTM D737 for resistance to airflow, ASTM D2986 for particle penetration, TAPPI T 411 for thickness testing, and IEST-RP-CC021.1 for combustible material content determinations [6–11]. The water repellency test unit was designed, fabricated, and validated based on the procedural document for the E1R3 in MIL-STD-282 [12].

The autopsy and analysis process included a detailed set of protocols followed to determine testing results. Qualified procedures and the general layout used in the autopsy and analysis of aged and new media are listed below.

- Filter Photomapping and 3D Imaging.
- Filter Decasing, Pleat Sampling, and Specimen Generation.
- Tensile Strength, Percent Elongation, and Wet Tensile Strength Determination in Accordance with AG-1 and TAPPI T 494.
- Resistance to Airflow and Particle Penetration with Polyalphaolefin (PAO) in Accordance with AG-1, ASTM D737, and ASTM D2986.
- Water Repellency Using Similar Methods to AG-1 and MIL-STD-282.

- Thickness in Accordance with AG-1 and TAPPI T 411.
- Combustible Materials Content Using Thermogravimetric Analysis in Accordance with AG-1 and IEST-RP-CC021.1 Using a Thermogravimetric Analyzer.

RESULTS

Media obtained from stored and in service aged filters and three purchased rolls of nuclear grade filter media underwent testing to determine physical property degradation using AG-1 qualification tests. The results of these qualifications tests do not suggest an actual increase or decrease in a property of all media over time, since the value before aging or service exposure is unknown. Instead, the results of property determinations of these filters with different operational histories, ages, and designs show whether the property currently meets the qualification requirements of AG-1. Therefore, the results of these tests show relative values, such as medium of one age having a greater tensile strength than medium of a more advanced age or different operational history, rather than showing a 'reduction' in the tensile strength of any particular medium specimen over time.

Summary of Tensile Strength and Percent Elongation Results

TAPPI T 494 requires rejecting values for samples that meet certain criteria including but not limited to slipping in the jaws, breaking within the clamping area, or shows evidence of uneven stretching across its width. If more than 20% of the samples for a given sample set are rejected, TAPPI T 494 requires rejecting all readings obtained for that sample set [7]. Some data that includes more than 20% of samples breaking in the clamping area have been included in the plots to provide additional data points. These data points are labeled as not meeting the TAPPI T 494 requirements.

Tensile strength w. r. t. history and age is shown in the following figures. AG-1 requirement minimums for tensile strength in the machine and cross directions are 0.43 and 0.35 kN/m, respectively. Six media samples with an in service history that were tested in the machine direction, and six media samples with an in service history and two media samples with an in storage history that were tested in the cross direction did not meet the tensile strength requirements given by AG-1.

Figure 2 and Figure 3 show the tensile strength in the machine and cross directions with respect to (w. r. t.) history and age.

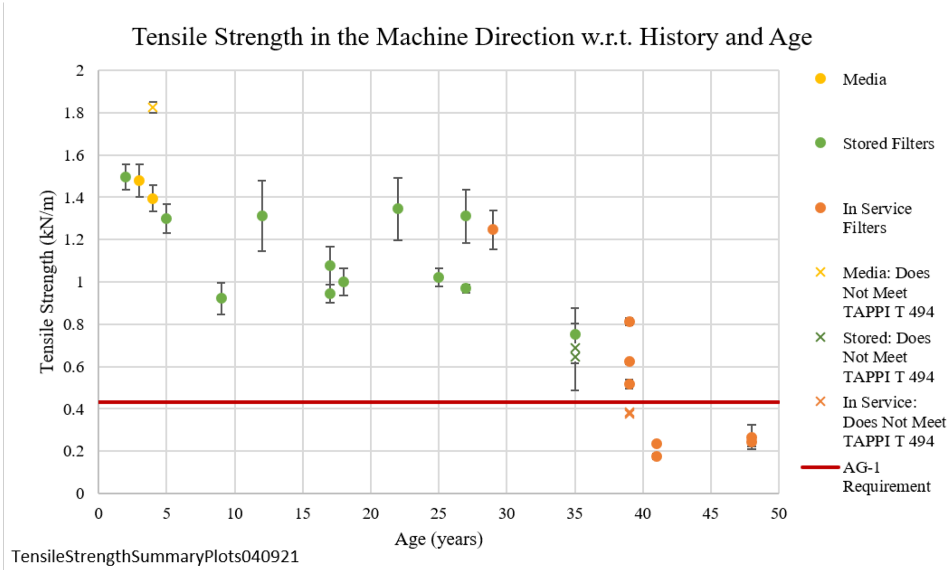

Figure 2. Tensile strength in the machine direction w. r. t. history and age.

