EVALUATION OF REGENERABLE FILTER MEDIA

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ABSTRACT

High efficiency particulate air (HEPA) filters employing fibrous glass filtering media are used extensively throughout the DOE complex and are a critical element in treating off gases from waste treatment processes. These filters are capable of lowering particulate matter (PM) emission rates to levels much lower than regulatory thresholds, however, they have definite limits with regard to mass loading capacity and ability to withstand certain upset conditions. The most commonly identified threats to HEPA filter performance are moisture and rapid blinding of filters by smoke. Filtering media of sintered metal or ceramic has been suggested as an alternative for fibrous glass, yet unit cost and operational parameters such as differential pressure across the filters have reduced their deployment as alternatives to HEPA filters. There does seem to be great potential for using these types of filters, however, as protective pre-filters for nuclear grade HEPAs. Regenerable pre-filters do not have to achieve HEPA performance levels and so lower pressure drop units can be developed. Additionally, these filter media have much greater strength and can withstand the rapid blinding of a process upset with out failing structurally. Finally, these filters will not be adversely affected by moisture and can serve to protect the conventional HEPA from becoming wet.

A series of tests have been conducted using sintered metal fiber filter media (Porvair) and ceramic media (CeraMem) to evaluate their performance after repeated loading and washing cycles. Filter media has been loaded and washed using a variety of challenge conditions intended to simulate conditions encountered in tanks and waste treatment applications. Challenge aerosols have been produced using formulations of a variety of surrogates for DOE waste streams from Savannah River and Idaho facilities. Filter media have been challenged with both wet and dry aerosols followed by cleaning cycles using a variety of wash solutions. Media were evaluated for pressure drop and filtering efficiency changes from one cleaning cycle to the next. Microscopic examination of filter media has also been conducted to determine the extent to which residues remain after cleaning. Results reported will include durability of filter media to repeated washing by water and various acids as measured by retention of filtering efficiency, effectiveness of wash solvents as measured by pressure drop across the cleaned media and microscopic analysis.

INTRODUCTION

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. In addition to this low loading capacity, there are other operating parameters that restrict use of HEPA filters. Traditional HEPA filters use a fibrous glass filtering media that is sensitive to a variety of environmental conditions, most notably humidity or water droplets. It has been previously reported that wetting of the media can result in reduction of filtering efficiency below the definitional 99.97% and repeated wetting can result in physical tearing of the media. [1] There are other applications of HEPA filters that involve high concentrations of acid gases and concern exists with the durability of conventional AG-1 filters under these conditions.

Alternatives to the fibrous glass filter media (both sintered metal and ceramic) have been proposed and evaluated over the past decade. [2,3] These alternative media have highly desirable attributes such as: (1) increased tensile strength and resistance to tearing, (2) ability to withstand weakening effects of moisture, (3) ability to withstand higher temperatures, (4) ability to withstand high concentrations of acid gases, and (5) ability to be repeatedly cleaned with back pulses of either air or liquid. Because of the cleanable nature of these filters, they are often referred to as regenerable filters.

The advantages of regenerable filters offer significant promise for reducing costs and human exposure in a variety of air filtration applications. The ability to clean filters in place under conditions where rapid loading is anticipated or where wet aerosols will be encountered will reduce the volume of wastes generated and reduces both disposal costs and the potential for human exposure. With these potential savings, it should be clear to the reader that there must be disadvantages that hinder wide use of these novel filters.

Regenerable filters are sufficiently more expensive than conventional HEPA filters in that they must last four to five times longer to be cost effective. Additionally, there is currently no AG-1 standard for these alternative filters, although the ASME Committee on Nuclear Air Cleaning Technology is currently reconsidering metal fiber filters. It should also be pointed out that older types of sintered metal filters had a much larger pressure drop (dP) across the filter, at times greater than 50 inches w.c. In general, the higher the filtering efficiency, the higher the pressure drop across the media. Newer media, made from sintered metal fiber as opposed to sintered metal powder, have dPs much closer to that of glass fiber media. Progress has also been made with ceramic filter membranes to achieve dPs in the range of one to three inches w.c. Pressure drops of around three inches w.c. can routinely be achieved for these types of filters, particularly if a filtering efficiency of approximately 99.9% is acceptable.

The lack of an AG-1 standard for regenerable filters coupled with general concerns about HEPA filters voiced by stakeholders has resulted in cleanable filters being considered as prefilters in applications too aggressive for conventional units. This allows use of cleanable filters that can withstand higher loading rates, high moisture content, and high temperatures to protect the AG-1 HEPA filters and reduce the rate at which they must be changed out. However, it is necessary to confirm the ability of such filter media to be repeatedly cleaned and retain its function.

