Evaluation of Emissions from HEPA Filters as a Function of Challenge Conditions

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ABSTRACT

High efficiency particulate air filters (HEPA) are employed in a wide range of emission control applications, particularly when radioactive materials are involved. These units are capable of removing in excess of 99.97% of particulate matter 0.3 micrometers in diameter or larger; however, they do not have a high loading capacity. To prevent these "absolute" filters from blinding in a very short period of time, HEPA filters are normally used as the last element of an off-gas treatment system. Traditional HEPA filters use a fibrous glass filtering media that is sensitive to variety of environmental conditions, most notably humidity or water droplets.

The Department of Energy has an ongoing effort to close sites that are no longer essential and to process legacy wastes for active sites for long-term disposal/storage. HEPA filters play a significant role in eliminating PM emissions from these processes. Stakeholders have expressed concerns about the feasibility of monitoring PM emission rates downstream of HEPA filters, particularly in light of the Hazardous Waste Combustor (HWC) MACT.

A series of studies has been conducted to evaluate the particulate matter emission rates downstream of HEPA filters under of variety of conditions. These conditions include variation of challenge conditions: (1) PM particle size distribution, (2) PM composition, (3) relative humidity, and (4) temperature. Additionally, tests have been conducted under a variety of failure modes to determine the practical limits for measuring downstream PM emissions from filters with: (1) leaking seals, (2) pin holes, (3) moisture damaged media, and (4) excessive loading (differential pressure across the filter).

A variety of measurement techniques was employed in this series of studies. Instrumentation included: (1) Scanning Mobility Particle Sizing systems, (2) Electrical Low Pressure Impactors, (3) diffusion batteries, (4) condensation particle counters, (5) electrometers, and EPA Reference Method 5i. A comparison of the results from these measurement techniques will also be presented.

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 if formally referred to as the "DIAL HEPA Filter Monitoring Project" and 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.[1,3] 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 effort.

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 Figure 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.

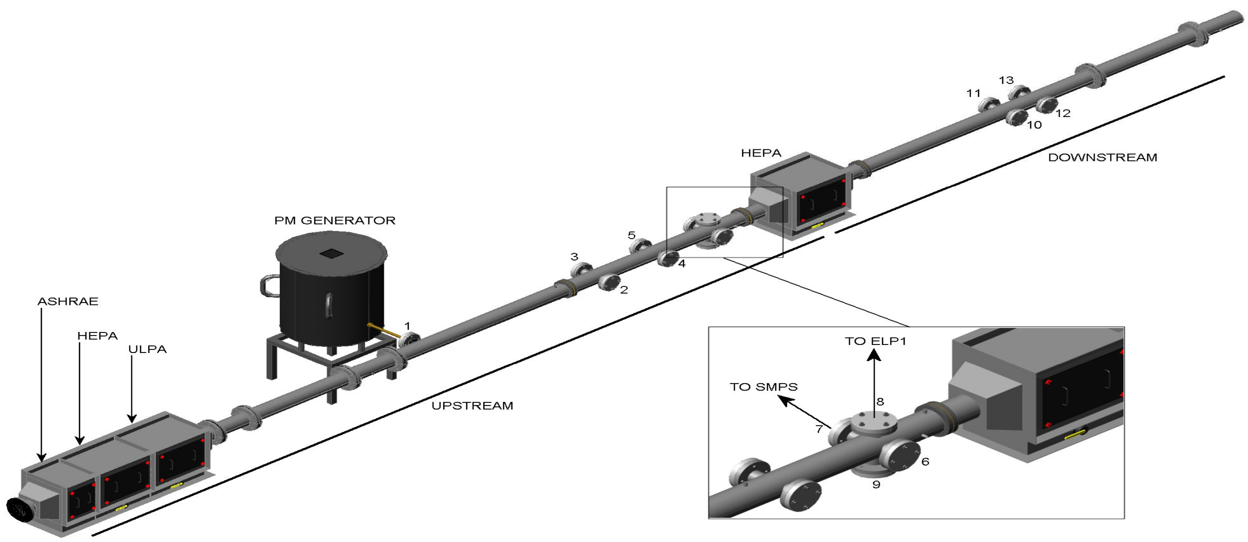

Figure 1. DIAL HEPA filter test stand with aerosol generator.

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 have 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 Particles. 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.

A general indication of the stability of mass loading for filter testing is provided in Figure 2. These plots are represent fluctuations of the PM mass challenge concentrations as a function of time as measured by an ELPI immediately upstream of the filter housing. Two different pumps have been employed with the particle generator to produce the PM challenge. The plot on the left shows the time stability of PM mass generation as produced using a Harvard syringe pump to deliver the KCl solution to the atomizing nozzle. Continuous duty feeding of the salt solution is accomplished by reversing plunger direction for opposing syringes (i.e., one set of syringes pumps while the opposing set is filling). Periodic oscillations in the challenge rate for this configuration are produced when the syringe pump changes direction of feed. This occurs on an approximately 20 minute interval. Short duration increases in mass loading rates (spikes) are caused by cycling of air dryers that feed the atomization nozzle and drying chamber of the particle generator.

The plot on the right of Figure 2 is representative of PM mass loading rates achieved using a micro-drive gear pump. The larger spikes seen in this plot are a result of the nozzle becoming partially fouled with a corresponding change in the spray pattern.

