EVALUATION OF MASS EMISSION RATES DOWN STREAM OF HEPA FILTERS AS A FUNCTION OF SOURCE TERMS AND SELECTED FAILURE MODES

R. Arunkumar, J. A. Etheridge, J. C. Luthe, B. A. Nagel, O. P. Norton, M. S. Parsons,
D. M. Rogers, K. U. Hogancamp, C. A. Waggoner
Diagnostic Instrumentation and Analysis Laboratory, Mississippi State University

ABSTRACT

High efficiency particulate air (HEPA) filters are commonly employed to control particulate matter (PM) emissions from processes that involve management or treatment of radioactive materials. Public concern has grown significantly over the past few years concerning the use of HEPA filters and how their functional status is monitored. A study has been conducted to evaluate emission performance of HEPA filters under a variety of challenge conditions including those that result in failure or blinding of the filters.

Filter efficiency is typically evaluated by challenging the filter media with an aerosol of dioctylphthalate (DOP), an oily organic liquid. Testing conducted at DIAL has included challenging filters with both water soluble and insoluble inorganic salts. Filter loading during this testing was monitored by the conventional technique of measuring differential pressure. Filter performance was evaluated by comparison of up versus down stream concentrations of PM. Measurements of PM concentrations were made both up and down stream of the filter using EPA Reference Method 5i, electrical low-pressure impactors (ELPI), differential mobility analyzer/condensation particle counters (DMA/CPC), diffusion batteries/condensation particle counters, and condensation particle counters (CPC). This array of instrumentation allowed for simultaneous determination of up and down stream particle number densities, particle size distributions, and filtering efficiencies as a function of time and challenge PM.

Filters were challenged under a variety of conditions that can arise in DOE applications such as: low relative humidity, high relative humidity, controlled challenge (inorganic PM <30mg/m^3), uncontrolled challenge (smoke >30mg/m^3), and filters with physically damaged media or seals (i.e., leaks). Findings will be reported that correlate filter function as measured by traditional (differential pressure) techniques in comparison with simultaneous instrumental (ELPI, DMA/CPC, and CPC) determination of up and down stream PM concentrations. Additionally, emission rates and failure signatures will be discussed for filters that have either failed or exceeded their usable lifetime.

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 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.

The study described in this paper was designed by a national Technical Working Group (TWG) as a part of joint effort by the US Department of Energy (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. This project was undertaken in response to a combination of two driving forces: (1) the PM portion of the hazardous waste combustor (HWC) MACT standard requiring reduced PM emission limits and the potential requirement of continuous emission monitors for PM and (2) the TECH-23 Report on use of HEPA filters within the DOE Complex.[3] It should be pointed out that while this work was not part of the DOE 2000-2 initiative, it was developed to be supportive of that initiative.

A Draft Test Plan was developed in 2001 that was submitted to two ASME Peer Reviews. The objectives of this study are: (1) determine if instrumentation used in the study would be functional for monitoring the operational status of HEPA filters, (2) determine how changes in the source term (chemical and/or physical nature of the PM) affect instrumental accuracy or precision, and (3) correlate all measurements to results that are obtained with the standard EPA extractive method 5i. It should be pointed out that while numerous measurements have been made to evaluate HEPA filter performance, the focus of this study was directed at monitoring PM downstream of filters and not evaluating filter performance. All of the experimental work described in this paper has been carried out at the DIAL facilities on the campus of Mississippi State University. [4]

Experience has shown that it is helpful to explicitly delineate what this research project is from what it is not. The TWG focused this effort on the non- radiological measuring and monitoring of PM emission levels downstream of HEPA filters, not on the study of how or why HEPA filters fail. Activities described in the test plan are grouped under two general headings: (1) Failure Mode Study and (2) Source Term Study. Filtering efficiencies have been calculated for testing that has been conducted, however, the reader should keep in mind that the real focus of this study has been measurement of the very low PM concentrations downstream of the HEPA filters.

EXPERIMENTAL DESIGN

Air filters do not remove aerosol particles of differing diameters with equal efficiencies. All filters have a particle size that most easily passes through the filter media, called the most penetrating particle size (MPPS). The MPPS for HEPA filters is in the range of 130 nanometers in aerodynamic diameter. If test conditions are to be designed to maximize the number of particles penetrating a filter, the particle size distribution of the challenge should be weighted toward this MPPS. Challenge conditions for this study call for the ability to establish at least 30 mg/m^3 PM upstream of the HEPA filter with a particle size distribution that has a count median diameter (CMD) of approximately 130 nanometers and a geometric standard deviation (GSD) of approximately 2.0.