The work described in this paper will evaluate the function of ceramic and sintered metal regenerable media from two sources, CeraMem and Porvair, respectively. The performances of these filter media have been evaluated by challenging with both wet and dry aerosols. The challenge aerosol employed is largely water insoluble and simulates sludge high in iron (III) encountered in DOE tank waste. Loading rates, pressure drop curves, and filter efficiency (FE) curves are reported for these tests. Loaded filters have been cleaned and loaded three times to evaluate the extent to which baseline conditions (dP and FE) are reestablished. After repeated loading and washing, the filter media have been inspected by scanning electron microscopy (SEM) and compared to new media to determine the extent to which they are cleaned and evaluated for degradation of the media by the cleaning process.

Test Stand Design

The test objectives of this study necessitated development of two test stands. The first is a small-scale unit used to challenge small filters by withdrawing challenge aerosol from the larger scale test stand. The second test stand is typically used for filter testing activities and is referred to as the DIAL HEPA Filter Test Stand. For these tests, it was used to produce the aerosol to challenge the regenerable filters undergoing testing.

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 operating parameters 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 count median diameter (CMD) of approximately 130 nm and geometric standard deviation (GSD) of approximately 2.0

7) Particle injection without either introducing swirl into the test stand or excessively increasing relative humidity (RH).

Conditioning of Upstream Air. Inlet air passes through a 85% ASHRAE filter, a nuclear grade HEPA filter, and finally an ultra low particulate air (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.

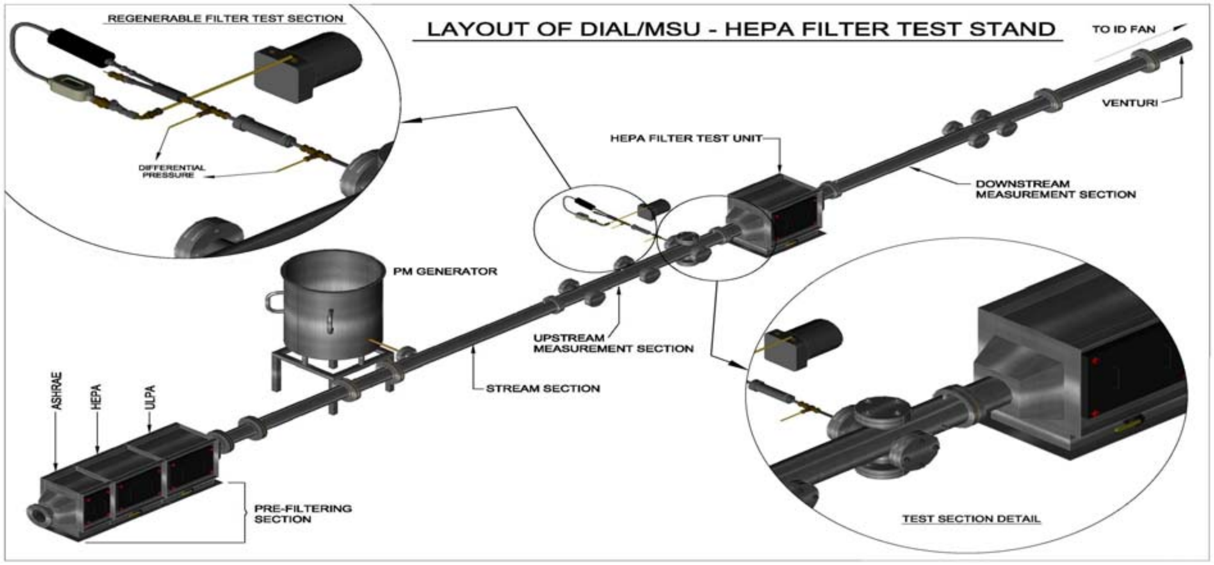

Fig. 1. DIAL HEPA Filter Test Stand with Aerosol Generator.

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 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
  - CMD ~130 nanometers
  - 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^oF 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 Pumps. 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. 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.

Three pump configurations are available for supplying test liquid to the nozzle. The first is 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 second pump configuration is a gear pump composed of an Ismatec MCP-Z controller and a Micro-Pump GA-V21.19VSB pump head with Kevlar gears. At a controller setting of 60 rpm, this pump configuration delivers approximately 10 ml/min using $^{1}/_{16}$” ID Tygon tubing and approximately 100 ml/min using $^{1}/_{8}$” Tygon tubing.

The third available pump configuration is a Cole-Palmer Model 7553-70 peristaltic pump with a Masterflex L/S Easy Load II pump head capable of six – 600 rpm. At a controller setting of two and using Masterflex L/S 13 Norprene tubing, this pump configuration delivers approximately 10 ml/min of liquid to the nozzle.

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/m^3 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. These same parameters have proven to be acceptable for generating other aerosols as well. The CMD will vary dependent upon on the aerosol generated.

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 a continuous operation pump.