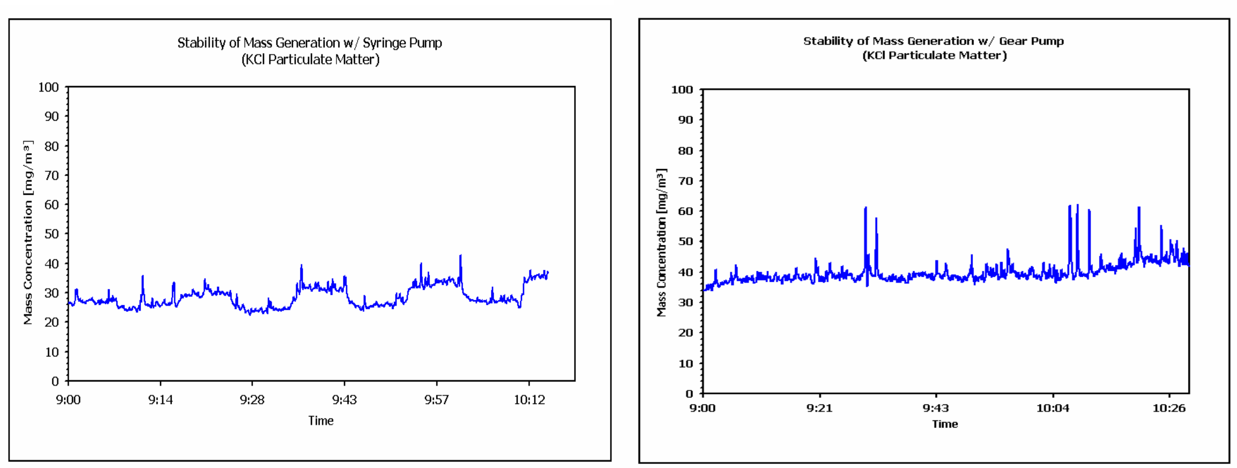

Figure 2. Plots of mass generation rate (mg/m^3) vs. time (hrs) demonstrating stability of challenge conditions. Plot on the left shows stability using a syringe pump to feed KCl solution to the atomizing nozzle. Plot on the right shows stability using a micro-drive gear pump.

The PM generation system has been developed to produce PM of various chemical matrices. Figure 3 shows the ability of the system to produce equivalent particle size distributions for potassium, iron (II), and iron (III) salts.

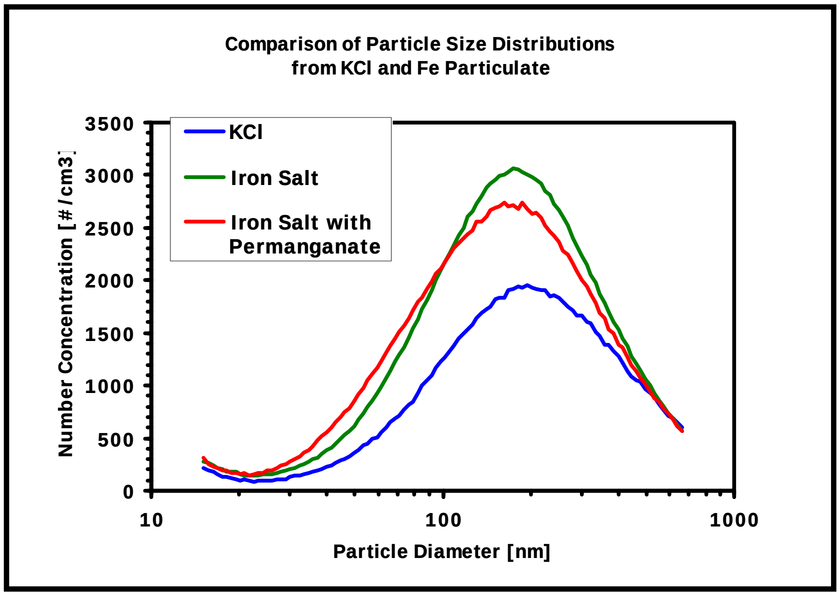

Figure 3. Plot of particle number concentration (#/cm^3) vs. particle diameter (aerodynamic diameter in nm).

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. With this in mind, test conditions and results are closely monitored to ensure that the filters achieve at least 99.97% filtering efficiency and have an initial pressure drop of no greater than a one inch water column.

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 l.

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. Downstream 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 (^oF)	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 4 provides a synopsis of the findings from this series of tests. All data are from the testing of a single filter. Figure 4(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 Figure 4(A) and (B) that the filter being tested has a differential pressure of approximately one inch of water column and a filtering efficiency of greater than 99.97%. Figure 4(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 depicted in Figure 4(D) are characteristic of all filters tested. The increase in filtering efficiency to near 100% was observed in all filters tested. Figure 4(D) shows the relatively rapid drop of particle concentration downstream to less than 0.5 particle/cc. This plot also contains a dP curve for the period of the test. From the combination of plots (A), (B) and (D) it can be seen that filter efficiency goes to virtually 100% by the time that the filter has had an increase of 0.2 or 0.3 inches wc dP.

The very low number densities of particles downstream of the filter are below normal detection limits for the diffusion battery, SMPS, and ELPI. It is not feasible to collect particle size distribution data with these units without extremely long sampling times. However, these long sampling times would rival the lifetime of the 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.

