

Factors Influencing HEPA Filter Performance – 9060

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ABSTRACT

Properly functioning HEPA air filtration systems depend on a variety of factors that start with the use of fully characterized challenge conditions for system design and then process control during operation. This paper addresses factors that should be considered during the design phase as well as operating parameters that can be monitored to ensure filter function and lifetime.

HEPA filters used in nuclear applications are expected to meet design, fabrication, and performance requirements set forth in the ASME AG-1 standard. The DOE publication Nuclear Air Cleaning Handbook (NACH) is an additional guidance document for design and operation HEPA filter systems in DOE facilities. These two guidelines establish basic maximum operating parameters for temperature, maximum aerosol particle size, maximum particulate matter mass concentration, acceptable differential pressure range, and filter media velocity. Each of these parameters is discussed along with data linking variability of each parameter with filter function and lifetime.

Temporal uncertainty associated with gas composition, temperature, and absolute pressure of the air flow can have a direct impact on the volumetric flow rate of the system with a corresponding impact on filter media velocity. Correlations between standard units of flow rate (standard meters per minute or cubic feet per minute) versus actual units of volumetric flow rate are shown for variations in relative humidity for a 70 °C to 200 °C temperature range as an example of gas composition that, uncorrected, will influence media velocity. The AG-1 standard establishes a 2.5 cm/s (5 feet per minute) ceiling for media velocities of nuclear grade HEPA filters. Data are presented that show the impact of media velocities from 2.0 to 4.0 cm/s media velocities (4 to 8 fpm) on differential pressure, filter efficiency, and filter lifetime. Data will also be presented correlating media velocity effects with two different particle size distributions.

INTRODUCTION

HEPA filters are commonly employed to control particulate matter (PM) emissions from processes that involve management or treatment of radioactive materials. Facilities within the US Department of Energy (DOE) complex are particularly likely to make use of HEPA filters in the processing of exhaust gases prior to release to the environment. 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* [1]. This report expressed concerns for the potential vulnerability of HEPA filters used in vital safety systems. Later that same year DOE initiated a response to the DNFSB's Recommendation 2000-2 by implementing measures with regard to 100 percent quality assurance testing of HEPA filters and a review of vital safety systems in general [2]. DOE's actions in this matter were also timely with regard to concerns being voiced by citizen groups over the performance of HEPA filters and how their functional status is monitored. Of particular concern are the threats to filter performance posed by water and smoke. While these two threats are both associated with fire scenarios, leaking reheaters can also pose a wetting threat to filters.

For the past several years, the Institute for Clean Energy Technology at Mississippi State University has conducted extensive research under its DOE sponsored HEPA Filter Monitoring Project. Studies have included moisture failure, source term loading, seal and pinhole leak tests, and media velocity. Details related to design, construction, and operation of the test stands utilized in these research efforts have been published [3]. Discussion of the experimental design related to these research efforts as well as results has been presented at numerous conferences [4, 5, 6] and published [7]. These discussions include aerosol generation, filters tested, and aerosol measurement instrumentation utilized.

RESULTS AND DISCUSSION

Moisture Failure/Wetting

The studies undertaken as part of this project were designed by a national Technical Working Group (TWG) as a part of joint effort by the DOE and the US Environmental Protection Agency (EPA) to coordinate research efforts to the maximum extent possible for issues associated with treatment and disposal of mixed wastes. During the early planning stages of this project it became clear to the TWG from the input gathered from facility personnel, permit writers, and other stakeholders that the most important data to collect would be for effects caused by the wetting of HEPA filters. A series of three filters were tested by subjecting them to repeated cycles of challenge with increasing relative humidity. A test cycle began by challenging a filter under baseline conditions with a relative humidity (RH) of approximately 15%. After collection of a full suite of data at this RH, the humidity was raised to approximately 50%. Challenge of the filter was held constant at this RH while another set of data were collected and then the RH was raised to between 90 and 100%. Data from this set of test conditions were collected and then the particle generator was turned off and RH in the test stand was returned to 15%. The filter was dried overnight at this low RH and the test cycle was then repeated. This process was followed until the filter failed to demonstrate a filter efficiency of 99.97% when it was dry. Table I contains a summary of the test conditions used for one of the filters.