Solutions Used to Produce Test Aerosols

Previous work done by this laboratory has included challenging conventional AG-1 nuclear grade HEPA filters with aerosols comprised of potassium chloride or iron (II) and iron (III) salts. A preliminary series of tests were conducted with the regenerable filter media using both of these challenges for comparison purposes. The potassium chloride using potassium chloride (30 wt% solution) was prepared by dissolving 300 grams of potassium chloride in 1000 grams of distilled/deionized water. The iron as challenge agent utilized a 30-wt% iron (II) sulfate solution. This solution was prepared by dissolving 150 grams of iron (II) sulfate hepta-hydrate in 500 grams of 120^{0}F distilled/deionized water with stirring. To this solution, 30 ml of saturated potassium permanganate was added. The solution temperature was maintained at 120^0F with stirring until uniform light brown slurry was produced. Results for this series of tests are not reported in this paper, however, the authors will be happy to provide the data on request.

The primary challenge aerosol for testing reported in this paper was generated from a surrogate material developed for testing of a Radioactive Isolation Consortium (RIC) melter. This sludge, formulated for RIC by NOAH Technologies of San Antonio, TX, is iron (III) rich. Other major constituents include aluminum hydroxide, zirconium basic carbonate, strontium hydroxide, zirconium hydroxide, and oxalic acid. Because of its iron (III) content and availability, it was found to be an excellent source from which to produce an insoluble iron aerosol. The exact composition of the RIC surrogate is shown in Table I. Because of the insolubility of its components, the slurry required constant stirring while being pumped into the atomization nozzle of the DIAL generator.

Table I. Composition of RIC Surrogate

Analyte	Concentration (wt%)
Silver	0.304
Aluminum	8.36
Barium	0.085
Cadmium	0.024
Chromium	0.170
Iron	12.0
Lead	0.284
Strontium	9.21
Zirconium	0.109

% Moisture in sample = 85.4%

Description of Filter Media Tested

A series of tests were completed on two different regenerable media and testing has begun on a third and fourth type. The first are a porous ceramic support coated with a filtration membrane manufactured by CeraMem. The tested filters were 1-inch in length and consisted of a 4 x 4 matrix of parallel passageways extending the length of the filter each with a 4-mm square entrance. Every other passage is plugged on the inlet side to a depth of a 0.5-cm to prevent flow entrance; the remaining passages are plugged on the outlet side to prevent the flow from exiting. Consequently, the aerosol (gaseous fluid and particulate) must flow through the filtration membrane and ceramic support to exit the filter. Custom stainless steel filter holders were fabricated in-house for the testing of these filter coupons.

The second type of media included in this series of tests is a sintered metal fiber fabric marketed by Porvair. The Porvair media was die cut into 47-mm circles (the standard filter size used in RM5i sampling) and held in place by in-house fabricated stainless steel filter holders.

Testing is underway on sintered metal fiber and sintered metal powder media marketed by Mott Corporation. Two grades of the Mott sintered metal powder media are undergoing testing. As with the Porvair sintered metal fiber media, test samples were die cut to 47-mm circles and are held in place using the same filter holders as used with the Porvair.

PM Measurement Instrumentation

For these series of tests, four PM measurement instruments were employed. Upstream PSD and mass loading rate measurements were performed utilizing an electrical low-pressure impactor (ELPI) Model 3935 manufactured by Dekati Ltd of Finland. Sampling at a flow rate of 30 L/m, this instrument offers a broad measurement range of particle sizes, from 0.03 to 10 µm with 12 channels corresponding to the 12 stages of its inertial impactor. This size range can be extended down to 0.008 µm with the use of an electrical filter stage available from Dekati. The ELPI operates in a concentration range of 80 to $1\text{x}10^7$ particles/cm^3. The instrument is made up of essentially three components; a corona charger, low-pressure cascade impactor, and a multi-channel electrometer.

Upstream PSD and mass loading rate measurements were also performed with an aerodynamic particle sizer (APS) Model 3321 manufactured by TSI, Inc of St. Paul, MN. Sampling at one L/m, the APS provides real-time aerodynamic measurements in the range from 0.5 to 20 microns. It also measures light-scattering intensity in the equivalent optical size range of 0.37 to 20 microns. The APS particle concentration range is 0.001 to 10,000 particles/cm^3.

Downstream PSD measurements were performed utilizing a scanning mobility particle sizer (SMPS) Model 3936L22 also manufactured by TSI, Inc. This systems offer a particle sizing range from 0.01 to 1.0 µm within a concentration range from two to 10^8 particles/cm^3. The measurement cycle time for the SMPS is selectable from 60 to 600 sec with a resolution of up to 162 channels and scan times from 10 to 300 sec. The system operates at a sample flow rate of 0.3 L/m.

Downstream particle concentration measurements were performed utilizing a TSI condensation particle counter (CPC) Model 3010 with a sample flow rate of one L/m. The 3010 CPC has lower size detection limit of 0.01 microns and an upper concentration limit of 10,000 particles/cm^3.

Regenerable Filter Loading Procedure

The test apparatus used for loading the regenerable filters is shown in the inset of Figure 1. With the SMPS, CPC and vacuum pump disconnected, the filter holder was swaged into place, and a small HEPA filter was connected to the filter holder inlet. The SMPS and CPC were connected to the flow splitter and an initial reading was made to determine if the setup was leak-tight (downstream CPC concentration less than one particle/cm^3). If the leak-check failed, the connections were tightened until a passing measurement was sustained.