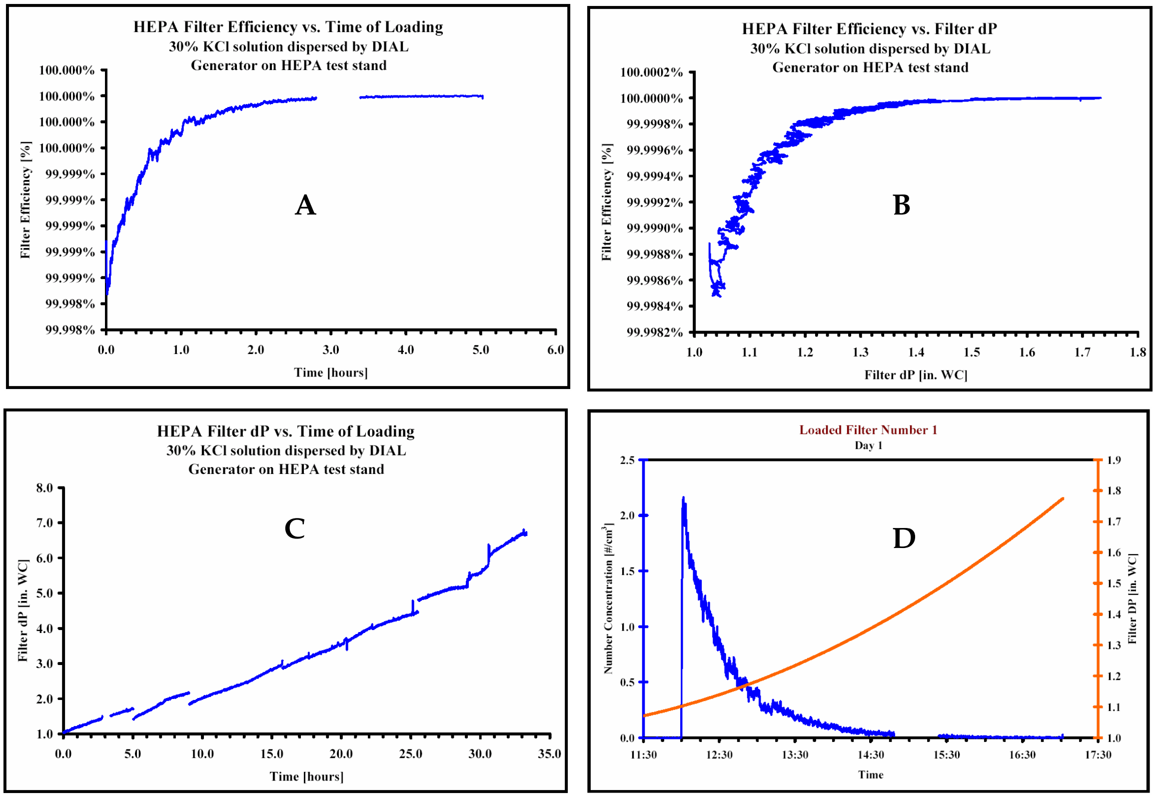

Figure 4. Results of testing activities conducted during the Baseline Filter Testing Study.

Moisture Failure Study

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 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 5 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 5(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 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 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.