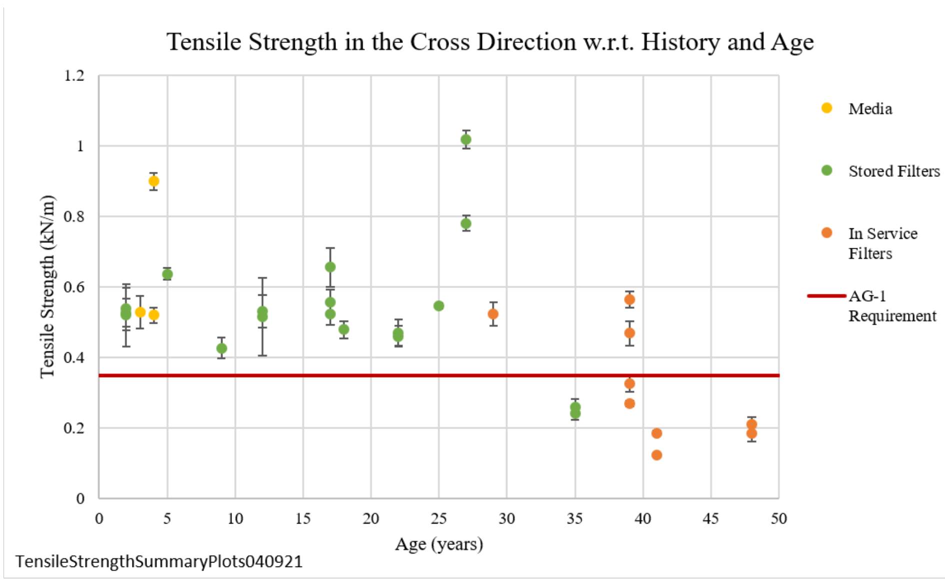

Figure 3. Tensile strength in the cross direction w. r. t. history and age.

Figure 4 and Figure 5 show percent elongation w. r. t. history and age. The AG-1 requirement minimum for percent elongation is 0.5% in both the machine and cross direction.

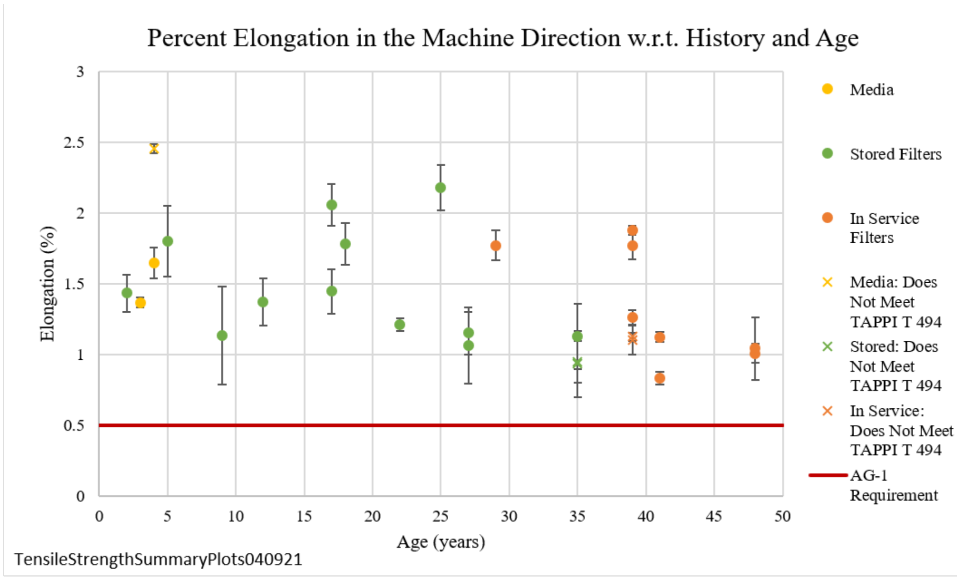

Figure 4. Percent elongation in the machine direction w. r. t. history and age.