The vacuum pump was connected and adjusted to obtain a total flow of three L/min, and a dP reading across the filter was recorded. Subsequently, the vacuum pump was adjusted to the desired test flow (15 L/min), and an initial dP reading was recorded. Aerosol generation was started, and the filter test apparatus was connected to the test stand once the APS measurement stabilized. The filter loading continued until the filter dP reached twice the initial value.

During the filter loading, four concentration measurements were recorded continuously. Upstream measurements drawn directly from the test stand were made with the APS and ELPI, and downstream measurements were made with the SMPS and CPC drawing from the filter.

The APS was employed with a 10:1 diluter (ATI-D10) manufactured by ATI. A correction to Stokes's law based on particle density is necessary due to the nozzle velocities used in the APS; consequently, the density was estimated to be 3.3 g/cm^3 for correction of the data. As demonstrated by Peters and Leith, the counting efficiency of the APS is approximately 50% for all particle sizes. [4] All reported measurements include the dilution factor, Stokes correction, and counting efficiency correction.

The ELPI (Electrostatic Low Pressure Impactor, manufactured by Dekati) sampled from the test stand with two Dekati ejector-type diluters with an overall dilution factor of 75:1. A density of 3.3 g/cm^3 was utilized in the ELPI data to calculate and determine Stokes diameters for each stage and aerosol mass concentration.

Filter Media Washing and Drying Procedure

The following procedure was utilized to wash and dry selected regenerable filters. A 10% nitric acid solution (pH = 0) was prepared by diluting 50 ml of concentrated nitric acid to 500 ml with distilled/deionized water. Selected filters were washed by pouring five ml of 10% nitric acid into the outlet end of the filter holder. A small vacuum was used to pull the liquid through the filter. This acid wash was followed by a second wash with five ml of distilled/deionized water. Again a small vacuum was used to pull the liquid through the filter. Filters were dried by blowing compressed air from an air dryer at 10 psi through a HEPA filter, then through approximately 25 feet of copper tubing coiled inside a 250^0F oven, and lastly through the inlet end of the filter holder. Filters were dried in this manner for two hours.

Filter Media Characteristics

The CeraMem filters are honeycomb type ceramic filters and the ones tested had four mm channels. The coupons employed for this study were effectively one-inch cubes with four filtering channels. Data provided in Table II give the surface area of the filtering membrane, media rated flow, and volumetric flow rate for testing the coupon. Additionally, an average dP for this type filter has been provided based on testing over a dozen similar units. Filter efficiency for the challenge conditions used in this work have ranged from mid 80% to mid 90% values.

The Porvair sintered metal fiber filter media used in this study was die cut into 47 mm circles. Equivalent data for this filter media is provided in Table II.

Table II. Rated Flows and Standard Pressure Drops for Clean Filters

Filter Type	Filter Area [cm^2]	Rated Media Velocity [ft/min]	Rated Flow [L/min]	Standard Pressure Drop [in. w.c.]
CeraMem	18.5	5	2.8	1.4-1.6
Porvair	22.9	4	2.1	2.1-2.8
Mott Grade 2	22.9	4	2.1	5.1-5.6
Mott Grade 0.5	22.9	4	2.1	22.2-22.5

Filter Loading Data

Table III provides data for the loading/washing cycles for one Porvair and two CeraMem filters. Data for a single Porvair filter are included due to the consistency of their behavior and two CeraMem data sets are provided due to the variability in the manner of preparation of the filter coupons. It should be pointed out that larger CeraMem filter coupons do not demonstrate the variability of the smaller units.

The manner in which filters are loaded and washed has been described in an earlier section of this paper. The column headed Loading represents the iteration number; 1 represents the initial loading sequence, 2 represents loading after the first wash cycle, and 3 represents the final loading. Two sets of dP data are provided for each loading iteration. Both types of filters have virtually the same surface area and are rated at the same media velocity, so the rated flow for either type is three L/min. The dP values for three L/min flows are provided for clean (Before) and loaded (After) filters. Filters were loaded to approximately twice the initial dP. For all filters besides MOTB-001, flow rates of 15 L/min were used during the loading process to reduce the amount of time required to achieve a significant increase in dP. Due to the high initial dP and limitations of the testing system, MOTB-001 was loaded at only 6 L/min. The initial and final dPs are provided for this higher flow rate also.