In order to achieve the objectives outlined in the HEPA Filter Monitoring Test Plan, it is important to employ filter challenge conditions equivalent to those encountered in facilities subject to the HWC MACT. Additionally, the range of test conditions possible must include those that are capable of causing filter failure within a relatively short period of time. The two predominant parameters that have been associated with filter failure are loading rates in excess of 30 mg/m^3 and relative humidities in the 90 to 100 percent range.

Test Stand Design

The test objectives of this study necessitated development of two test stands. The first is a small-scale unit that can be used to compare measurement methods under the most controlled of conditions. This unit referred to as the Calibration Test Stand has been used extensively for calibration of instrumentation and qualification of measurement methods. The second test stand is used for filter testing activities and is referred to as the DIAL HEPA Filter Test Stand.

The DIAL HEPA Filter Test Stand was developed to evaluate PM emission levels downstream of HEPA filters under various, highly controlled conditions. A schematic of the facility is shown in Fig. l. The parameters that were established by the TWG as design criteria for this test stand include:

1) Flow rate range -- 50-375 cfm (250 cfm nominal)
2) Inlet temperature -- ambient to 300 F
3) Relative humidity -- 15%-100%
4) Filter size -- 12"x12"x11 ½ "
5) Port availability for making multiple, simultaneous measurements upstream and downstream of the filter.
6) Particle generation of sufficient PM to establish 30 mg/m^3 challenge at the HEPA filter with a CMD of approximately 130 nm and GSD of approximately 2.0
7) Particle injection without either introducing swirl into the test stand or excessively increasing RH.

Conditioning of Upstream Air

Inlet air passes through a 85% ASHRAE filter, a nuclear grade HEPA filter, and finally an ULPA filter to remove PM to below detectable levels. This conditioned air then enters the upstream measurement train of the test facility through a 6" diameter venturi flow meter.

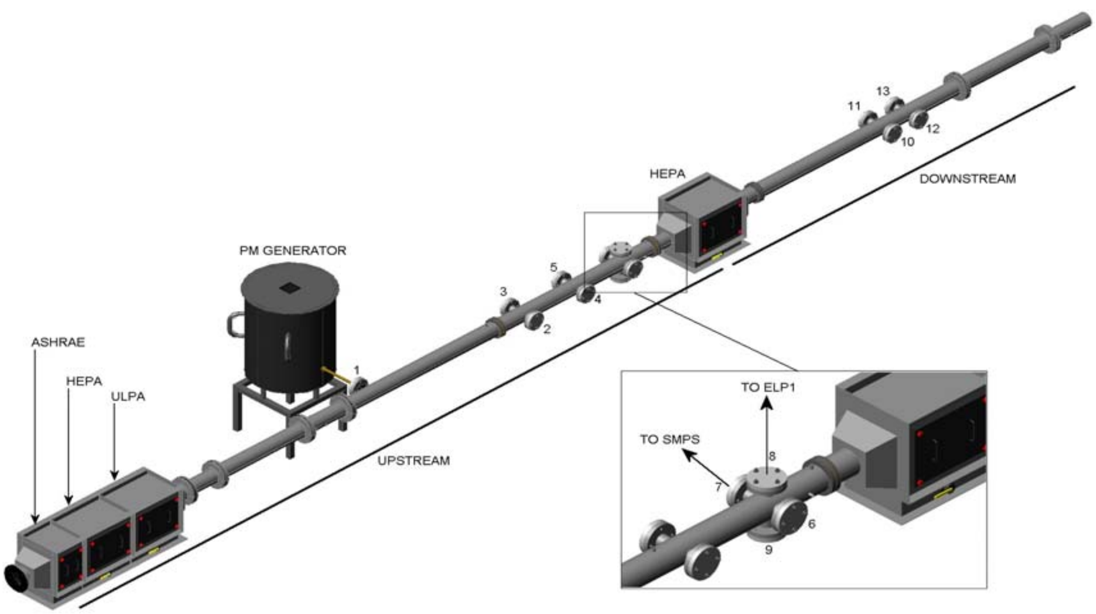

Fig. 1 DIAL HEPA Filter Test Stand with Aerosol Generator

Inlet air to the test stand can be provided from several sources. If relative humidity (RH) levels are not within an acceptable range for the testing to be conducted, air can be drawn from either inside or outside the building. If lower RH levels are desired a Hankison Model HHS-260 air drier is employed to reduce the RH to acceptable levels. The system can also be fitted with a water or steam injection system to elevate RH to levels higher than ambient air. A variety of water injection devices are available for use including an acoustic evaporation system, Laskin nozzles, and an ATI Model PSL aerosol generator.