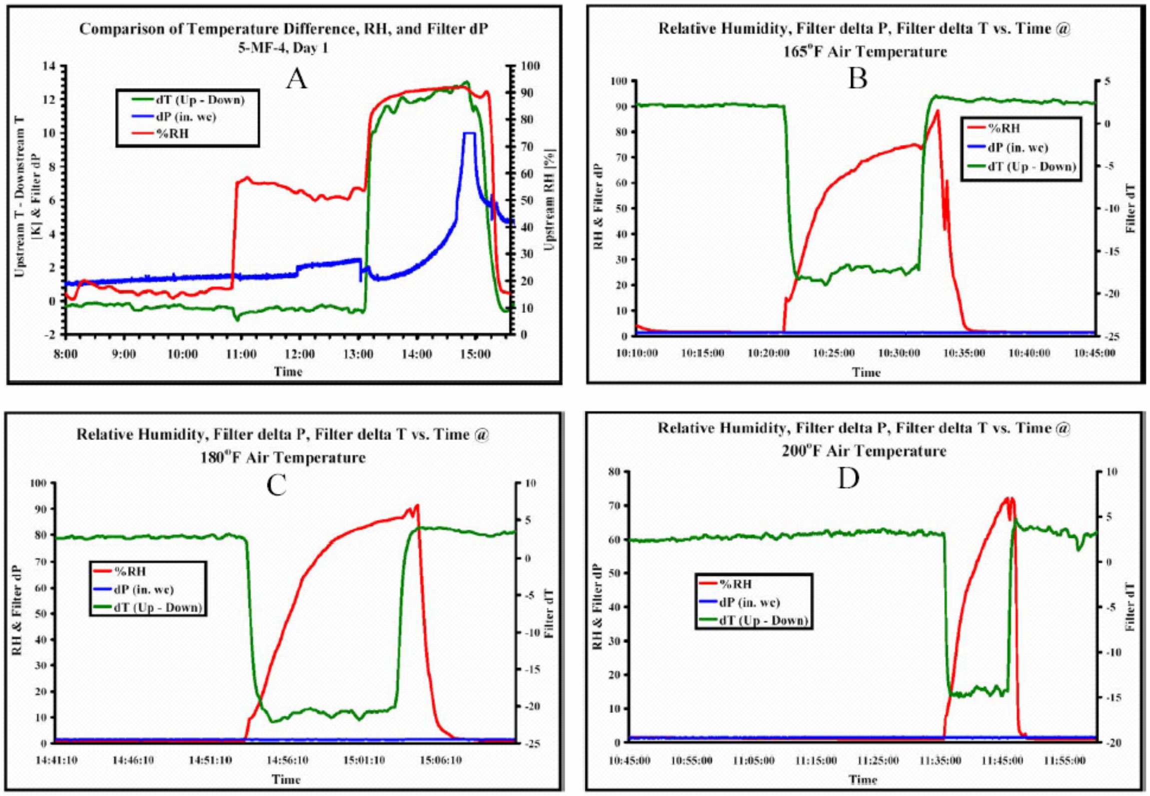

Figure 5. Results of testing activities conducted during the Moisture Failure Mode Testing Study.

Few HEPA filtration systems for mixed waste treatment 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 Figures 5(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. It appears from these data that as long as evaporative cooling is possible, dT across the filter housing is a sensitive and rapidly responding indicator of liquid water reaching the filter.

Figure 6 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.

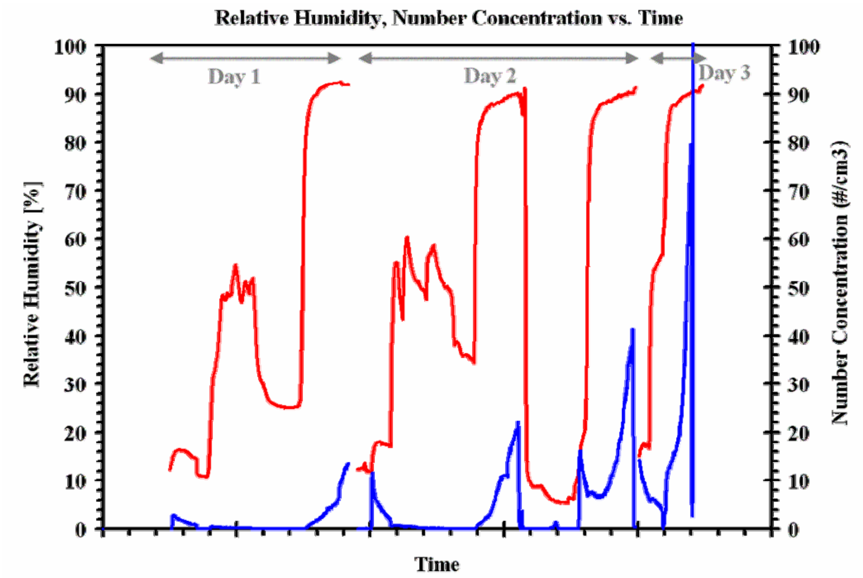

Figure 6. Results of three days of moisture failure testing of a HEPA filter.

Table III 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 6 and Table III 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.

Table III. 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 7 show the condition of a filter after it has completed the full sequence of testing. The photo on the left shows small tears in the filter media that occur in localized areas after repeated wetting. 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 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 medial during testing.

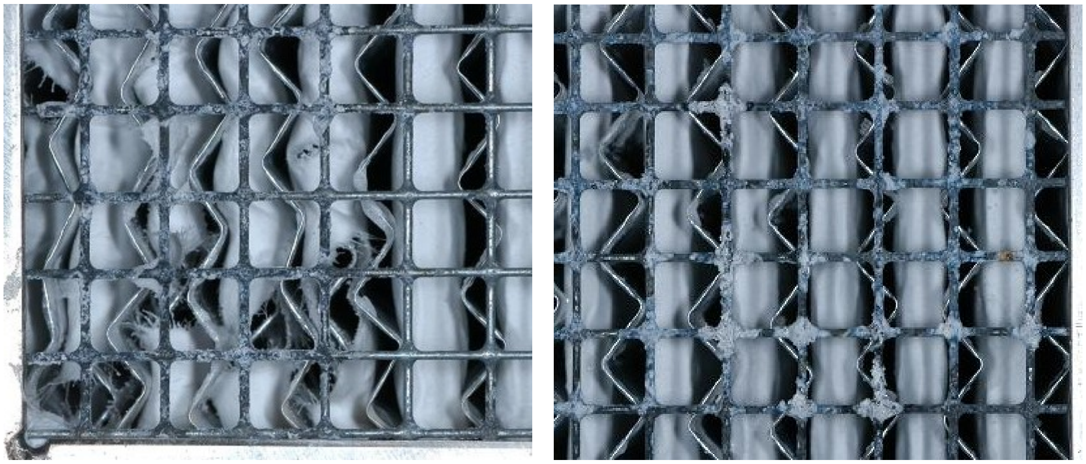

Figure 7. Photos of rear surface of HEPA Filter that has undergone moisture failure testing.

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 after installation and periodically while it in use to confirm proper function. A series of tests was developed to evaluate leak detection methods using a dry aerosol challenge. Two sets of conditions were studied, leaking seals and pinholes or small tears in the filter media. Challenge conditions were the same for both studies and a representative set of test conditions is included in Table IV.

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 IV. Average Test Conditions of the DIAL HEPA Filter Test Stand During Testing sctivities 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

A partially loaded HEPA filter was modified to simulate pinholes by inserting short pieces of brass tubing through the filter media. The photos in Figure 8 show how a filter has been modified for this test. The picture on the left is of the front of a pleat in the central portion of the HEPA filter where a portion of the protective wire screen has been removed (approximately one inch square) and the brass tubing has been installed. The photo on the right is of the back of the filter directly opposite the brass tubing (pinhole). A small amount of salt can be seen to have built up on the inside surface of the protective screen.