Figure 1A contains a representative example of the data collected during these series of tests. This figure demonstrates the correlation between RH (red) and differential pressure (dP, blue) across the filter and differential temperature (dT, green) across the filter housing. Elevated RH challenge conditions were achieved by injecting water aerosol into the test stand approximately 15 diameters (7.5 feet) upstream of the filter. The RH of the flue gas was measured up and downstream of the filter. No liquid water was detected at the 15 or 50% RH test levels. However, the filter became wet and liquid water started to accumulate in the housing in front of the filter in a short period of time after the RH was raised to 90%.

Table I. Average Test Conditions of the ICET HEPA Filter Test Stand During Testing Activities for the Moisture Failure Mode Study.

Volumetric Flowrate (cfm)	250
Media velocity (ft/sec)	4 - 6
Temperature (°F)	77
RH	Low: 13.7% Mid: 51.1% High: 91.6%
Static Pressure on Test Stand (in WC)	3.2 in. wc subatmospheric
Particle loading rate:	
mg/m ³	25
#/cm ³	5x10 ⁵

PM	KCl
PM: CMD (nm) GSD	130 2.00

Figure 1A displays the correlation of dP (blue), dT (green) and RH (red) for the testing of a partially loaded HEPA filter with an ambient (room temperature) air flow. It is clear from the data in this plot that monitoring dP is not as sensitive or as rapidly responding as monitoring differential temperature for sensing the presence of liquid water in the air flow upstream of the filter. The dT curve (green) responds in concert with an increase in addition of moisture, either as a negative inflection (downstream T > upstream T) at low RH or as a much larger positive value (upstream T > downstream T) at an RH above 60%. It can be deduced that at high RH and low temperature air flows moisture rapidly converts the HEPA filter into an evaporative cooler. In this type of application monitoring dT across the filter housing and can serve as a very inexpensive and effective method for detecting liquid water reaching the filter.

Figure 1B shows the relative humidity curves and downstream PM concentrations for a filter as it is cycled through a moisture failure test. Notice that initial test conditions include approximately 15% RH followed by periods of exposure to 50 and 90+% RH. This particular filter underwent three days of testing.

Table II contains numerical data for downstream PM concentrations under the different RH test conditions. Trends seen in data for testing of the specific filter presented in Figure 1 and Table II are representative for all filters tested. The following observations can be made: (1) repeated wetting of a filter results in a deterioration of filter performance, (2) it is possible for a filter to “fail” (or demonstrate a filter efficiency less than 99.97%) when wet and yet recover filter efficiency when dry, and (3) no filter was found to fail irreversibly the first time it became wet.