Test Stand Ductwork

The up and downstream ductwork for the test stand is made of 316L stainless steel tubing that has been electro-polished on the inside to 10 Ra to minimize PM deposition on the walls. Sections of ductwork are joined using CF-style vacuum flanges to prevent outside air infiltration and facilitate tightness testing of the test stand. Sections of the flow channel have been designed with appropriately located 3” ports to facilitate injection of particulates or sampling of the air stream. Pipe fittings have been placed along the length of the stand for affixing thermocouples or RH probes. Appropriate distance has been provided between the PM injection and measurement locations to allow mixing of the PM upstream of the filter and the ports where measurements are made.

The test facility can be sealed off with blind flanges at inlet and outlet ends in order to perform leak testing of the pressure boundary using the *Pressure Decay Method* in accordance with ASME N510-1995.

Filter Housing for Test Filter. The HEPA test filter housing is a KG1 series (non-bag in/out) stainless steel unit manufactured by Flanders Inc. It accommodates standard 12”x 12” x 11 ½” HEPA filters with front face gaskets. Any other unit that will mate up to the 6” tubing flanges can replace this filter housing. The housing has provision for the measurement of pressures upstream and downstream of the filter, as well as a number of clean-out holes and a drain.

Downstream Test Section

Downstream measurement sections are equivalent to upstream sections and are fitted with a two sets of dual 3” opposing ports in addition to probe and sensor fittings. A venturi flow meter similar to the upstream one is located downstream of the last test section. Comparison of measurements from the two flow meters is used as a check for infiltration of air into the system while testing is being conducted.

Measurement Instrumentation

The test train is equipped with two venturi flow meters upstream and downstream of the HEPA test filter. Flow rates from each venturi are calculated using dual sets of differential and absolute pressure transducers. This allows for both redundancy and verification of measurements. A dual set of differential pressure transducers along with a Magnehelic pressure transmitter determines the pressure across the test HEPA filter. Relative humidity measurements are made with the use of a Vaisala HMP-238 transmitter. All of the above instrumentation has NIST traceable certification.

Control of Testing Conditions and Data Logging

Measurement and control of the flow parameters are performed on a Lonworks, network based system. Data are acquired, logged and periodically backed up onto a data server through the use of a personal computer.

Outlet air from the test facility is routed to a 10Hp, Spencer Turbine VB-075, vortex blower that provides the suction for drawing air into the facility. A bypass valve upstream of the blower is controlled to provide the required airflow range in the test facility.

Particle Generation

The design of the DIAL particle generator was governed by the following set of performance requirements:

- Mass loading rate of 30 mg/m^3 at the HEPA filter
- Specific particle size distribution with
    - Count mean diameter (CMD) ~130 nanometers
    - Geometric standard deviation (GSD) ~ 2 or less
- Dry aerosol at HEPA filter
- Air flow rate from particle generator must be less than 10 cfm or 5% of total volumetric air flow rate in test stand
- No more than 10 ml/min water flow into test stand in order to maintain low relative humidity
- Continuous operation for length of test
- Stable particle size distribution (PSD) and mass generation rate
- High through-put efficiency
- Ability to vary PSD, chemical composition of aerosol matrix, and mass generation rate

Particle Generation Chamber

The particle generation chamber is a stainless steel tank 30 inches in diameter and 38 inches in height. The walls of the tank are heated to 200^{o}F to aid in the process of drying the challenge aerosol and to reduce thermophoretic wall losses. The top of the generation chamber is fitted with a halo made from one inch copper tubing to facilitate addition of dry heated air. This configuration allows addition of the drying air in a manner so as to reduce wall deposition and increase generation efficiency of the unit.

Aerosols leave the chamber via a one-inch diameter stainless steel tube located approximately 10 inches from the bottom of the tank. This exit tube is fitted with a downward pointing 90-degree elbow located along the midline of the chamber.

Atomizing Nozzle and Pump

Production of liquid aerosols within the generation chamber is accomplished using a Spraying Systems nozzle. This air-atomizing nozzle is a ¼ J SS stainless steel nozzle body with a SU1A SS stainless steel spray set up. The atomizing nozzle operates as an external mix nozzle. The test liquid and compressed air flow through separate chambers in the nozzle and do not come into contact with each other until they exit the nozzle. The nozzle produces a cone-shaped round spray pattern. A Harvard Apparatus programmable push pull syringe pump model number PHD 2000 supplies test liquid to the nozzle assembly. The unit is fitted with four 60 ml latex free plastic syringes manufactured by Becton Dickson. There are dual check valves attached to the syringes, which allow the liquid to enter and exit the syringe properly. The atomizing nozzle is positioned along the midline at the top of the generation chamber. It functions by using 30 liters per minute of air to atomize a liquid stream of 10 milliliters per minute.