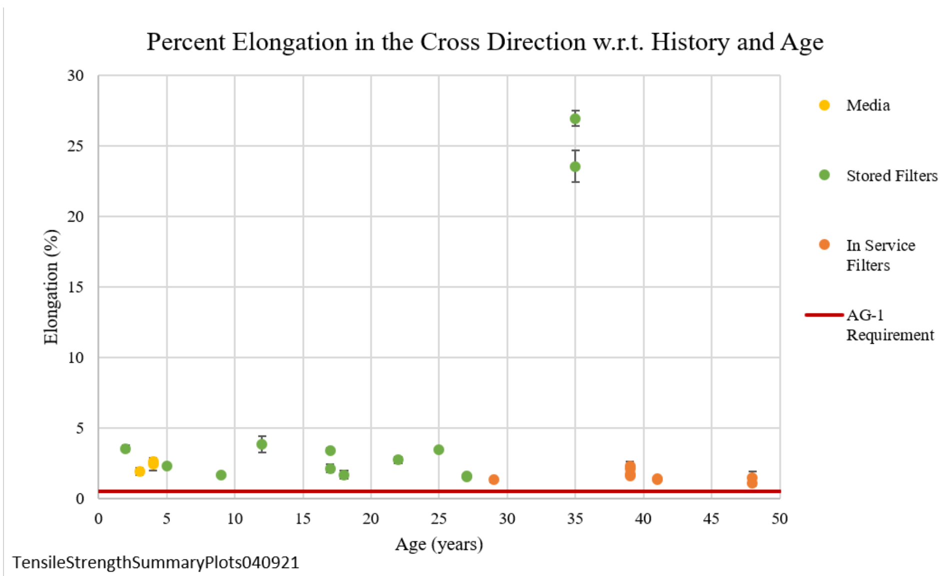

Figure 5. Percent elongation in the cross direction w. r. t. history and age.

Wet tensile strength results w. r. t. history and age are shown in Figure 6. The AG-1 requirement minimum for wet tensile strength in the cross direction is 0.17 kN/m. Five media samples with an in service history and three media samples with an in storage history did not meet AG-1 requirements.

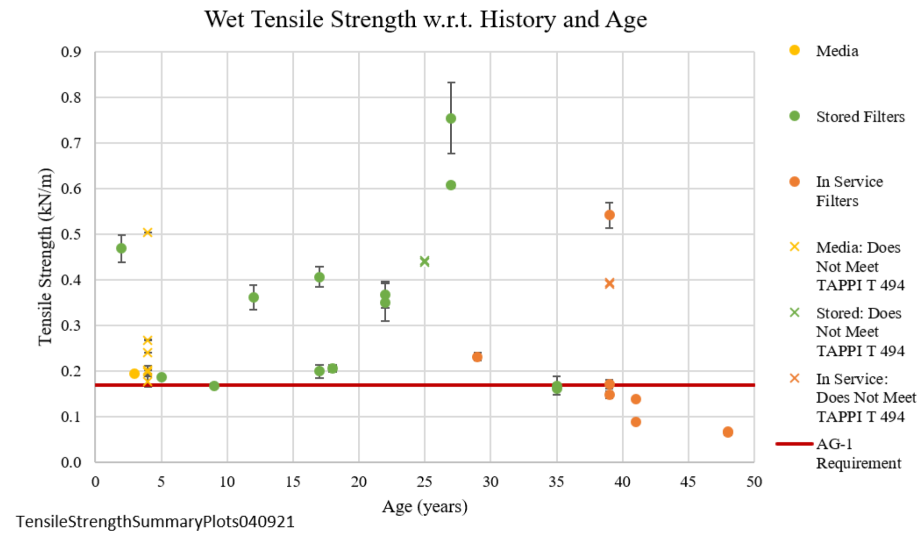

Figure 6. Wet tensile strength w. r. t. history and age.

Summary of Resistance to Airflow and Particle Penetration Results

AG-1 requires media to have a resistance to airflow maximum of 0.4 kPa (1.6 in. w. c.). Media samples from four filters did not meet the resistance to airflow AG-1 requirement, as shown in Figure 7. Three of those four filters were loaded to 1.0 kPa (4 in. w. c). and challenged at elevated conditions at ICET as part of filter testing. Media from the fourth filter that did not meet the requirement was removed from a 28-year-old filter that had been in service; therefore, failure of these media samples to meet the AG-1 requirement cannot be solely attributed to aging because of the loading on the media.

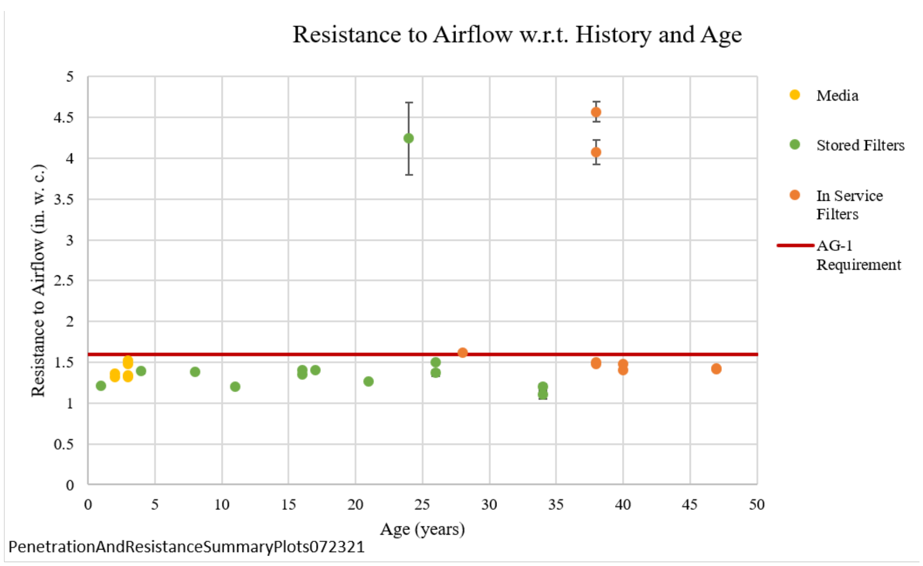

Figure 7. Resistance to airflow w. r. t. history and age.