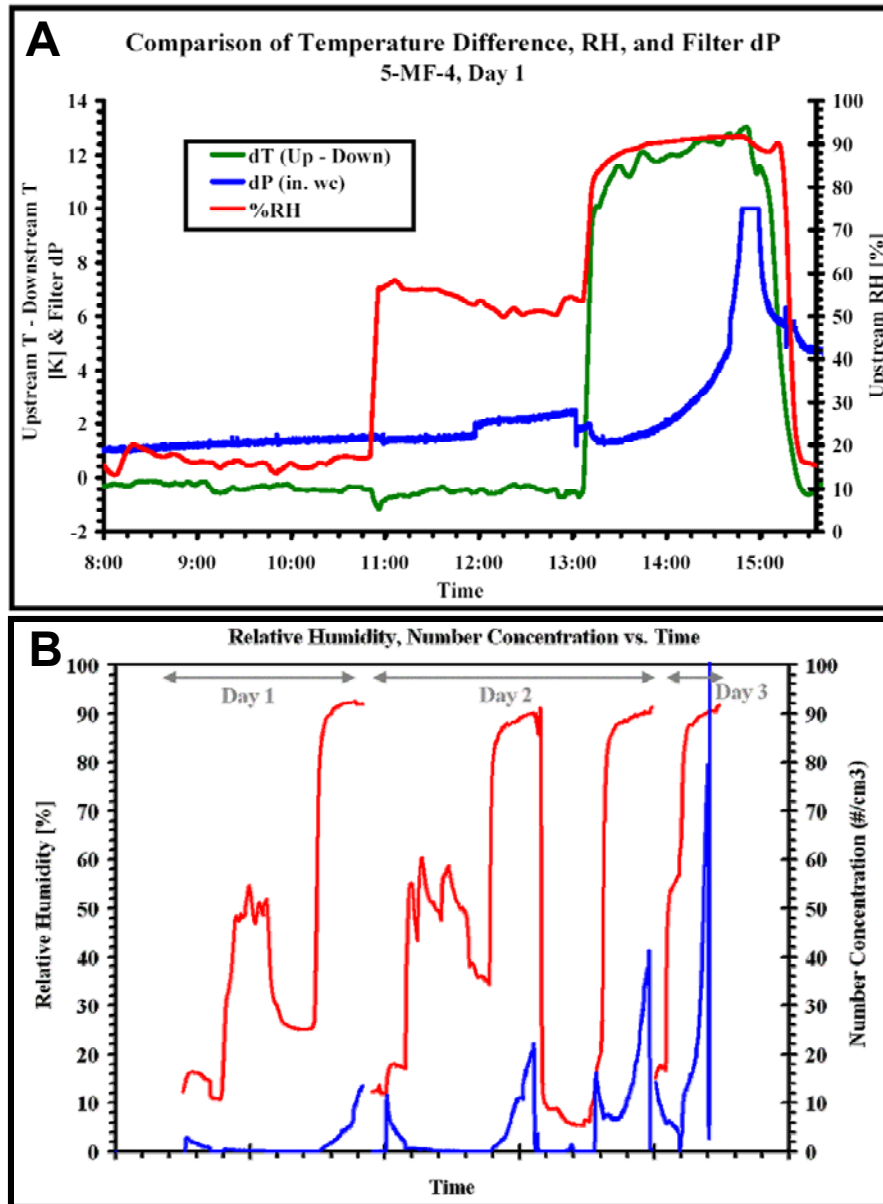


Fig. 1. Results of testing activities conducted during the Moisture Failure Mode Testing Study.

Table II. Filtering Efficiency Decline of Filter Undergoing Repeated Wetting for Three Days.

Day	Downstream Number Concentration (#/cc)	% Filter Efficiency
1	14	99.995
2A	21	99.993
2B	40	99.987
3	>2000	<99.33

The pictures contained in Figure 2 show the condition of a filter after it has completed the full sequence of testing. The top photos and the photo on the bottom left show small tears in the filter media that occur in localized areas after repeated wetting. These tears are particularly evident around glue joints at the filter frame or bottom of filter media pleats. Nearly all of the tears that developed in this particular filter occurred in the region included in this photo. The protective wire screen for these filters has a mesh size of approximately 0.25 inches that can aid in estimating the size of the individual tears. The photo on the bottom right shows deposits on the wire mesh in an area of this same filter in a location that does not include a visible tear. This provides evidence that liquid aerosols have penetrated or been given off the back of the filter media during testing causing obvious downstream contamination of equipment.

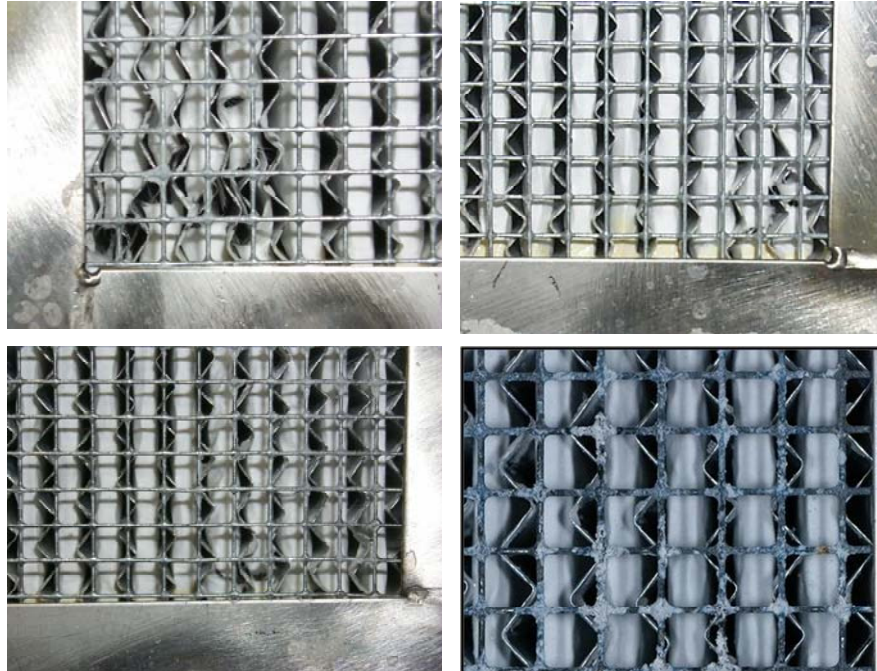


Fig. 2. Photos of rear surface of HEPA Filter that has undergone moisture failure testing.