Air Flow Control

Two compressed air streams flow through the mass flow controllers, one for atomizing the test liquid and the other used as sheath air to sweep the walls of the generation vessel and dry the aerosol droplets. Both air streams are dried by a compressed air dryer (Hankison DH-60) prior to entering the mass flow controllers. The mass flow controller for the air sheath is an Aalborg GFC 571S with a flow range of 0 to 200 liters per minute. The mass flow controller for the nozzle air is an Aalborg GFC 471S with a flow range of 0 to 100 liters per minute. Connections on the inlet and outlet of both mass flow controllers are 3/8 inch tubing. Wetted parts inside the mass flow controllers are stainless steel.

The sheath air stream is controlled at 130 liters per minute and is heated by an oven manufactured by Apex Instruments. The oven uses four finned high density strip heaters capable of heating the unit to a temperature of 550^{o}F and the drying air to approximately 450^{o}F. The temperature of the air stream as it exits the sheath air halo at the top of the generation chamber is nominally 200^{o}F.

Removal of Large Aerosol Particle

A cyclone is located between the particle generator and the test stand and is employed to remove a majority of the particles larger than three micrometers in diameter.

Temperature Measurements

All thermocouples used in the DIAL particle generation system are type "K." The measurement locations of the thermocouples are as follows: (1) Temperature of the strip heaters, (2) Temperature of the air stream as it exits the air heater, (3) Surface temperature of the stainless steel tank, (4) Temperature of the air as it exits the copper ring, (5) Temperature of the aerosol at the particle generator exit, (6) Surface temperature of the outlet tube, and (7) Temperature at the entrance to the cyclone. All thermocouples were purchased from Omega Engineering.

Ability to Tune PSD and Mass Loading Rate

The ability to "tune" the particle generator is a very important requirement. The optimum operating conditions for generating 30 mg/m3 KCl challenge PM with a 130 nm CMD and 2.0 GSD were determined to be 30 liters per minute air supplied to the nozzle, 10 milliliters per minute liquid solution supplied to the nozzle, 130 liters per minute air sheath flow rate at a temperature of approximately 200^{o}F, wall temperature of 200^{o}F for the particle generator, and 300^{o}F wall temperature for the tubing leaving to the test stand.

Duty Cycle

It is also very important that the particle generation system be capable of continuous operation due to the length of some of the tests. Certain sets of tests require the particle generation system to run continuously for 10 to 12 hours at a time. Therefore, a very durable, reliable system was necessary. This was achieved with the stainless steel materials of construction and continuous operation syringe pump.

Filters Tested

Filters used in this study are nuclear grade AG-l HEPA filters that employ foam rubber seals and have been acquired from Flanders Filters Inc. Nuclear grade HEPA filters are normally individually tested with DOP to ensure that they are compliant with all specifications. However, to prevent any possibility of DOP residue from interfering with this testing effort, filters used in this study were provided without DOP testing.

RESULTS

Baseline Filter Study

The filtering efficiency of an individual air filter increases with differential pressure across the filter (i.e., as it becomes more loaded). An initial study was undertaken that involved challenging the test filter under a set of standard conditions and monitoring both the differential pressure across the filter and its filtering efficiency. This testing was completed with three new filters under the conditions listed in Table I.

The purpose of this testing was to determine the correlation between differential pressure and filtering efficiency as a filter loads with particulate matter and serve as a baseline for failure mode and source term studies.

This includes the following correlations:

1. Differential Pressure across the filter vs. % Loading of the filter.
2. Filtering Efficiency of the Filter vs. % Loading of the filter.
3. Down stream PM concentrations under baseline challenge conditions.
4. Practical detection limits for different instrumentation used.
5. Final calibration of the test stand and components under baseline conditions.

Table I Average test conditions of the DIAL HEPA Filter Test Stand during testing activities for the Baseline Filter Testing Study.

Volumetric Flowrate (cfm)	250
Media velocity (ft/sec)	4 - 6
Temperature (^{o}F)	79.65
RH	13.6
Static Pressure on Test Stand (upstream of filter) (in WC)	3.2 in. wc subatmospheric
Particle loading rate: mg/m^3 #/cm^3	 25 $5x10^5$
PM Matrix	KCl
PM: CMD (nm) GSD	 130 2.00

Figure 2 provides a synopsis of the findings from this series of tests. All data are from the testing of a single filter. Figure 2 (A) shows the correlation between Filtering Efficiency and Time of Loading for a new filter. It should be pointed out that since these filters had not been tested with DOP, the initial filter efficiency values were used to verify that the individual units qualify as a HEPA filter. It can be seen from data in Figs. 2(A) and (B) that the filter being tested has a differential pressure of approximately 1 inch of water column and a filtering efficiency of greater than 99.97%. Figure 2(C) has been provided to show the time required to load this filter to above six inches wc under the challenge conditions contained in Table I.