AG-1 requires media to have a maximum particle penetration of 0.03%. The particle penetration plot in Figure 8 shows results w. r. t. history and age. Media from a 34-year-old stored filter did not meet the AG-1 requirement for particle penetration.

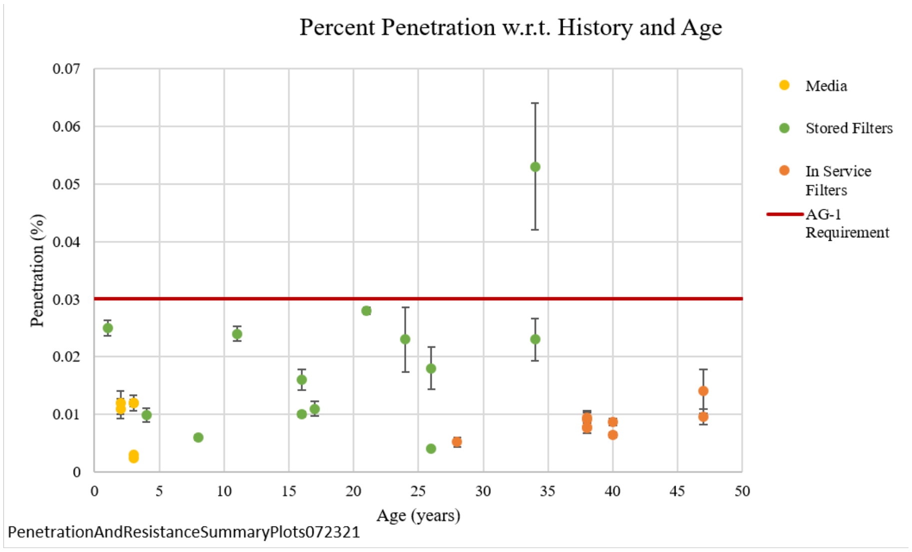

Figure 8. Percent penetration w. r. t. history and age.

Summary of Water Repellency Results

AG-1 requires that the average water repellency for media not be less than 5 kPa (20 in. w. c.) and have no individual measurements less than 4.5 kPa (18 in. w. c.). Figure 9 shows the results of water repellency w. r. t. history and age. Two stored filters and six in service filters did not meet the AG-1 requirement for water repellency. One of the two 39-year-old filters and a 25-year-old filter that did not meet the AG-1 requirement were loaded prior to testing which may have affected the results. A 29-year-old in service filter did not meet AG-1 requirements due to its lowest test result being below 4.5 kPa (18 in. w.c.), not due to overall average.

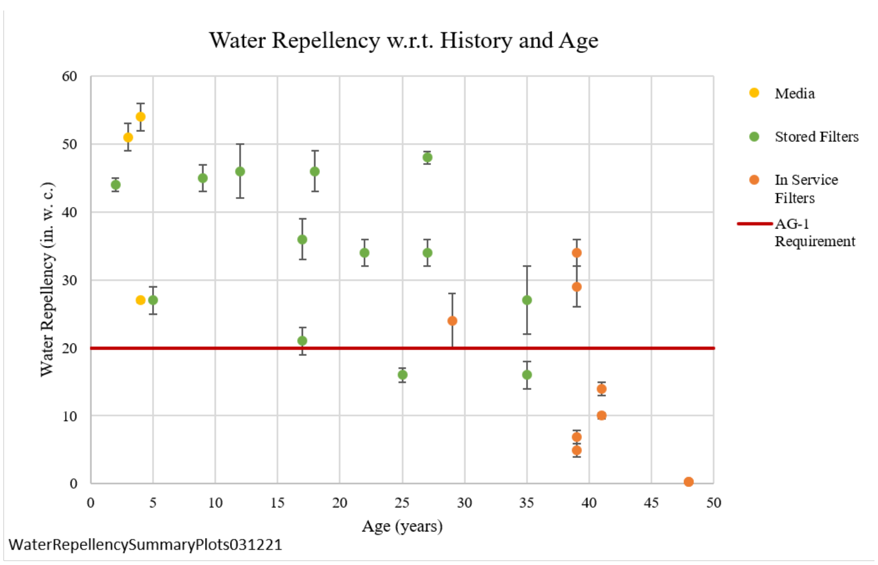

Figure 9. Water repellency w. r. t. history and age.