Smoke/Soot from Fire

Of equal concern as the effect of wetting on HEPA filter performance during a fire scenario is that of smoke/soot. Fires affect the performance of HEPA filters due to the accumulation of smoke aerosols on the filter surface. This accumulation of smoke aerosols rapidly increases the pressure drop across the filter. Extensive focus has been placed on the effect of smoke during review of vital safety systems employing nuclear-grade HEPA filters [8, 9]. Researchers have determined that soot aerosols rapidly agglomerate and the aerodynamic mass equivalent diameter of soot aerosols to be ~50 nm [8].

A comparison of filter loading studies conducted by ICET utilizing KCl and soot as challenge agents is provided in top portion of Figure 3. The top portion of this figure demonstrates the correlation of differential pressure across the filter versus the calculated mass of PM collected by the filter at a given point in the testing process. The projected mass values are calculated by scaling the weight gain of the filter by cumulative upstream particle concentration measurements. Inspection of this figure reveals that the same mass of soot loads a filter almost five to twenty times as fast as KCl PM to an equivalent differential pressure. This implies that the expected life of a filter (the absolute mass of PM that it may collect) can vary widely as a function of the challenge material. As shown earlier, the count median

diameter (CMD) of the KCl particulate matter is ~130 nm with a geometric standard deviation (GSD) of 2.0. The CMD of the soot was found to be less than 90 nm with a GSD of 2.5.

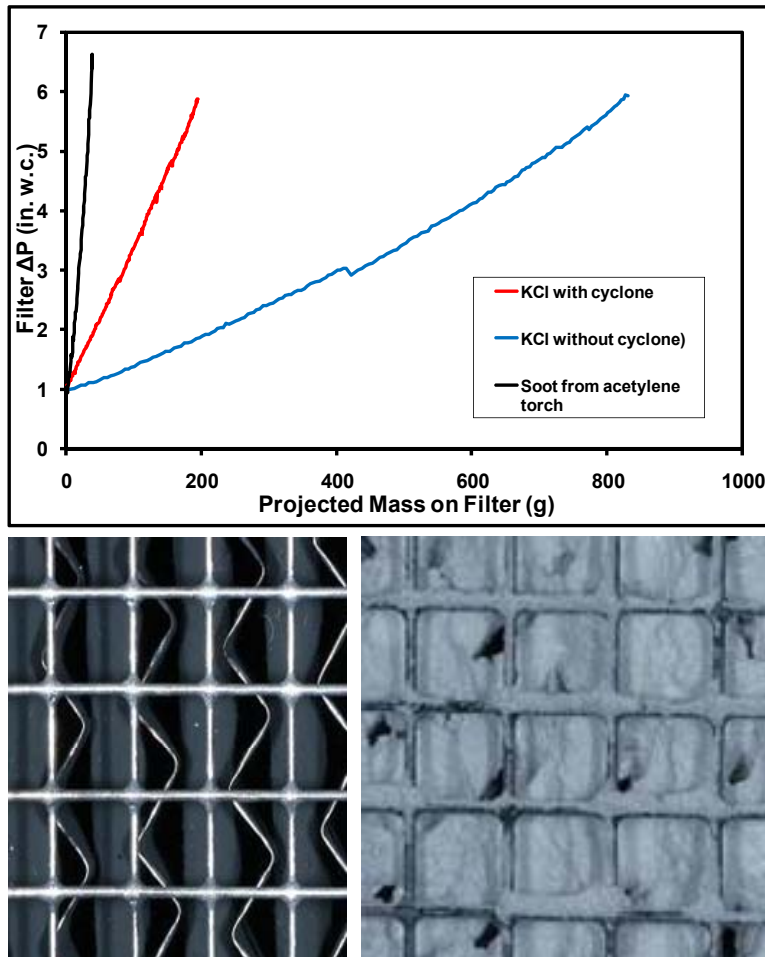


Fig. 3. Top: Comparison of loading rates for three PM challenges. Bottom: Photos of the front surfaces of HEPA filter that has been with soot (left) and KCl (right).