The relatively rapid increase in filtering efficiency and corresponding decrease in particle concentration downstream of the filter are characteristic of all filters tested. The increase in filtering efficiency to near

100% was observed in all filters tested. Figure 2 (D) shows the drop of particle concentration downstream to less than 0.5 particle/cc. Such low number densities of particles are below detection limits for the diffusion battery, SMPS, and ELPI, so it is not feasible to collect particle size distribution data with these units. It would be possible to set up extremely long sampling times with at least some of this instrumentation and collect statistically valid data, however, these long sampling times would be much longer than the life of a filter. A condensation particle counter has been used as the principal downstream detector during periods of testing a functioning filter. It is data from this unit that is used to compute filtering efficiency.

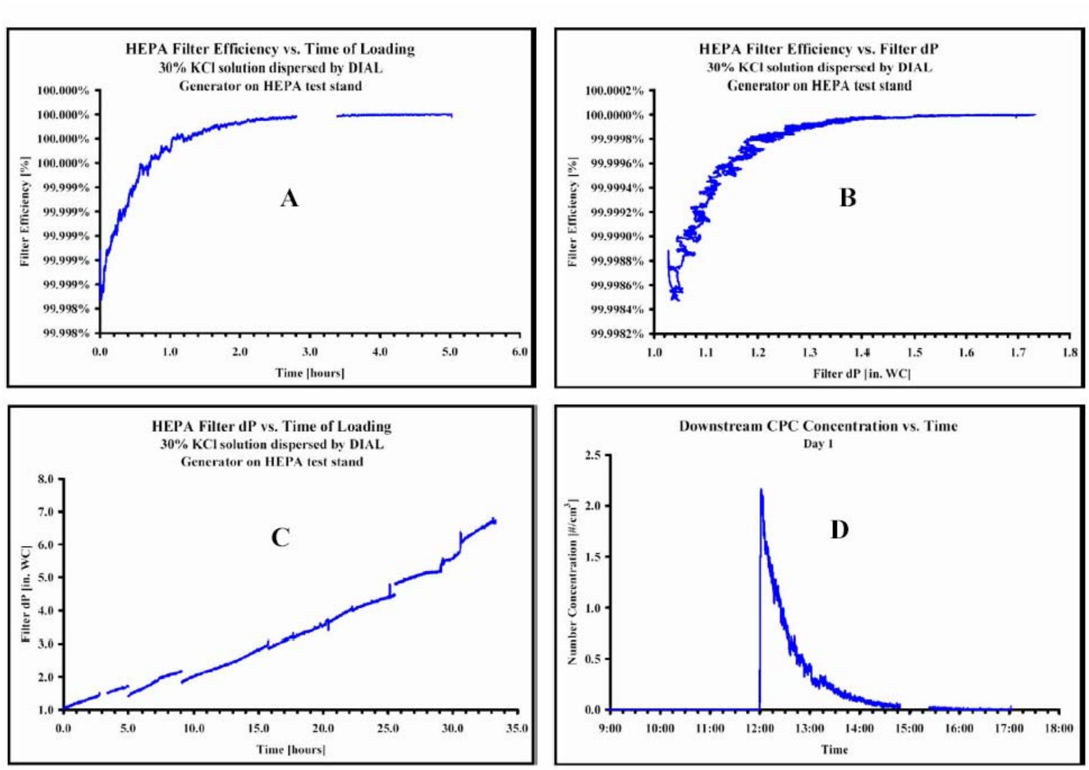

Fig. 2 Results of testing activities conducted during the Baseline Filter Testing Study

Moisture Failure Study

It became clear to the TWG from the input gathered from facility personnel, permit writers, and other stakeholders that their greatest area of concern dealt with effects caused by the wetting of HEPA filters. A series of three filters were tested by carrying them through repeated cycles of challenge with increasing relative humidity. A test cycle began by challenging a filter under baseline conditions with a relative humidity 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 II contains a summary of the test conditions used for one of the filters.