Summary of Thickness Results

AG-1 requires media have a minimum thickness of 0.38 mm (0.015 in.) and a maximum of 1.02 mm (0.040 in.). Test results from thickness measurements of aged HEPA filter media w. r. t. history and age can be seen in Figure 10. An in service filter, a stored filter, and a media sample set did not meet the AG-1 requirements for thickness.

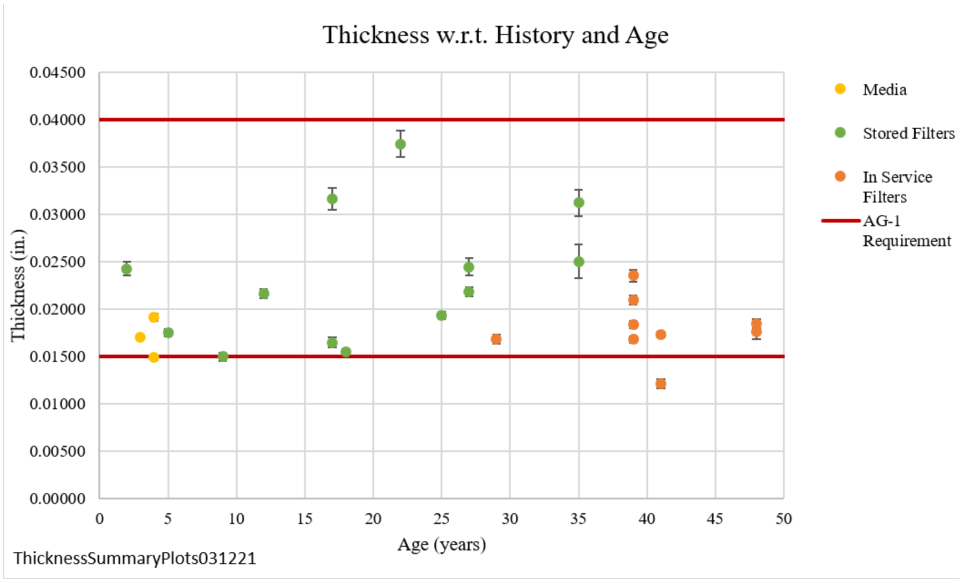

Figure 10. Thickness w. r. t. history and age.

Summary of Combustible Material Content Results

AG-1 requires that the combustible material in the filter media shall not exceed 7% by weight. Figure 11 shows the percent loss by weight of combustible material content w. r. t. history and age for each sample. The media from two stored filters and seven in service filters did not meet the AG-1 requirement. Media from the 24 year old stored filter and two of the 38 year old in service filters that did not meet the AG-1 requirement were loaded during filter testing at ICET; therefore, failure of these media samples to meet the AG-1 requirement cannot be solely attributed to aging because of the loading on the media.

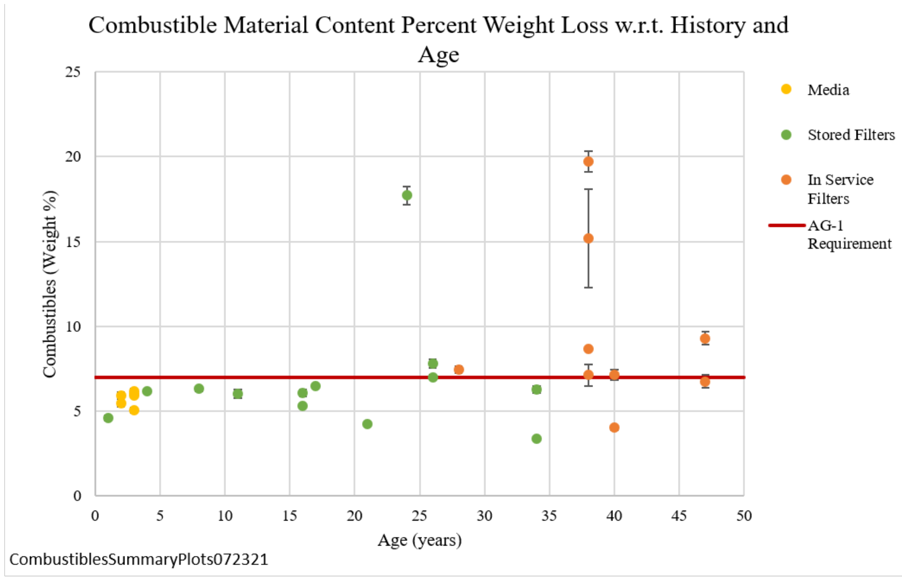

Figure 11. Combustible material content percent weight loss w. r. t. history and age.