The bottom portion of Figure 3 illustrates two filters that were loaded to 6 in. w.c. The filter on the left was loaded with soot produced from an acetylene flame while the filter on the right was loaded with KCl. Inspection of the pictures again illustrates the variability in mass loading of soot and KCl required to produce a dP of 6 in. w.c. Also illustrated by these photos is the fact that the amount of KCl required to reach 6 in. w.c. resulted in bridging of the particulate matter across the face of the filter pleats whereas no bridging of soot particulate matter across the face of the filter was demonstrated.

Media Velocity and Variation between ACFM and SCFM Values

A significant amount of discussion has occurred with respect to the AG-1 Section FC stipulation of a 5 feet per minute (fpm) maximum velocity [10, 11]. The origins of this ceiling value in addition to the advances made in development of media over the past forty years have been discussed at length. A related area of discussion has involved control of process equipment using either standard or actual values of volumetric flow rates. There are two primary perspectives on this issue, one dealing with the more

intuitive recognition that actual flow rates are directly capable of controlling media velocity and the more analytical perspective centered on the accuracy of converting mass flow data into either standard or actual volumetric units. Often these two perspectives are included in any discussion/debate associated with controlling equipment using the units of either acfm or scfm.

Researchers at ICET addressed portions of the debate by providing results of filter loading experiments over a range of media velocities from four feet per minute to approximately eight feet per minute [6]. Data were reported showing media velocity effects on the most penetrating particle size, filter loading rates, and loading capacity of filters. There was additional discussion of how this information can be used in identifying considerations and monitoring instruments needed when selecting either acfm or scfm units for controlling an operating system.

Data collected during filter testing were used to calculate filter efficiency, MPPS, and downstream values of the GMD and GSD. Measurements recorded during the first five minutes of testing of a new filter were used to compute measures of static filter performance. Continuous up and downstream measurements were made for the full time period of testing each filter. These values were used to compute equivalent performance values to describe the dynamic trends in the loading process of each filter. Lifetime filter performance measurements were made up to the point at which the filter dP increased to 6 in. w.c.

Figure 4A shows the correlation of downstream GMD and GSD for two media velocities as a function of increase in differential pressure across the filter. The behavior observed at 2.5 cm/s is typical for 16 of the 18 filter evaluations performed: as the filter loads, the GMD of the aerosol downstream of the filter decreases. At a 250 Pa increase in filter dP, the decrease was typically on the order of 10-15 nm. Beyond this point, downstream aerosol concentrations were sufficiently low as to not permit valid statistical analysis. Also evident in data collected at 2.5 cm/s is a decrease in the GSD of the aerosol penetrating the filter. Here, the GSD decreased from 1.48 to 1.41. This behavior is also representative for the majority of filters tested.

The findings discussed in this study can be used to put into perspective the differences in filter performance when there is a difference between the target and real media velocity. The potential for this discrepancy between intended and real media velocity can arise from mathematical uncertainty associated with converting mass flow data to volumetric flow values. More specifically, equations relating flow through a filter media to mass flow measurements are not explicit. However, variability of gas composition resulting from variation in process chemistry or conditions may induce a much greater source of error.

