# FURTHER DEVELOPMENT OF THE CLEANABLE STEEL HEPA FILTER, COST/BENEFIT ANALYSIS, AND COMPARISON WITH COMPETING TECHNOLOGIES*

by

W. Bergman, G. Larsen[1], R. Lopez, K. Wilson, C. Witherell and M. McGregor
Lawrence Livermore National Laboratory
Livermore, CA 94550

## ABSTRACT

We have made further progress in developing a cleanable steel fiber HEPA filter. We fabricated a pleated cylindrical cartridge using commercially available steel fiber media that is made with 1 µm stainless steel fibers and sintered into a sheet form. Test results at the Department of Energy (DOE) Filter Test Station at Oak Ridge show the prototype filter cartridge has 99.99% efficiency for 0.3 µm dioctyl phthalate (DOP) aerosols and a pressure drop of 1.5 inches. Filter loading and cleaning tests using AC Fine dust showed the filter could be repeatedly cleaned using reverse air pulses. Our analysis of commercially optimized filters suggest that cleanable steel HEPA filters need to be made from steel fibers less than 1 µm, and preferably 0.5 µm, to meet the standard HEPA filter requirements in production units.

We have demonstrated that 0.5 µm steel fibers can be produced using the fiber bundling and drawing process. The 0.5 µm steel fibers are then sintered into small filter samples and tested for efficiency and pressure drop. Test results on the sample showed a penetration of 0.0015 % at 0.3 µm and a pressure drop of 1.15 inches at 6.9 ft/min (3.5 cm/s) velocity. Based on these results, steel fiber media can easily meet the requirements of 0.03 % penetration and 1.0 inch of pressure drop by using less fibers in the media.

A cost analysis of the cleanable steel HEPA filter shows that, although the steel HEPA filter costs much more than the standard glass fiber HEPA filter, it has the potential to be very cost effective because of the high disposal costs of contaminated HEPA filters. We estimate that the steel HEPA filter will save an average of $16,000 over its 30 year life. The additional savings from the clean-up costs resulting from ruptured glass HEPA filters during accidents was not included but makes the steel HEPA filter even more cost effective.

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[1] Present address: Kennerley-Spratling, Inc., 2116 Farallon Dr., San Leandro, CA 94577-6694

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We also present the results of our evaluation of competing technologies with metallic and ceramic powder filters, ceramic fiber filters, and reinforced glass fiber filters. In general, the metallic and ceramic powder filters have pressure drops in excess of 25 inches of water for HEPA grade efficiencies and are therefore not viable candidates. The ceramic fiber filters cannot meet the HEPA efficiency because the fiber diameters are too large. The reinforced glass fiber filter is a promising candidate for the cleanable HEPA filter but requires additional development and testing to confirm its potential to be repeatedly cleaned.

This report is based upon material extracted from a DOE technical review of the Mixed Waste Integrated Program and from the final report of a systems analysis of cleanable steel HEPA filters.[1,2]

## I. Introduction

Cleanable steel filters have been used for many years by various industries, including the nuclear industry, to provide high efficiency filtration with minimal maintenance. These filters were made from steel powder that was sintered together and formed into a hollow cylinder. Compressed air pulses were directed into the interior of the cylinder to dislodge particle deposits that had formed on the outside of the cylinder. Figure 1 illustrates the basic concept of the cleanable steel filter having multiple filter elements in a single housing, a blow-back gas for cleaning, and a hopper for collecting the particles.