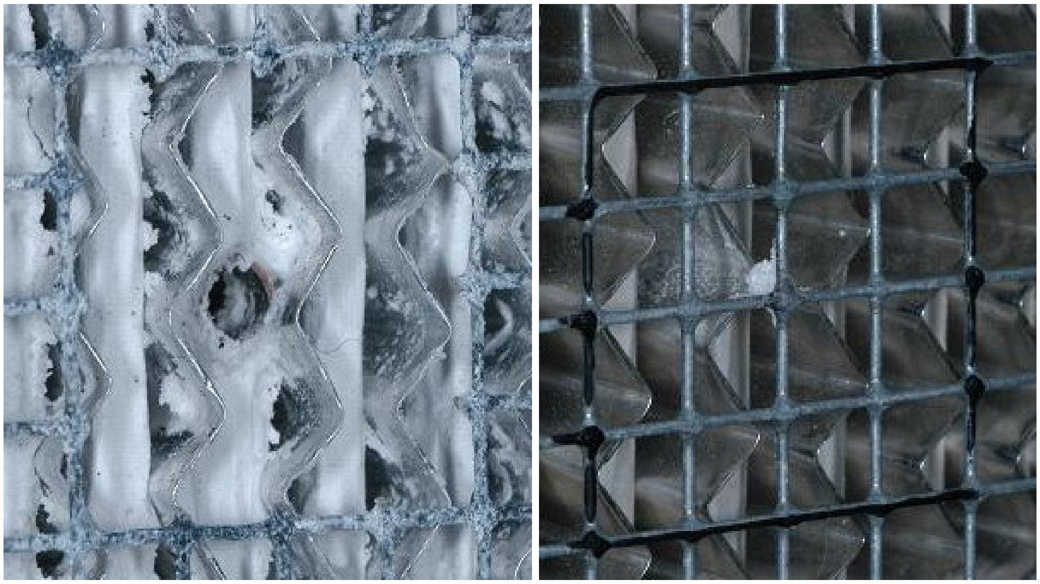

Figure 8. Photos of front and back of HEPA filter that has been modified for pinhole leak test.

Figure 9 provides representative results from a portion of this testing activity. The data displayed in this series of plots was collected while two 11/64-inch i.d. pieces of tubing were installed in the filter, one in the central area and one in the center of a quadrant. The box(es) containing two small circles show the orientation of the filter during the collection of data. Figure 9(C) provides a comparison of particle size distributions for downstream PM when the filter is in the different positions. Also included in this plot is a particle size distribution for data collected with a single $11/64^{th}$ hole in the filter. Only nominal difference in the particle size distributions is noted.

The plot found in Figure 9(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 Figure 9(D) revealing at least a qualitative difference in the removal efficiency for particles near the MPPS (130 nm) as a function of hole position.

Representative results for the Seal Leak study are given in Figure 9(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 Figure 9(B) provides a comparison of the up and downstream normalized particle size distributions for one, two, three, and four shims. It can be seen that the PSDs up and downstream are equivalent.