Table II Average test conditions of the DIAL HEPA Filter Test Stand during testing activities for the Moisture Failure Mode Study

Volumetric Flowrate (cfm)	250
Media velocity (ft/sec)	4 - 6
Temperature (^oF)	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 #/cm^3	 25 $5x10^5$
PM	KCl
PM: CMD (nm) GSD	 130 2.00

Figure 3 contains a representative example of the data collected during this series of tests. This figure demonstrates the correlation between relative humidity and differential pressure across the filter, and differential temperature 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 under 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%.

Figure 3(A) 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 rapid 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 and 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.

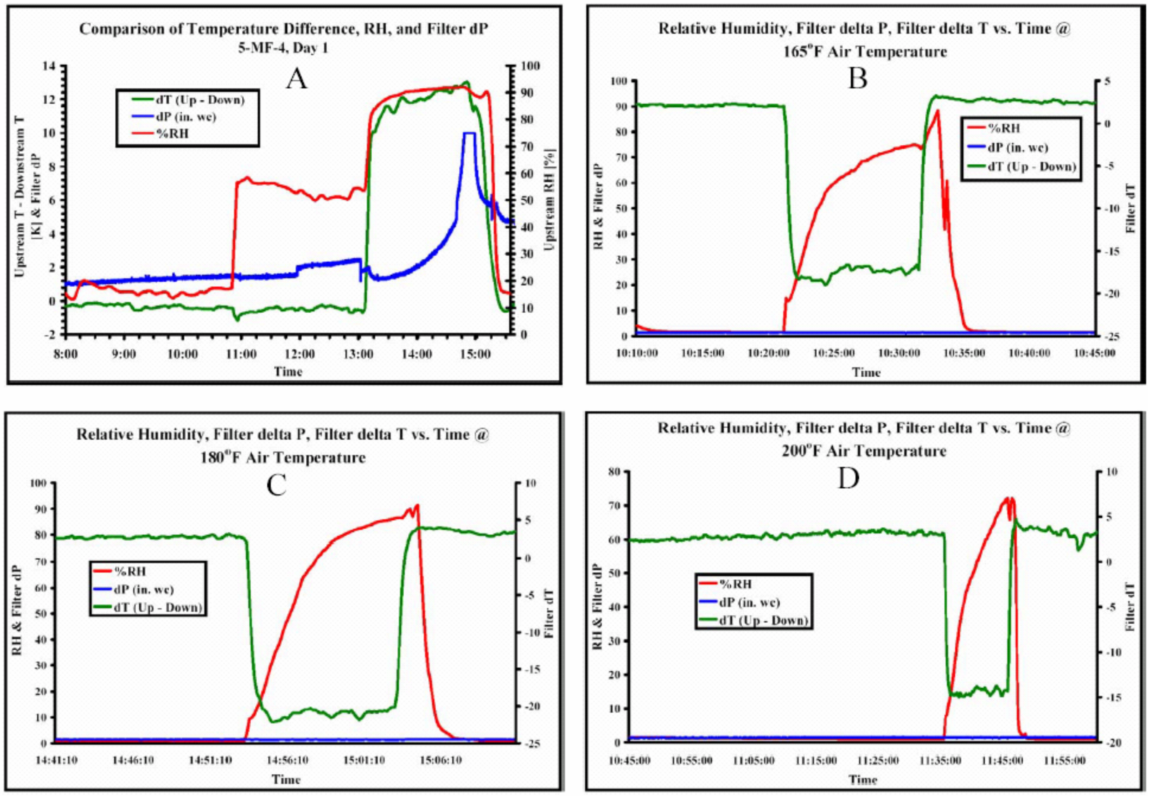

Fig. 3 Results of testing activities conducted during the Moisture Failure Mode Testing Study

Very few HEPA filtration systems function at room temperature, so another set of evaluations was scheduled for temperatures that range from 150 F to 200 F. The plots included in Figs. 3 (B), (C), and (D) show that dT also correlates well with addition of a water spray at these higher temperatures. It is significant to note that the upstream temperature measurement is of lesser magnitude implying that the thermocouple is being cooled more than the filter by the evaporating water.

Seal Leak and Pin Hole Study

Another area of concern that was expressed by stakeholders was the potential for detecting improper installation of filters. Filters are currently challenged with DOP when they are installed to confirm proper installation and a series of tests were developed to evaluate detection methods using a dry aerosol challenge. Two sets of conditions that could lead to leaks were studied, leaking seals and pinholes or tears in the filter media. Challenge conditions were the same for both studies and a representative set of data is included in Table III.

Seal Leaks were simulated by placing a series of shims between the seal and the filter housing at one corner of the filter. Pinholes were simulated by inserting short pieces of brass tubing into the face of a pleat of the filter in a manner so that the air would pass down one of the corrugations of the aluminum separator plate.