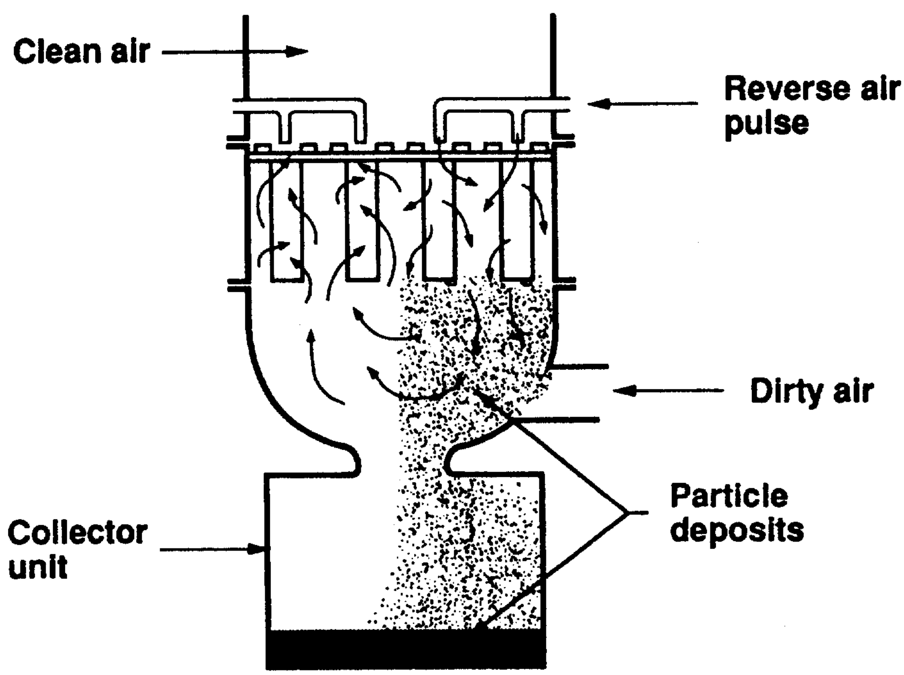



Figure 1. Typical cleanable filter with multiple cartridges and a blow-back cleaning apparatus.

The cleanable filter shown in Figure 1 is a well established design used with many other filter elements such as cloth bags, ceramic tubes, and polymeric tubes. Design variations include other filter shapes than cylinders such bayonets, stacked plates, hollow panels, etc. All filter elements have an exterior surface for collecting the deposited particles and an interior volume through which the cleaned gas exits and through which a blow-back gas is used to dislodge the deposited particles.

The applications for these filters range from recovery of catalysts in petroleum refineries to off-gas filtration in incinerators. Rocky Flats had used sintered metal filters to remove the suspended particulate from a fluidized bed incinerator that burned transuranic waste contaminated with plutonium.[(3)] The sintered metal filters were repeatedly cleaned by reverse air pulses. Kirstein et al also showed that sintered metal filters had excellent performance in both removal efficiency and reverse air-pulse cleaning for applications in another incinerator.[(4)] The filters are robust and require minimal maintenance. Despite the excellent performance of the sintered metal filters, they only had about 60% DOP efficiency when clean and had relatively high pressure drops.[(5)]

In the early 1980s, researchers in Europe had developed high efficiency air filters using the new filter media from Bekaert that was made from 2 μm steel fibers. Dillmann et al described the use of 2 μm stainless steel fibers to make deep bed filters for use as vent filters in nuclear power reactors.[(6,7)] The deep bed filters had efficiencies comparable to the glass HEPA filters but were much larger and could not be cleaned. Klein and Goossens showed major improvements in filter efficiency with decreasing diameter of the steel fibers from 12 to 4 μm.[(8)] However, the efficiencies were far below HEPA grade. They also showed that deposits of methylene blue aerosols could be efficiently cleaned from a cylindrical filter by washing with a water spray.

By the late 1980's, Pall Corp. had developed cylindrical filter elements using steel media having separate layers of sintered steel fibers and sintered steel powder. Randhahn et al described a stainless steel filter from Pall Corp.[(9)] that had efficiencies comparable to a HEPA filter, but they did not report any pressure drops. The filter consisted of two layers of 5μm fiber media and one layer of fine powder metal. Our tests showed that the filter had a pressure drop of 2.2 psi (61 inches of water) at 13 cfm, which corresponds to 1,000 cfm through a standard size HEPA filter.[(10)] A variation of the Pall filter with lower pressure drop and lower efficiency was installed as a prefilter in all of the French nuclear power plants.[(11)]

In 1990 Bergman et al showed that by eliminating the use of steel powder and using the smallest available steel fibers, filters could be made that had the same efficiency as a HEPA filter and a pressure drop only three times as great.[(12)] Bergman then used this new filter to begin developing a cleanable steel HEPA filter.[(13)]

Two designs of the cleanable steel HEPA filter have been developed to date: an assembly of multiple cartridges housed in a standard 2' x 2' x 1' frame and multiple cartridges housed in a pressure vessel. We developed the basic design parameters for the steel filter that can be retrofitted into the standard HEPA housing.[14] This filter design consists of 64 individual filter cartridges housed in a standard HEPA filter frame of 2' x 2' x 1'. We were only able to use 150 $ft^2$ of media in the filter instead of the minimum 200 $ft^2$ found in glass HEPA filters. This limitation was due to the clindrical cartridge design, that prevented more media from being used. The cleanable steel filter, shown in Figure 2, consists of 64 cartridges assembled into the HEPA filter housing.