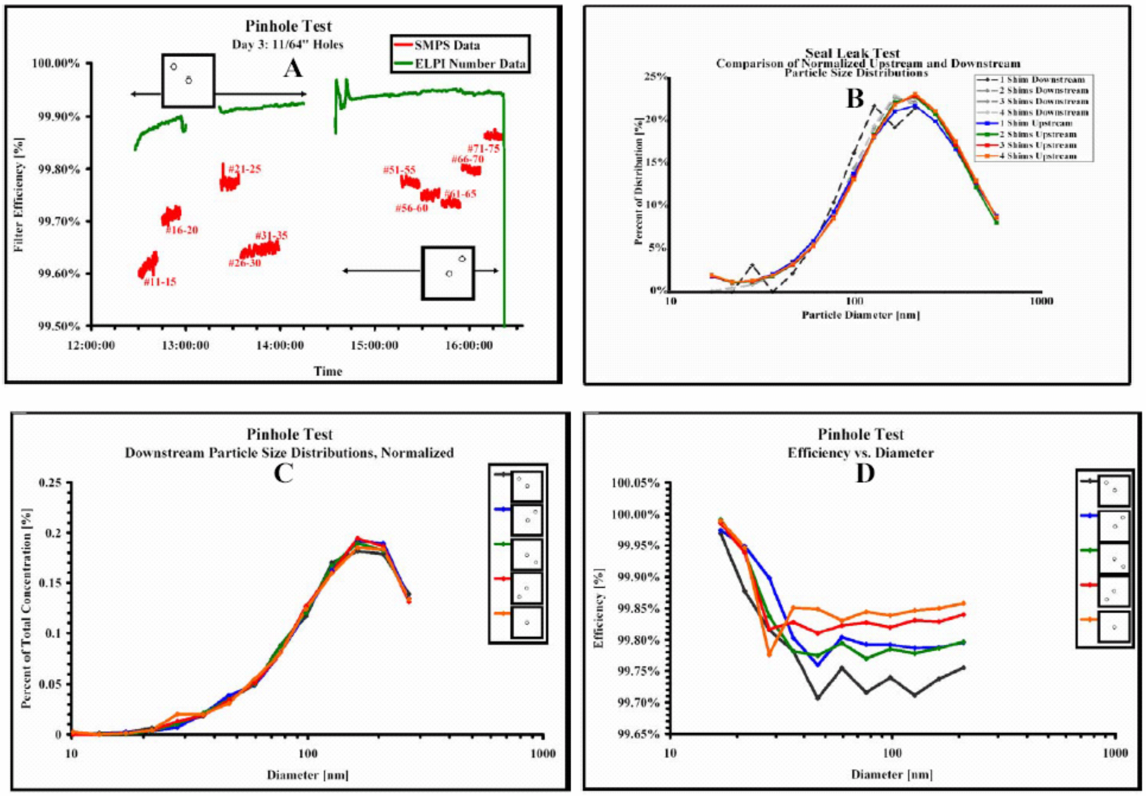

Figure 9. Results of testing activities conducted during the Seal Leak and Pin Hole Failure Mode Testing Study.

Figure 10 contains photos of the filter used for the seal leak test. These pictures were taken after testing with four shims inserted between the seal on the front of the HEPA filter and the sealing surface on the filter housing. Clear evidence of the leak can be seen on both the filter seal and the interior of the housing.

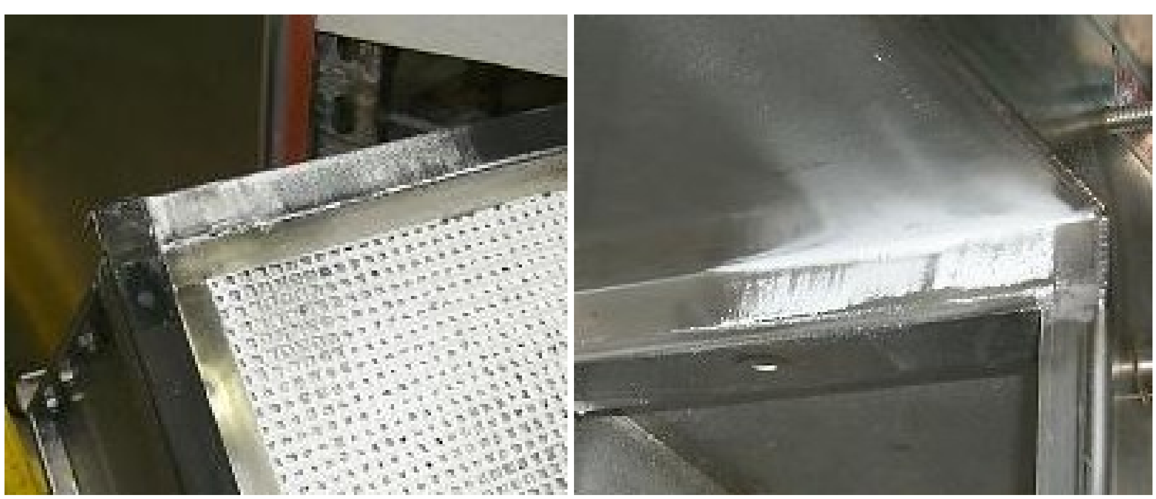

Figure 10. Photos of filter seal and filter housing sealing surface for seal leak test.

Source Term Study

A 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 V.

Table V. 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 (^{o}F)	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 Figure 11. This figure demonstrates the correlation of differential pressure across the filters versus the calculated mass of PM collected by the filter at a given point in the testing process. The cumulative loading curves are provided for four filters, three that were challenged with KCl and one challenged with soot. Standard literature values of the bulk densities for both KCl and soot were used with the ELPI software to calculate the mass loading rate (PM concentration in mg/m^3). As will be seen later, these values can only be depended on to provide approximate values.

Figure 12 displays the difference between total mass loadings that are projected from instrumental measurements (ELPI) and the measure mass gained by the filter during testing. Each filter was dried at 120^{0}C for two hours and weighed prior to testing. At the conclusion of testing, the filter was carefully removed from the filter housing and dried and reweighed. It is clear from Figure 12 that the ELPI underestimates the challenge rate for KCl and overestimates for soot.

All loading rate measurements for these tests were made using Dekati diluters to reduce the PM concentration to an acceptable range for the ELPI. There are variety of factors that can cause the measurement errors that are reflected by the data of Figure 12 that include (1) impactor loading, (2) humidity in the air stream, (3) particle density, and (4) diluter performance.

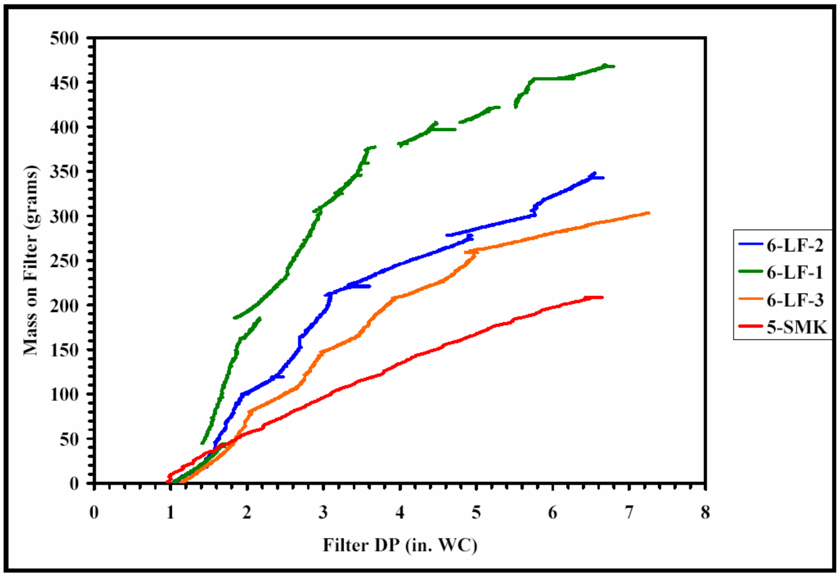

Figure 11. Results of testing activities conducted during the Source Term Testing Study.