Table III. dP before and after Loading

Filter	Loading	ΔP @ 3 L/min [in. w.c.]		ΔP @ 15 L/min [in. w.c.]	
		Before	After	Before	After
PRVR-015	1	1.6	3.2	8.0	16.2
PRVR-015	2	1.5	3.1	7.9	16.0
PRVR-015	3	1.6	3.2	7.9	15.9
CERA-A15	1	2.1	4.8	12.3	24.0
CERA-A15	2	2.4	3.1	13.4	20.5
CERA-A15	3	2.5	5.0	13.6	26.0
CERA-A17	1	2.7	5.3	14.3	27.0
CERA-A17	2	2.8	5.1	14.6	27.0
CERA-A17	3	2.8	5.1	15.0	27.0
MOTB-001	1	5.6	9.0	10.7*	18.6*
MOTB-001	2	5.1	9.9	10.6*	20.0*
MOTB-001	3	5.3	10.9	9.3*	19.5*

Table IV provides an estimate of the amount of material collected on the filter for each loading cycle. Projected mass loadings are calculated from both ELPI and APS measurement data. A larger catch is projected for the ceramic filters due to the higher starting dP for the CeraMem filter coupons.

Table IV. Projected Mass on Filter

Filter	Loading	Projected Mass on Filter [mg]	
		ELPI*	APS**
PRVR-015	1	9.8	9.8
PRVR-015	2	12.0	6.9
PRVR-015	3	8.7	6.4
CERA-A15	1	22.6	17.1
CERA-A15	2	28.1	22.3
CERA-A15	3	11.7	10.0
CERA-A17	1	9.7	15.0
CERA-A17	2	34.8	29.6
CERA-A17	3	10.5	11.3
MOTB-001	1	13.1	N/A
MOTB-001	2	8.8	2.3
MOTB-001	3	4.3	2.0

* Using dilution factor of 75 and density of 3.30 g/cm^3.

** Using dilution factor of 10, counting efficiency of 50%, and density of 3.30 g/cm^3. Stokes correction (to account for density-dependent particle behavior) is used.

It has already been pointed out that the initial dP of a filter media is directly related to its filtering efficiency. In general, the greater the solidus (lower the porosity) and the thicker the filter media, the higher its initial dP and filtering efficiency. The Porvair media evaluated in this series of tests demonstrated an approximate 80% filtering efficiency for the test challenge. It should be pointed out that all filter efficiencies listed in this paper are based on particle count, not on mass removal. Data in Table V provide up (N_{up}) and downstream (N_0) particle concentrations from which filtering efficiency is computed. It should be further stated that these values listed are time averaged for the first few minutes of filter challenge. Filter efficiencies increase fairly rapidly as the filters load.

Table V. Initial Downstream Concentration (N_0), Upstream Concentration (N_{up}), and Filtering Efficiency

Filter	**Concentration [#cm^3]**		**Initial Filtering Efficiency [%]**
	N_0*	**N_{up}****	
PRVR-015	2775	125000	98%
PRVR-015	3450	159000	98%
PRVR-015	2150	127000	98%
CERA-A15	5030	89200	94%
CERA-A15	3370	230000	99%
CERA-A15	3375	188000	98%
CERA-A17	2230	219000	99%
CERA-A17	2450	217000	99%
CERA-A17	2850	249000	99%
MOTB-001	23542	106400	92%
MOTB-001	19346	72400	89%
MOTB-001	18539	71400	90%

* Downstream concentration immediately after filter exposed to aerosol measured by 3010 CPC.

** Upstream APS measurement with dilution factor of 10, counting efficiency of 50%, and density of 3.30 g/cm^3. Stokes correction (to account for density-dependent particle behavior) is used.

The filter efficiencies listed in this Table should be compared to the FE curves provided in Figures 2 and 3 to gain a more realistic perspective of the operating efficiencies of the filters.

Filter Loading Curves

Figures 2 and 3 provide loading data for representative filters of the two manufacturers. Figure 2 (A) and 2(B) show the rate of capture of particulate material challenge as a function of increase in dP for a Porvair filter. It will be noticed that for this unit, the filter loaded faster for the second and third iterations. Figure 2(C) provides an indication of the change in most penetrating particle size (MPPS) for the filter as it loads. The geometric mean particle size (ug) decreases consistently from approximately 110 nanometers to 85 nanometers as the filter loads from 7 to 14 inches dP. This reduction in MPPS is relative independent of the number of times the filters have been loaded and washed. Figure 2 (D) shows the filter efficiency curve for the three loading sequences. While there is some difference in the initial dP (clean) for the three iterations, the filter efficiency rapidly converges to the profile of a new filter.

Figure 3 (A) – (D) provide equivalent data for a representative Mott sintered metal powder filter. Likewise, Figure 3 (E) – (H) provide equivalent data for a representative CeraMem ceramic filter. Comparison of the loading vs. dP curves for the two filter types indicates the metal fiber filters are more difficult to clean to original dP after the first loading.