FERMI FILTERS: DEGRADATION DUE TO FATIGUE RATHER THAN AGE

A set of four filters from Enrico Fermi Nuclear Generating Station, aged 36 years upon receipt at ICET, had the same manufacturer, similar manufacture dates, and the same design. The location of origin provided operational history documentation for the 30 years of service for these filters. The filters were installed from 1986 to 2016 in the Technical Support Center (TSC) HVAC system with normal operating conditions of 70% RH, 3 to 32 °C (37.5 to 90 °F) at 0.94 m^3/s (2000 CFM). These filters were 36 to 39 years of age when evaluated. Media from two of the filters exhibited decreased tensile strength and water repellency when compared to media from the other two. Figure 12 and Figure 13 compare the tensile strength of the four Fermi filters.

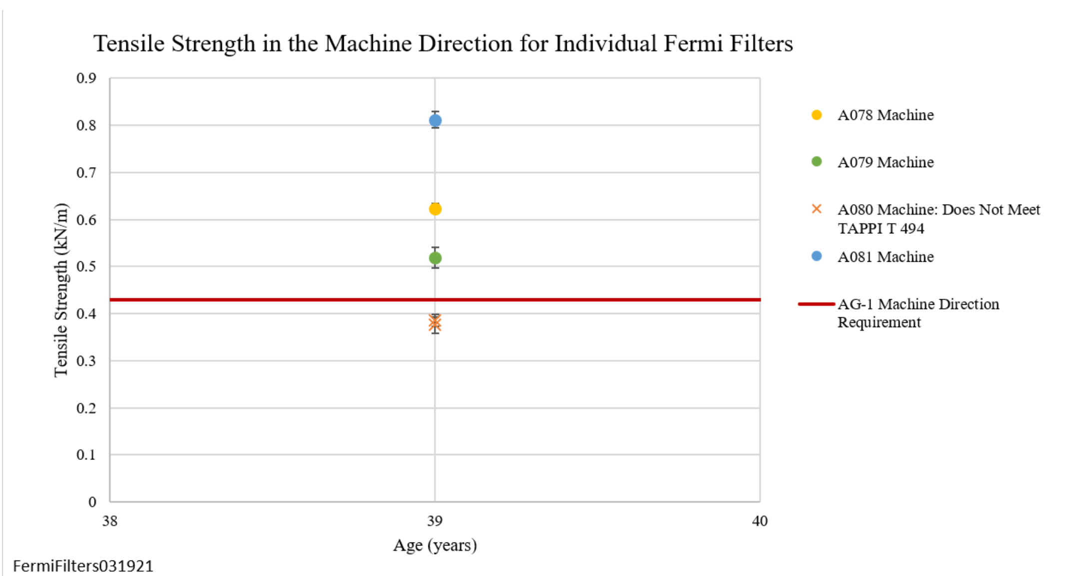

Figure 12. Tensile strength in the machine direction comparison for Fermi filters.

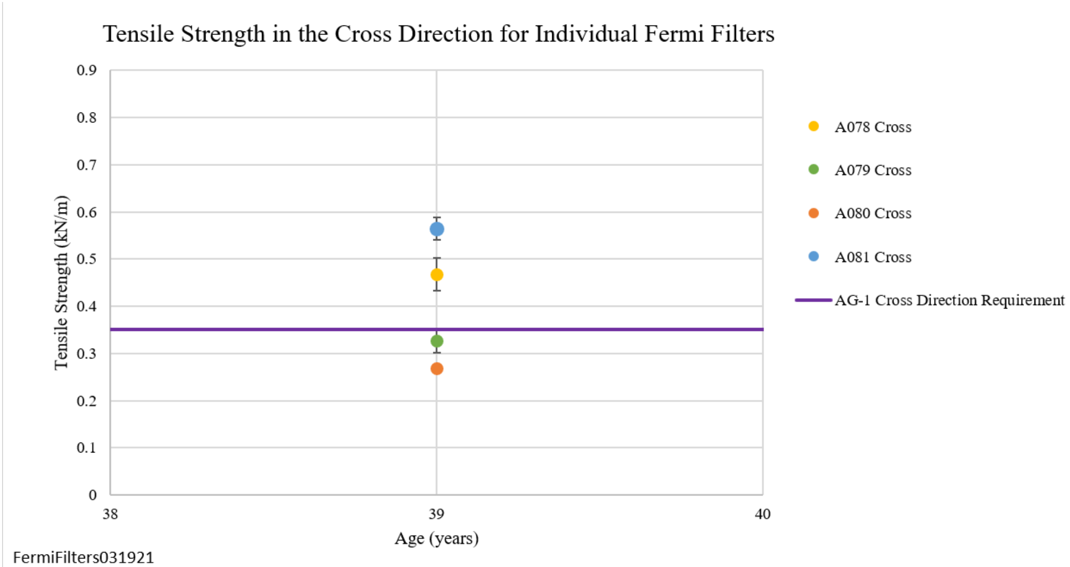

Figure 13. Tensile strength in the cross direction comparison for Fermi filters.