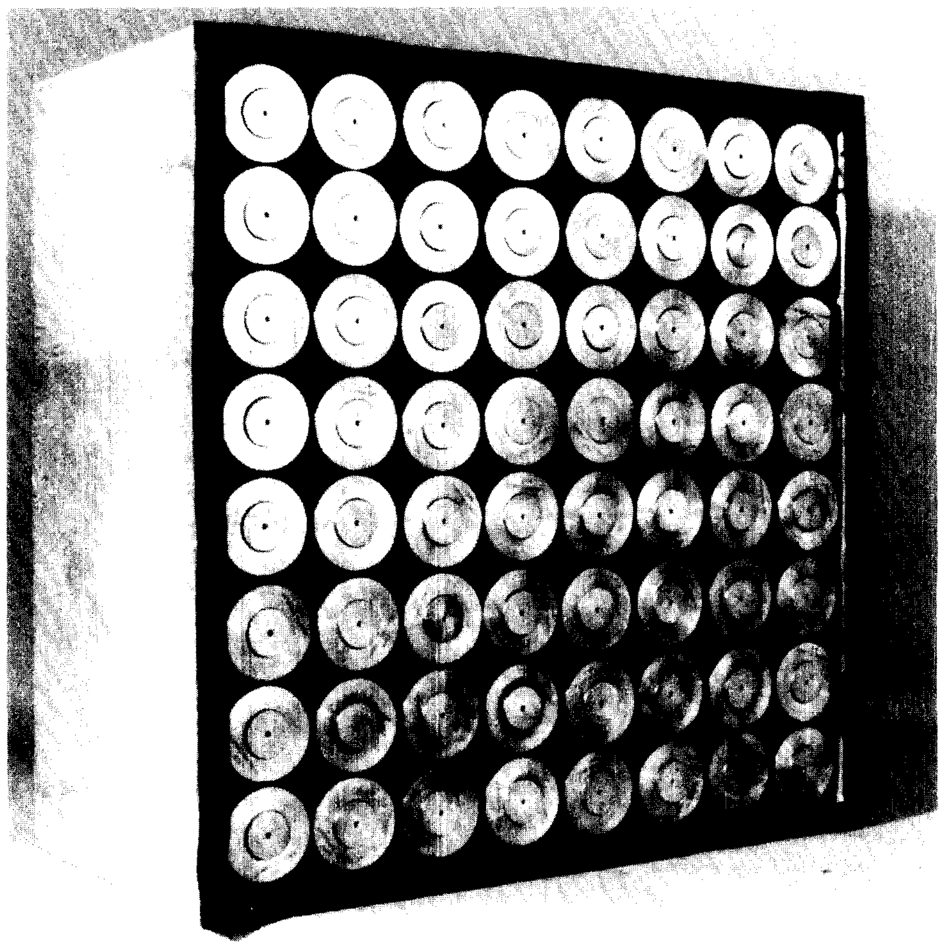


Figure 2 Photograph of the assembled cleanable steel filter using the flat panel design with 64 cartridges

We made two cleanable steel filters like that shown in Figure 2 using filter cartridges from Pall Corporation and Memtec Corporation and evaluated their performance.[14] The filter media used to make the filter cartridges was made from 2 μm steel fibers sinctered into sheets and pleted to increase the surface area. Both filters met the required 0.03 % DOP penetration, but had a pressure drop of 3 inches and weighed over 200 pounds. After a successful laboratory demonstration that the filters could be repeatedly cleaned by reverse air pulses and reused, both filter units were evaluated in the exhust stream of a uranium oxide grit blaster at the Y-12 Plant in Oak Ridge, TN.[15] The field evaluation was not completed because water accumulation in the exhaust system caused excessive pressure drop and interfered with the filter cleaning studies.[15] Since additional funds were not available to dry the wet exhaust, the field evaluation was prematurely terminated.