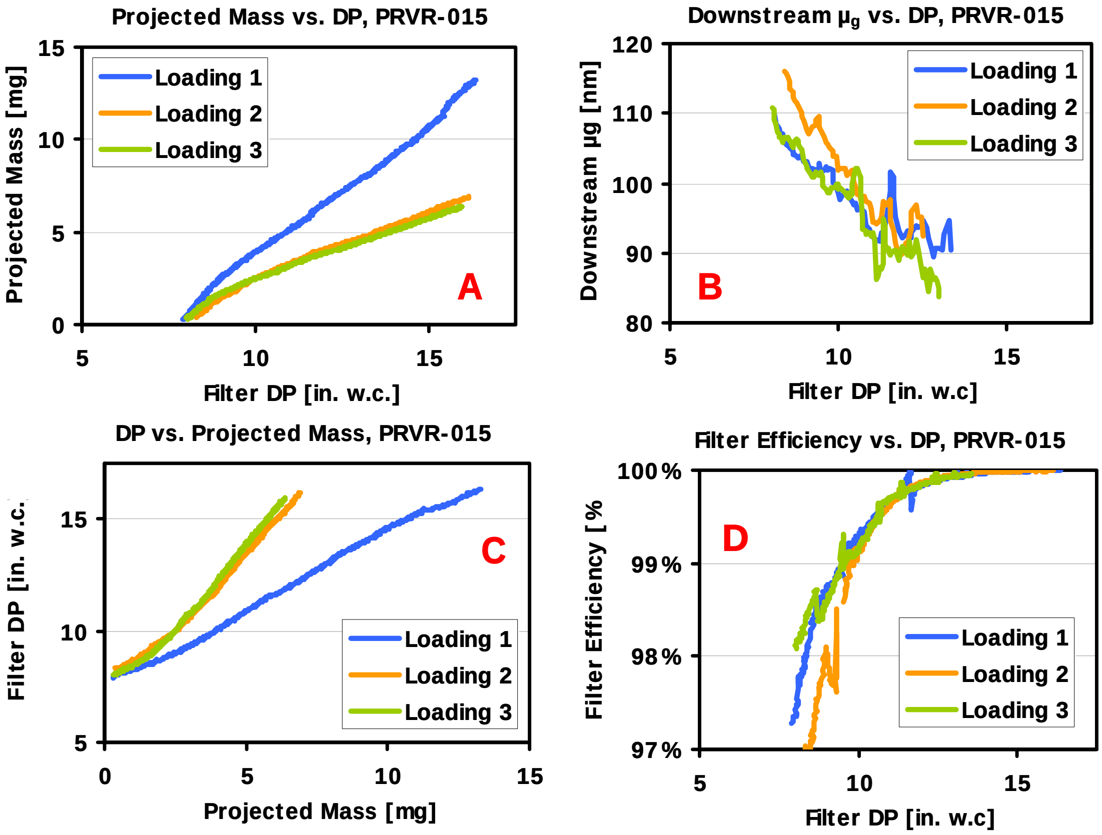

Fig. 2. Loading Curves for Provair Filter # PRVR-015.