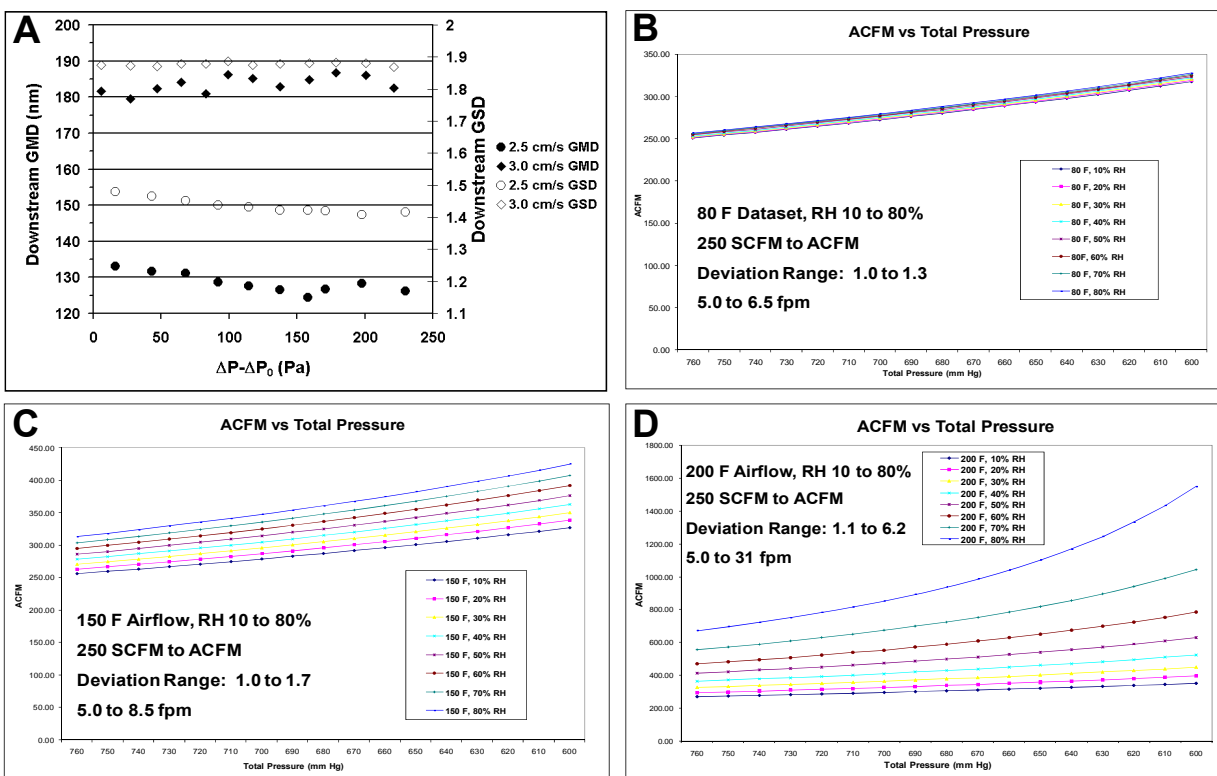


Fig. 4. A: Changes in GMD and GSD of the Aerosol Stream Passing through a Test Filter. B: Plot of ACFM Values Equivalent to 250 SCFM at 150 °F for Relative Humidity Values Ranging from 10 – 80%. C: Plot of ACFM Values Equivalent to 250 SCFM at 150 °F for Relative Humidity Values Ranging from 10 – 80%. D: Plot of ACFM Values Equivalent to 250 SCFM at 200 °F for Relative Humidity Values Ranging from 10 – 80%.

There are three major categories of conditions that cause deviation between the actual and standard values of volumetric flow: variation of gas pressures, gas composition, and temperature. Conversion of temperature and pressure effects is relatively straightforward and the most frequently addressed because these parameters are monitored and easily incorporated into control software. Additionally, deviation of operating conditions from standard temperature and pressure are typically relatively constant. However, significant fluctuations can occur for gas composition episodically or over time and gas composition is not as frequently monitored. This is particularly true for relative humidity.

Gas density changes due to changes in composition may result from variations in reaction products, but it should be recognized that relative humidity changes as a function of gas temperature offers significant potential for variability. To gain a better sense of the magnitude of the effect of RH as a function of temperature, a series of calculations was performed to generate curves correlating actual and standard volumetric flows as a function of gas pressure.

A series of curves was generated showing the effect of RH on scfm to acfm conversions as a function of gas pressure for a given temperature. Figures 4B, 4C and 4D give three sets of curves: 80, 150, and 200 °F. Figure 4B presents a family of curves that show the variation of acfm values for a 250 scfm air flow as a function of gas pressure at 80 °F. Individual curves are given for 10 through 80% RH. At 80 °F the amount of water in air to produce 20% RH is small and produces little error. The 10% RH curve in this figure can be used to represent the correlation between SCFM and ACFM for temperature and pressure

effects. If the mass to volume conversion is accomplished including only pressure and temperature, the differential between SCFM and ACFM values will basically equate to the difference between the 10% RH line and corresponding values on the appropriate RH line. The error introduced by failing to take variation of RH into account at 80 °F is minimal.

For very low RH values at 80 °F the SCFM to ACFM difference is negligible at 760 mm Hg. At 80% RH and 600 mm Hg the difference between SCFM and ACFM is on the order of 30%. If a filtration system is controlled using SCFM values and neglects RH, then a 250 SCFM air flow at 600 mm Hg, 80% RH, and 80 °F would equate to 328 ACFM. This flow rate will produce an actual media velocity of 6.5 fpm. Based on the studies discussed here a 6.5 fpm media velocity would have a minimal impact on most penetrating particle size and filtering efficiency. While the life time of the filter may be limited by this lack of control, it is not likely that the system would fail to function properly.