Figure 14 compares the wet tensile strength of the four Fermi filters.

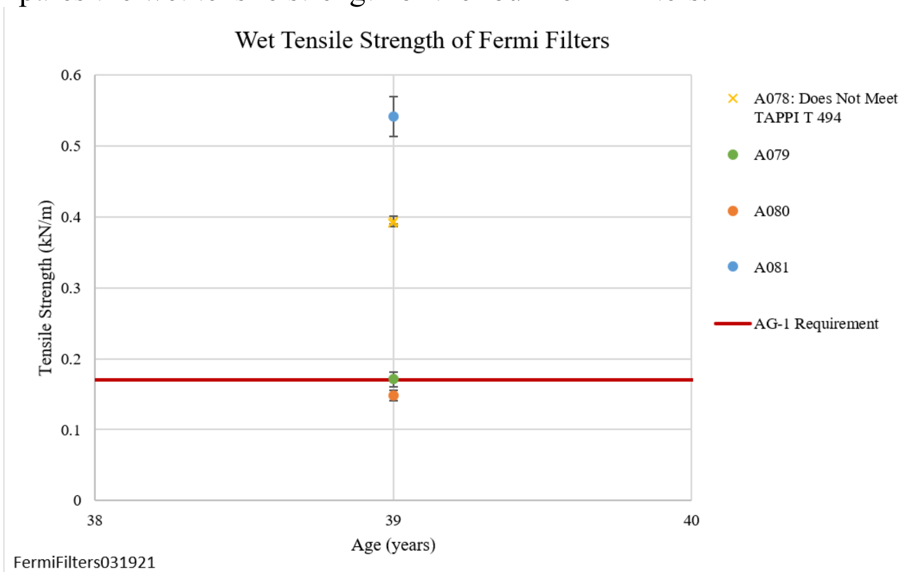

Figure 14. Wet tensile strength comparison for Fermi filters.

Figure 15 compares the water repellency of the four Fermi filters.

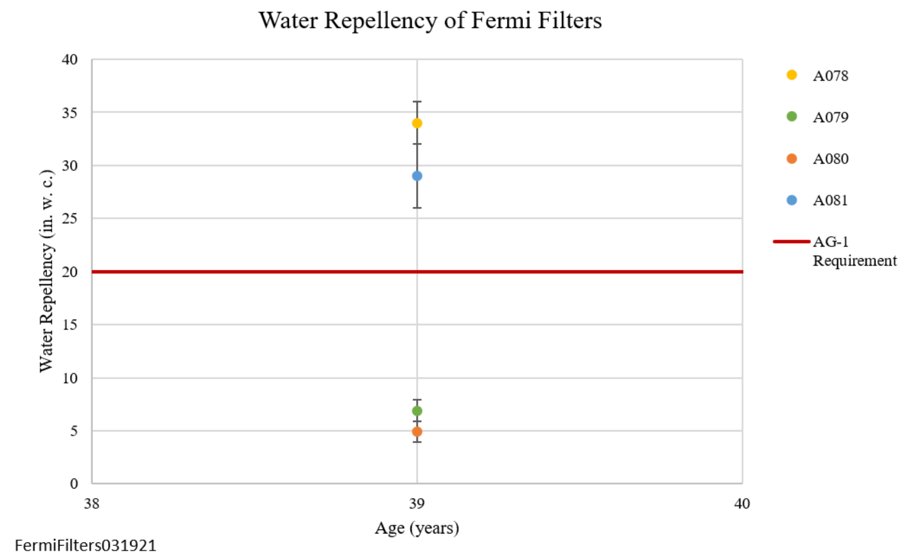

Figure 15. Water repellency comparison for Fermi filters.

Two filters from this set (A078 and A081) show tensile strength and water repellency results much greater than the other two filters (A079 and A080). It was determined from the operational history documentation that two filters were installed upstream of charcoal absorbers within the system, while the other two were downstream of the absorbers, indicating that the two sets experienced different conditions during service. It is unknown which filters were installed in each location. Figure 16 shows the locations of the filters during service, with red indicating upstream placement of two filters and green indicating downstream placement of two filters. The filters were rated at 0.47 m^3/s (1000 CFM) and were installed in a 0.94 m^3/s (2000 CFM) capacity system. It is believed that the filters were installed with two in parallel with each filter seeing 0.47 m^3/s (1000 CFM).