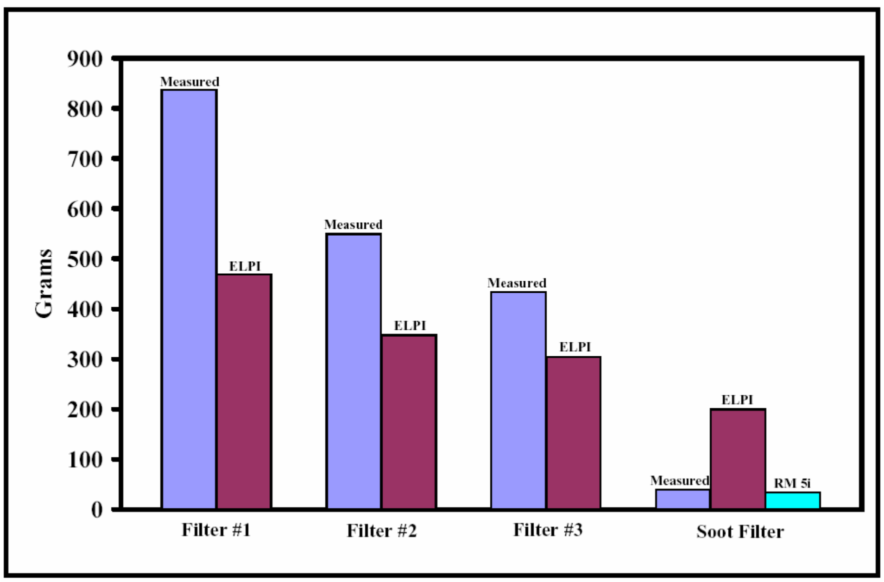

Figure 12. Comparison of projected (calculated) vs. measured mass loadings
of filters tested in the Source Term Study.

Figure 13 contains photos of the front surface of filters that have been loaded to a dP of six inches wc by different challenge PM. The left photo is of a filter that has been loaded with soot. This is in stark contrast to the photo on the right which shows a filter that has been challenged with KCl.

Figure 13. Photos of the front surfaces of HEPA filter that has been with soot (left) and KCl (right). Each filter has been loaded to six inches wc differential pressure.

The Nuclear Air Cleaning Handbook (NACH) indicates that a HEPA filter has been fully loaded when the differential pressure (dP) across the filter has reached 6 inches of water column (wc). The NACH further indicates that the mass of PM necessary to fully load a 2'x2'x2' HEPA filter will be on the order of 500 grams. DIAL has employed 1'x1'x1' HEPA filters in all of the testing activities we have conducted and one would expect one of these units to collect 125 grams by the time that it is fully loaded. Data in Figures 11 and 12 show that the actual loading can vary from one-third to six times this predicted value. The difference in loading capacity is clearly seen by comparing values from KCl and soot testing activities. Figure 11 shows that the mass loading capacity of soot is clearly less than that of KCl. Soot concentrations and particle size distributions are very difficult to measure in the ranges used for this testing, however it is believed that the lower loading rate for soot is more a function of the particle size distribution than chemical composition.

Another trend can be observed in Figure 11. Filter mass loadings in the KCl tests dropped in successive runs, run 1 (6-LF-1) was greater than run 2 (6-LF-2) was greater than run 3 (6-LF-3). As described earlier, KCl challenges were made at a rate of approximately 30 mg/m^3 and with a particle size distribution achieved by passing the aerosol through a cyclone with a cut point of 3 microns. The cyclone was removed when measurement data were not being collected in order to decrease the length of time necessary to reach the next dP increment during this initial series of mass loading tests. A review of the data from these test runs revealed that the length of time the cyclone was taken out of the system decreased from run 1 to run 2 to run 3.

Another series of mass loading experiments was scheduled in order to verify that the downward trend in mass loading of the filters at 6 inches wc was a function of particle size distribution. Two additional filters were loaded. The first was loaded entirely using the cyclone and required only 206 grams of particulate to reach the 6" dP maximum. The second was loaded entirely without the cyclone and required 857 grams to reach 6" dP.

Table VI contains particle size distribution data for test runs with and with the cyclone. Figure 14 illustrates the difference in particle size distribution of the challenge agent with and without the cyclone. Figure 15 shows the loading curve for both of the filters as dP increased from 1" to 6" water column.

Table VI. Particle Size Distribution Data of KCl Used to Load HEPA Filters.