Equivalent sets of curves are presented for 150 and 200 °F in Figures 4C and 4D, respectively. At these elevated temperatures it becomes increasingly important to monitor for RH and correct gas densities in the mass to volume conversion calculations in order to ensure proper control of air flows. Within the pressure and humidity ranges represented in Figure 6, it can be seen that media velocities exceeding those tested in the above section may be achieved. Such elevated media velocities (exceeding 8 fpm) likely approach the point at which flows no longer follow Darcy's Law.

The effects of neglecting to take variation of RH into account as temperatures approach 200 degrees F become exaggerated relative to lower temperatures. While these theoretical curves are significant to point out the sensitivity of mass to volume calculations used to accomplish control of air flow systems, the actual flow rates that would be represented by higher RH curves in Figure 4 would likely produce significant elevated differential pressures for the filter experiencing such effects.

It is important to ensure accurate assessment of factors other than temperature and pressure that can influence gas densities in order to retain proper air flows during periods of process variability. This implies the need for thorough understanding of the ranges of variation and the identity of species in the air flows that may influence changes in gas density. For example, variation in CO concentrations may not have a large impact since its molecular weight is so close to that of air. However, variation in CO₂ concentrations, if large enough, can have a significant impact because of its higher molecular weight. The same is true for higher oxidation states of nitrogen, sulfur, and other oxides common to off gases from waste treatment activities.

CONCLUSION

HEPA filters are the last line of defense between conditions inside containment for nuclear process and the environment. Nuclear Grade HEPA filters are recognized for the stringent conditions under which they are designed, fabricated, and tested. They have proven their dependability of function over the years, however, it is important to remember that there are conditions for which they are incompatible or unsuited.

There are three areas of application for the information contained in this paper: (1) design of new HEPA filtration systems, (2) conducting safety reviews of vital safety systems under design basis conditions, and (3) operation and maintenance of existing systems. Design of new systems needs to be based on an accurate understanding of the mass loading rate (mg/m³) and particle size distribution of aerosols upstream of the filter. Maintaining a low mass concentration for aerosols upstream of the filter has been a

major objective for designers. However, it is clear from data reported in this paper that the lifetime (total mass collected) of a filter is also strongly influenced by the particle size distribution of the aerosol challenge.

The Nuclear Air Cleaning Handbook calls for system design to restrict particles greater than 2 μm from reaching the HEPA filter and to keep mass loading rates below 24 mg/m^3 . Design engineers need to have dependable data on both the mass of aerosols produced by process and the performance of air cleaning (prefiltration) activities upstream of the HEPA. Prefilter performance needs to be specified with respect to both the mass removal efficiency and the most penetrating particle size. Design engineers should have a good understanding of how problems with performance of prefiltration units or upset conditions in process will impact challenge conditions for the HEPA filters. A new 24 x 24 x 11.5 in (60.96 x 60.96 x 29.21 cm) HEPA filter challenged with 25 mg/m^3 of soot having a CMD of 70 nm will reach its maximum dP of 6 in w.c. (1500 Pa) in less than an hour. Design of filtration systems must be made in concert with engineers designing the rest of the process system.

Safety reviews of vital safety systems are critical to the development and operation of processes utilizing nuclear material. How these systems will operate when there is a fire within containment is routinely considered in these reviews. Information used to conduct these safety reviews comes from the scientific literature [8,9], the Nuclear Air Cleaning Handbook, and from guidance derived from individual DOE sites. None of these reference materials contain or refer to data that correlate filter performance to challenge by aerosols over wide particle size ranges.

Data reported in this paper reflect a strong need to correlate the performance of HEPA filters with particle size distributions as well as mass loading rates of the aerosols being removed from the air stream. A lack of such data leaves a large gap in peer reviewed literature that can be used in conduction of risk analyses. Due to the uncertainties of how HEPA filters behave during periods of heavy loading with soot, risk analyses will often take no credit for the filters reducing emissions. Research is needed to evaluate the lifetime performance of HEPA filters under a variety of conditions consistent with fire scenarios.

Operation of HEPA filter systems during normal operations can also be enhanced by information contained in this paper. Aging of process equipment and changes in process feed material can have impacts on the performance of filtration systems. The first indication of significance of these changes is often a reduction in filter lifetime. This results in increased operating costs, worker exposures during filter change out, and down time. The ability to detect moisture in the airflow, changes in mass loading rates, and shifts in particle size distributions can be used to infer more about what is occurring inside containment.

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