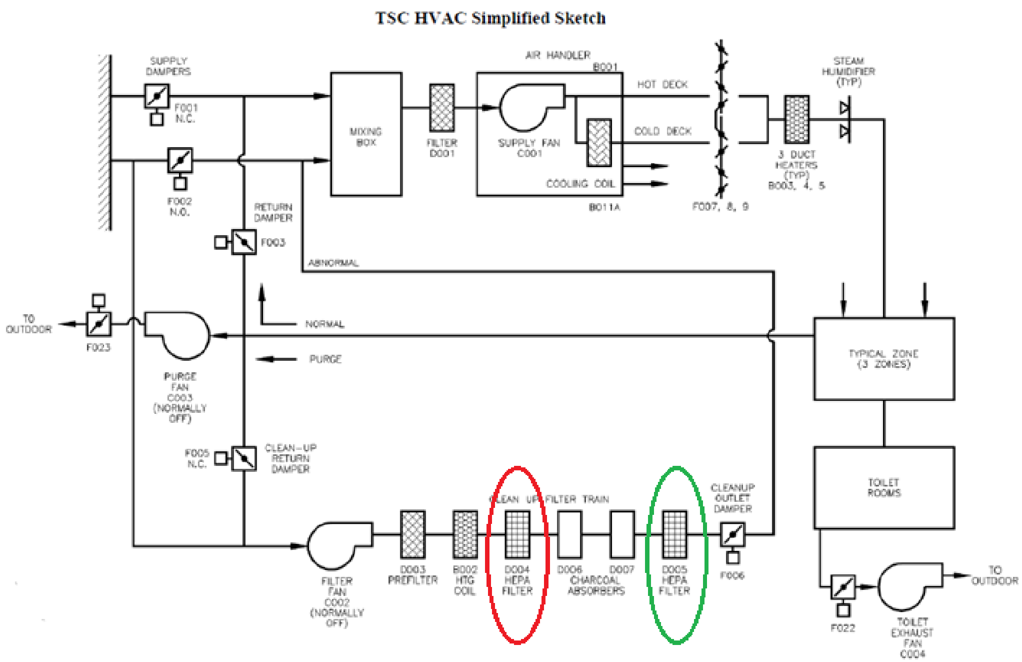

Figure 16. Location scheme for Fermi filters during the 30 years of service.

Based on the Fermi filter results, property degradation may not primarily be a function of age, but rather a function of fatigue and exposure. Media from these filters of the same age, model, and operational history do not exhibit the same properties, and this may be based on exposure during service. This data may validate the need to establish a separate shelf life (stored) versus service life for nuclear grade HEPA filters and precipitates the need for exposure and accelerated aging treatment studies to fully characterize the effect of the service environment on HEPA filter life.

CONCLUSIONS

Premature removal of operationally viable filters is cost prohibitive to facilities, but protracted use of functionally degraded filters carries risk to public and environmental safety. Fatigue and environmental exposure while in service may have more effect on filter performance than performance based only on age. The establishment of separate service and shelf lives is warranted based on the evaluation of in service filters of the same age and type installed in different locations within the same system with considerable differences in the measured media properties. Changes in properties due to differences in service exposures, as seen in the Fermi filters, suggest that differences due to service versus storage can result in greater variations in properties.

With the exception of one new media sample that did not meet the requirements for thickness, the test results indicated that all of the new media samples met AG-1 requirements. Test results also indicate that stored filters up to 25-years-old generally met the AG-1 qualification requirements for media. Excluding media samples with loading, stored filters up to 25-years-old met the AG-1 requirements for tensile strength and percent elongation in the machine and cross directions, resistance to airflow, particle penetration, water repellency, and combustibles. Most stored filters that were older than 25-years-old also met the AG-1 requirements for media. One nine-year-old stored filter did not meet requirements for thickness and wet tensile strength; however, this does not provide a clear indication that the properties of filter media change with age.

Regarding in service filters, all filters were 27-years-old or older. Some in service filter samples met the AG-1 media requirements, and some did not. However, due to a limited number of in service filters and limited documentation for service conditions, no conclusions can be drawn. One 27- to 29-year-old in service filter met all AG-1 media requirements except resistance to airflow, water repellency due to an individual lowest result being lower than the AG-1 requirement, and combustible material content. Each of these results may have been affected by possible loading on the media since the filter was in service. One 37- to 39-year-old in service filter met all AG-1 media requirements except combustibles. A second 37- to 39-year-old in service filter also met all media requirements except resistance to airflow and combustibles. This filter was loaded during testing at ICET, so the results may have been affected by the loading aerosol on the media.

The current study only includes one in service filter less than 30 years of age. To further investigate the service life of filters, additional aged in service filters are needed to help correlate results from stored filters with in service filters. Additionally, exposure conditions in the service location factor into degradation. Since there is limited availability of in service filters with different exposure conditions, the service life should be investigated using exposure and aging treatments.

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