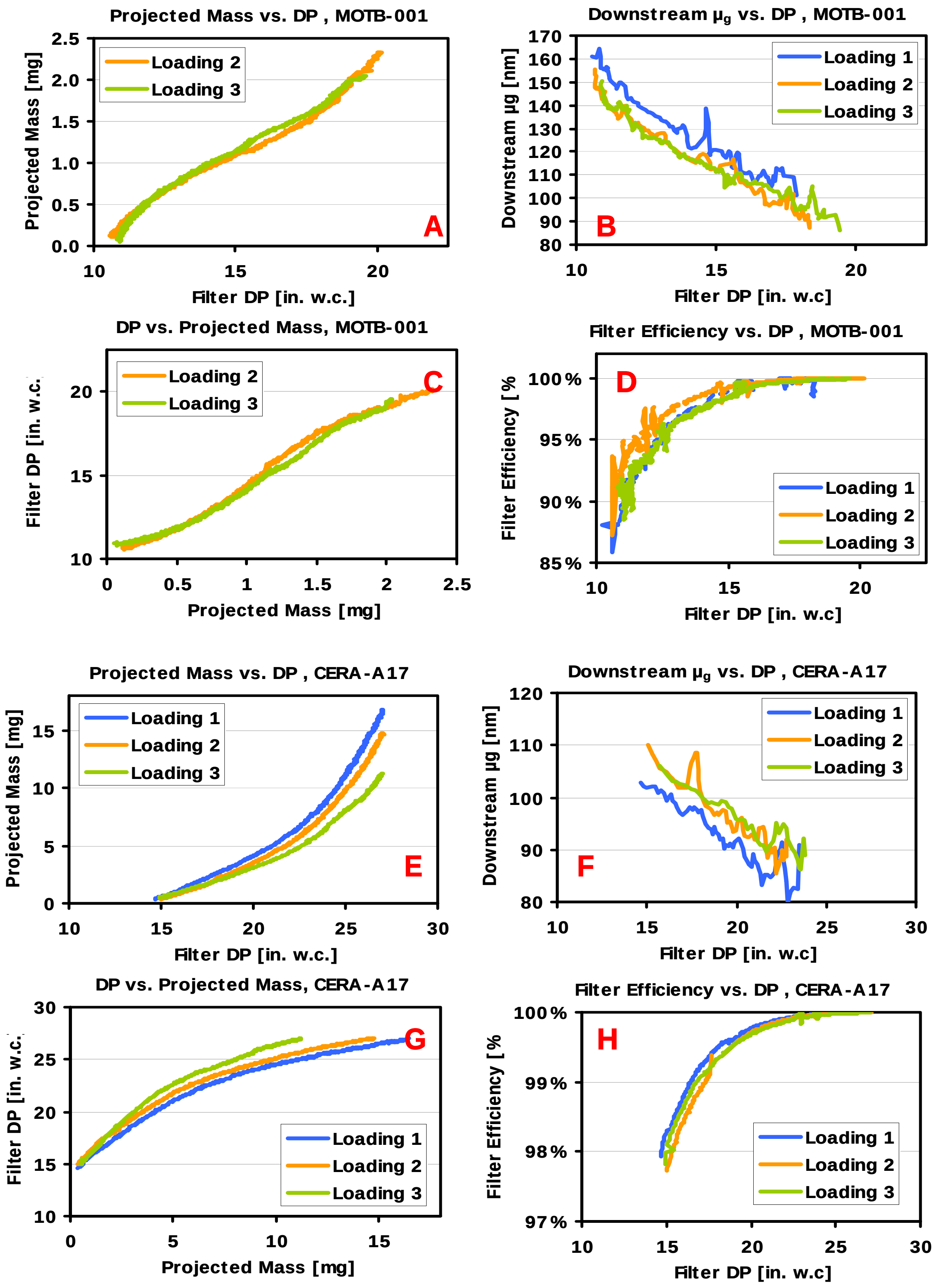

Fig. 3. Loading Curves for CeraMem Filter # CERA-A17 and Mott Filter # MOTB-001.