Table III Average Test Conditions of the DIAL HEPA Filter Test Stand during testing activities for the Seal Leak and Pin Hole Failure Mode Study.

Volumetric Flowrate (cfm)	250
Media velocity (ft/sec)	4 - 6
Temperature (^{o}F)	75
RH	16%
Static Pressure on Test Stand (in WC)	3.2 in. wc subatmospheric
Particle loading rate: mg/m^3 #/cm^3	 25 5x10^5
PM	KCl
PM: CMD (nm) GSD	 130 2.00

The plot found in Fig. 4(A) shows a comparison of filter efficiencies as measured by ELPI (green) and SMPS (red). Five data sets were collected for each pinhole arrangement (shown by the filter boxes) with no statistical difference between the configurations. Filter penetration curves are provided in Fig. 4(D) revealing at least a qualitative difference in the removal efficiency for particles near the MPPS (100 nm) as a function of hole position.

Representative results for the Seal Leak study are given in Fig. 4 (B). In this study a series of shims were placed between the upper right sealing surface of the filter and the filter housing. The plot in Fig. 4 (B) provides a comparison of the up and down stream normalized particle size distributions for one, two, three, and four shims. It can be seen that the PSDs up and downstream are equivalent.

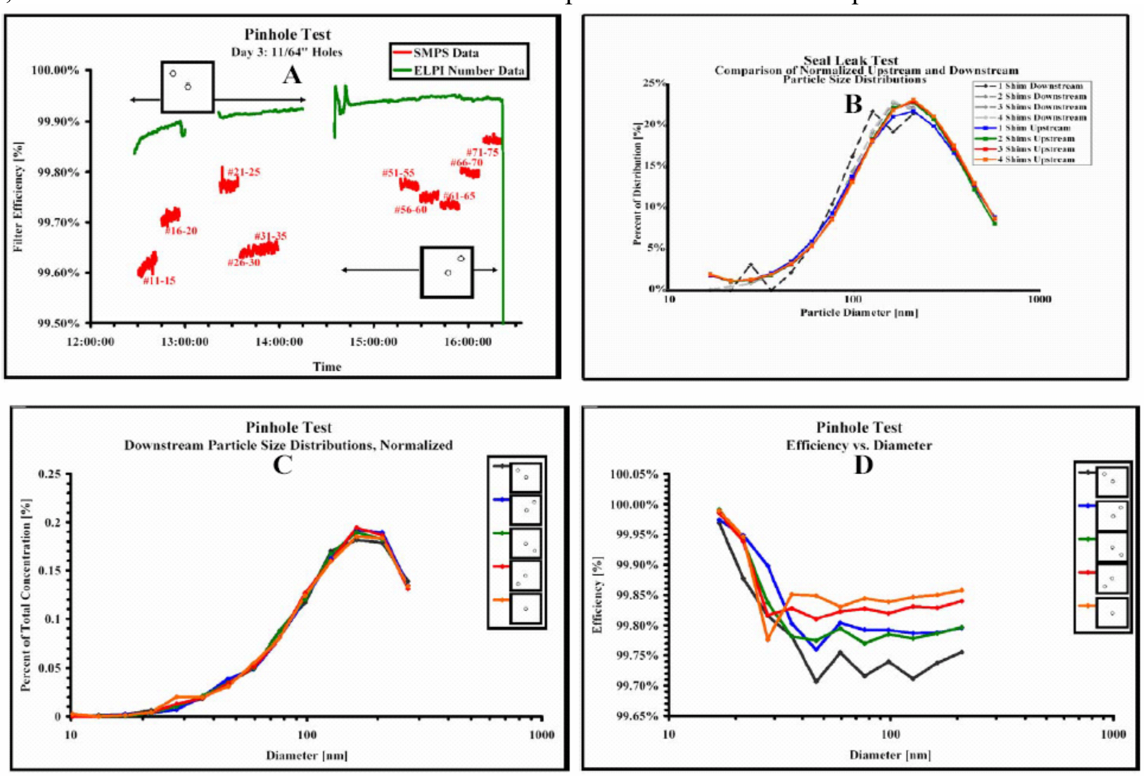

Fig. 4 Results of testing activities conducted during the Seal Leak and Pin Hole Failure Mode Testing Study

Source Term Study

A final series of tests were conducted to determine how changes in the composition of the challenge PM affects filter loading and performance. This study consisted of challenging HEPA filters to failure with KCl, soot, and an iron (III) salt. Test stand conditions used for the testing when soot was the challenge are included in Table IV.