	With Cyclone	Without Cyclone
Geometric Mean	1.449	2.625
Mean	2.082	3.311
Median	1.384	2.199
Geometric Standard Deviation	2.42	2.15

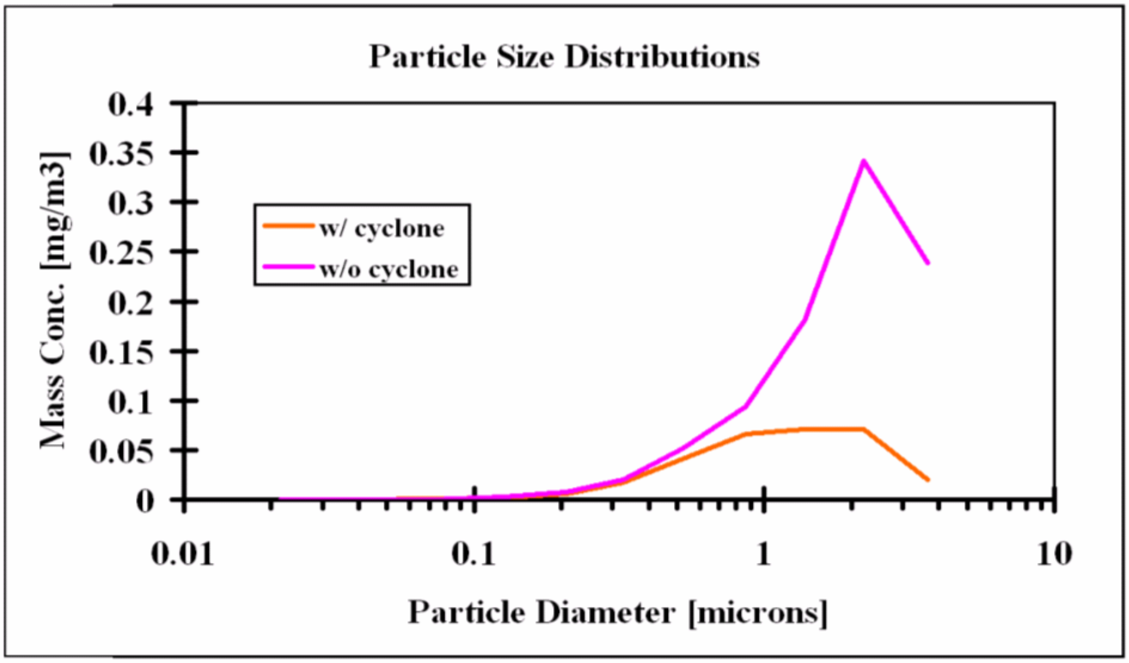

Figure 14. Particle size distribution of KCl with and without using a cyclone.

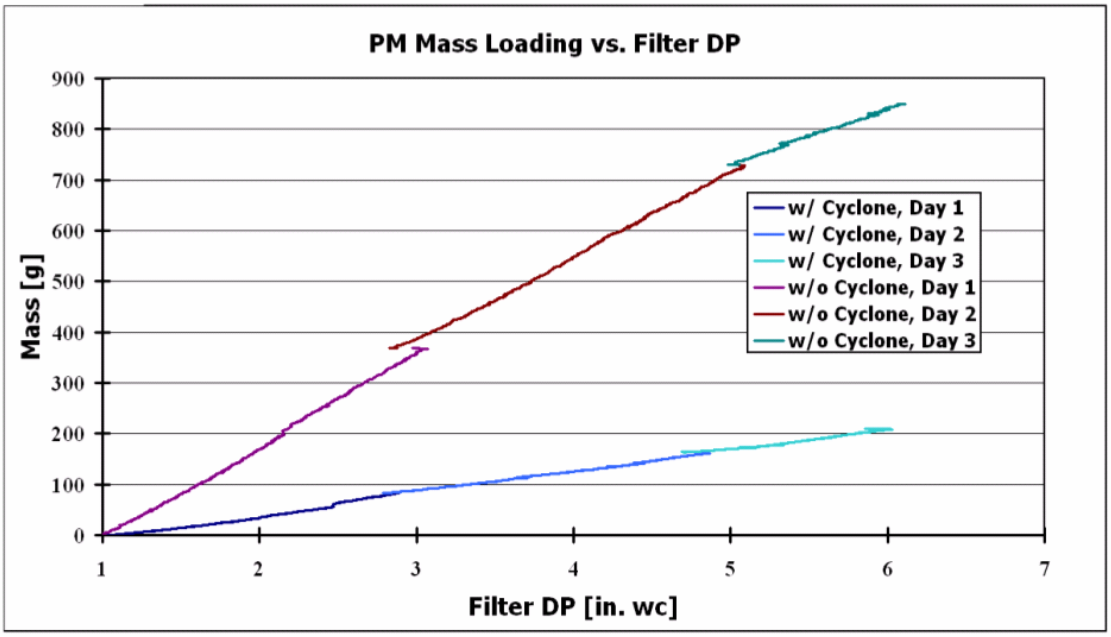

Figure 15. PM mass loading vs. filter dP with and without cyclone.

DISCUSSION

There are four 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 an 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 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, ranging from one-third to six times the mass of PM predicted by the Nuclear Air Cleaning Handbook. Two additional filters were challenged with KCl, one with and without the use of a cyclone. Data from these tests indicate that maximum filter loading varies greatly as a function of particle size of the PM challenge.

The reduced particle size distribution produced when a 3-micron cut point cyclone is employed required nearly ¼ the PM mass to reach maximum differential pressure as that required by the filter when challenged with the larger particle size distribution produced without the use of a cyclone. This finding is significant in that it can partially explain why some filters tend to last much longer than would be predicted by the NACH.

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