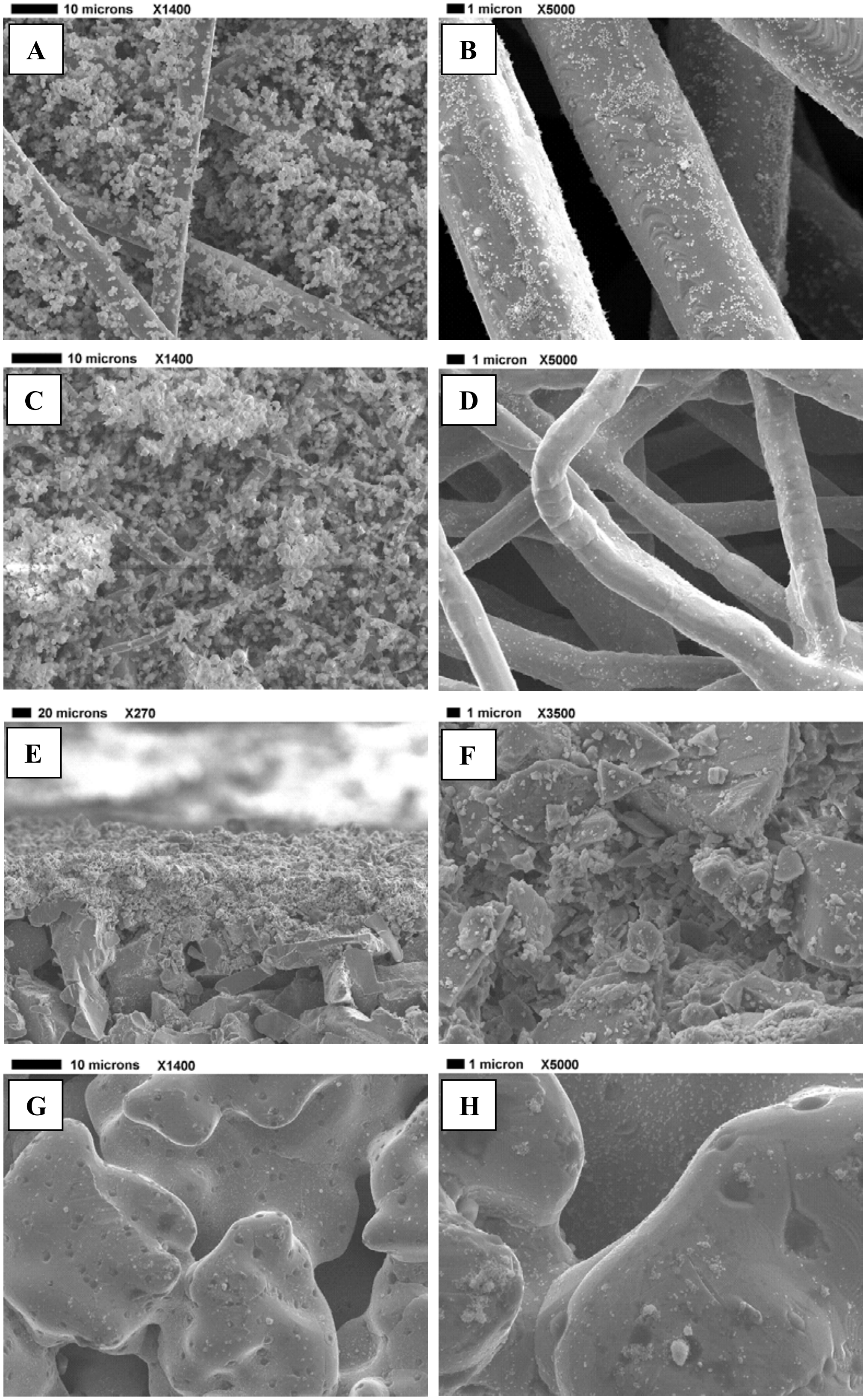

Fig. 4. Scanning Electron Microscope Pictures of Loaded and Cleaned Filters.

Figure 4 shows photos taken with a JEOL scanning electron microscope of a Porvair, a CeraMem filter, a Mott sintered metal fiber filter, and a Mott sintered metal powder filter. Figure 4(A) shows a Porvair sintered metal fiber filter loaded approximately 1.5 inches w.c. with RIC simulant. Figure 4(B) shows the same Porvair sintered metal fiber filter washed with 10% HNO_3 and dried. Figure 4(C) shows a Mott sintered metal fiber filter loaded with RIC simulant. Figure 4(D) shows a Mott sintered metal fiber filter after three load (RIC) and wash (10% HNO_3) cycles. Figure 4(E) is a CeraMem ceramic filter cross section showing silicon carbide substrate (large aggregate), filter membrane, and loading with RIC simulant. Figure 4(F) shows a CeraMem filter that has been loaded with RIC simulant and washed with 10% HNO3. Figures 4(G) and (H) show a Mott sintered metal powder filter after three load/wash cycles.

CONCLUSIONS

A selected set of regenerable media have received preliminary evaluation as to filtering efficiencies, loading capacities, and ease of regeneration. They have been tested by challenging with a water insoluble aerosol of appropriate particle size distribution so as to maximize penetration. These preliminary tests have been conducted using sintered metal fiber media, sintered metal powder media, and ceramic media. The media tested were chosen to have filtering efficiencies (from 90 – 98%) more applicable to use as pre-filters as opposed to final filtering elements.

Differential pressures across sintered metal fiber filters are much closer to the one to six inches of water column range encountered with nuclear glass fiber media HEPA filters. Metal fiber media tested demonstrated a differential pressure of approximately two inches water column at a rated media velocity of four feet/minute. Ceramic media tested demonstrated a pressure of 1.5 inches water column at a rated media velocity of five feet/minute. The Mott Grade 2 powdered metal media demonstrated a pressure of five inches water column at a rated media velocity of four feet/minute. It is likely that any of these media are compatible for use as pre-filters in existing systems with only minor modifications.

Most penetrating particle sizes (MPPS) for the solid aerosol challenge ranged from 160 nanometers down to 110 nanometers for the media tested. All testing indicated a decrease in MPPS as the filters loaded with loaded filters demonstrating an MPPS on the range of 80 to 90 nanometers.

All of the media tested demonstrated good cleanability using a weak acid wash to remove the predominantly Iron (III) particulate matter. Differential pressures after three load and wash cycles were effectively equivalent to initial differential demonstrated new media.

Notable among the results from these experiments would be the difference in profile of the dP vs. mass loading curves for fibrous media when compared to ceramic or sintered metal powder media. Loading curves for traditional HEPA filters and for the sintered metal fiber media tested tend to show an initial exponential increase in dP that transitions to a linear increase over the life of the filter. By contrast, the ceramic and sintered metal powder media tested demonstrated a more logarithmic dP vs. mass loading curve. This is likely due to increased surface filtration by the latter media.

REFERENCES

[1] Arunkumar, R.; Etheridge, J.A.; Hogancamp, K.U.; Luthe, J.C.; Nagel, B.A.; Norton, O.P.; Parsons, M.S.; Rogers, D.M.; and Waggoner, C.A.; "Evaluation of Mass Emission Rates Down Stream of HEPA Filters as a Function of Source Terms and Selected Failure Modes", Waste Management Conference, February 29 – March 4, 2004, Tucson, AZ

[2] Adamson, D. J. and Terry, M.T., "Insitu Cleanable Alternative HEPA Filter Media", Waste Management '02 Conference, February 24-28, 2002, Tucson, AZ

[3] Bergman, W.; Larsen, G.; Lopez, R.; Wilson, K.; Witherall, C.; and McGregor, M., "Further Development of the Cleanable Steel HEPA Filter, Cost/Benefit Analysis and Comparison with Competing Technologies", 24th DOE/NRC Nuclear Air Cleaning and Treatment Conference, July 15-18, 1996

[4] Peters, T.M. and Leith D., "Concentration Measurement and Counting Efficiency of the Aerodynamic Particle Sizer 3321", *J. Aerosol Science*, 34, 627-634 (2003).