Table IV Average Test Conditions of the DIAL HEPA Filter Test Stand during testing activities for the Source Term Study.

Volumetric Flowrate (cfm)	92.5
Media velocity (ft/sec)	4 - 6
Temperature (^oF)	86.3
RH	35%
Static Pressure on Test Stand (in WC)	3.2 in. wc subatmospheric
Particle loading rate: mg/m^3 $\#/cm^3$	 1000 $5x10^7$
PM	Acetylene soot
PM: CMD (nm) GSD	 90 2.48

A comparison of the results of this study is provided in Fig. 5. 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 calculated values for KCl are relatively easily accomplished, however the density of soot is not as easily established. The bulk density of soot is used for this calculation so it is possible that the projected value may be off by 20%. However, inspection of Fig. 5 reveals that soot loads a filter almost twice 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.

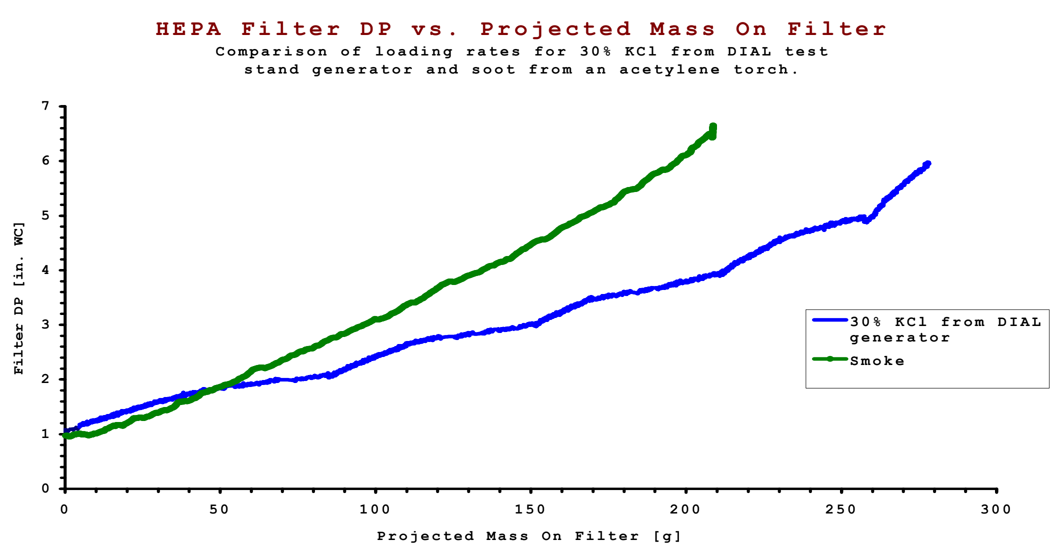

Fig. 5 Results of testing activities conducted during the Source Term Testing Study

DISCUSSION

There are three major findings to highlight from this effort. The first of these is that a properly functioning filter rapidly increases its filtering efficiency to approximately 100%. This results in very low number densities downstream of the filter. Although not statistically meaningful, measurements made in this study indicate that those particles downstream of the filter are almost exclusively at or near the most penetrating particle size of 130 nm. These low number densities make gravimetric measurement of emissions virtually impossible.

A second finding is that differential temperature across the filter housing is a very sensitive method to detect water in the air stream or wetting of the HEPA filter. As has been mentioned previously, the wetting of filters is a serious concern of permit writers and public interest groups because it has been associated with premature and possibly undetected failure of filters. Differential temperature measurements are a very easy and inexpensive method to protect filters from damage by moisture. It was also noted in this study that the filtering efficiency of a HEPA filter can fall below the definitional value of 99.97% when wet, but regain a filtering efficiency greater than 99.97% once it has dried. Only one of the three filters tested actually had the filter media tear during this test (after the fourth wetting cycle). It is very unlikely that a filter in service would ever be subjected to the conditions of this test. The filters were subjected to standing water in the filter housing on the upstream side that caused the bottom inch and a half of the filter to be submerged in water. Additionally, the dP across the filter became as high as 10 inches of water column

Finally, it appears from the data collected in this study that the chemical nature of the challenge can have a direct impact on the lifetime of a filter as defined by the absolute mass of PM removed. Once filters had been challenged to the point where they reached the maximum of six inches of water column differential pressure, the units were carefully removed from the filter housing, dried, and weighed. The mass of the loaded filter was compared to the mass of the filter prior to testing to determine the mass of PM captured. This value was discovered to fluctuate significantly with the challenge conditions. Values ranged from two to eight times the mass of PM predicted by the Nuclear Air Cleaning Handbook.

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