In addition to the panel filter design shown in Figure 2, the cleanable steel filter can be designed as a pressure vessel for use in applications that do not require retrofitting into existing housings. Pall Corp. has built several units in which multiple cartridges are housed inside a pressure vessel as shown in Figure 3. This is the design that was to be used in the vitrification plant at Hanford.[16,17] The filter in Figure 3 is cleaned using a reverse water flush. Tests by Pall using Arizona road dust show that fully loaded filters can be efficiently cleaned using the water wash.[18,19]

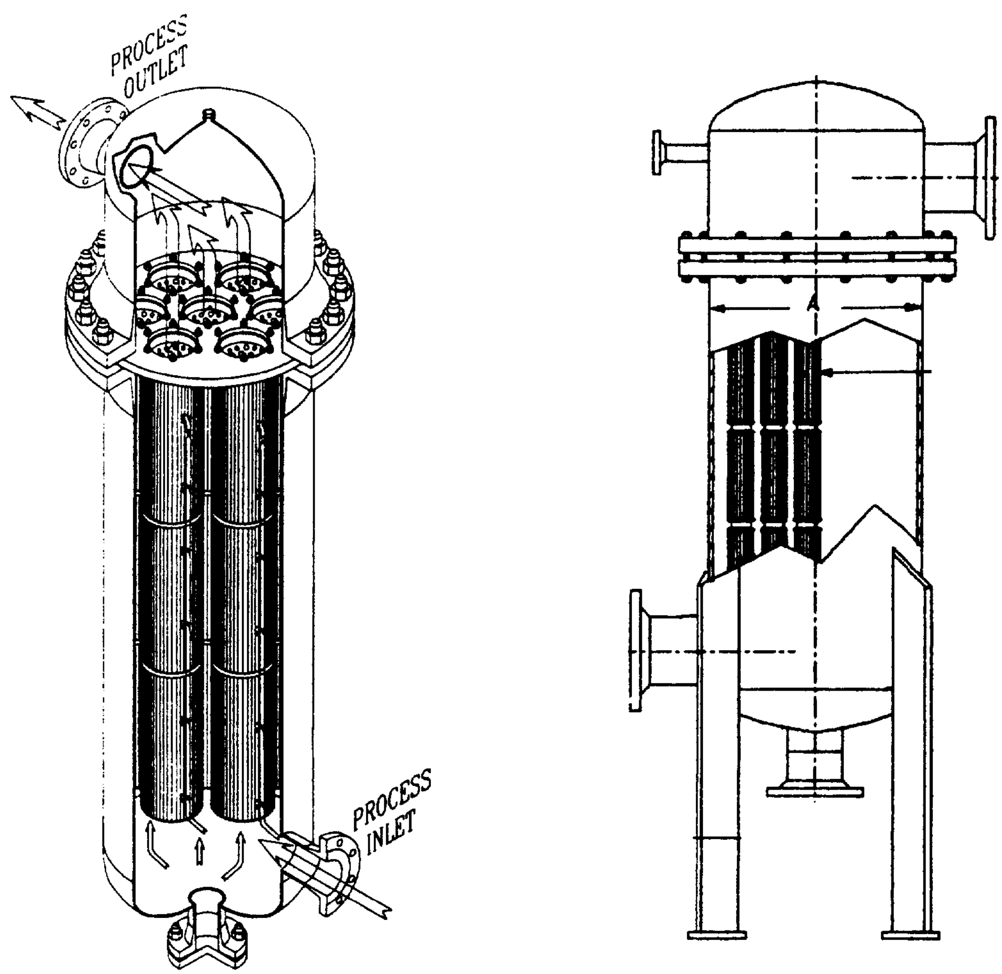



Figure 3. Drawing and schematic of the cleanable steel filter with filter cartridges housed in a pressure vessel.

Neither of the two steel HEPA designs shown in Figures 2 and 3 have been accepted by the nuclear industry as replacement for the glass HEPA filter. The cleanable steel filter shown in Figure 2, which is designed for both new and retrofit applications, has the overall dimensions of a standard glass HEPA filter, but has an unacceptable high pressure drop and weighs too much. Installing more powerful blowers to overcome the high resistance is not acceptable because of the extra cost and the misbalance introduced into existing building and system ventilation systems. In addition, special lifting and positioning equipment would be needed to install and remove the 200 pound filters. In our field demonstration of the cleanable filter, we built a specially designed alignment table and mounted it on a scissors lift in order to install the steel filter.[15] Unfortunately, this type of equipment could not be used in most existing HEPA filtration systems due to space limitations. The high pressure drop, high weight and special lifting equipment are only a problem in existing filtration systems and not in future systems that can be designed to accomodate the special requirements.

The pressure vessel design in Figure 3, which is intended for new filtration systems, also has high pressure drop, high weight and requires special lifting equipment. This design had been selected for use in a waste vitrification plant at Hanford prior to the cancellation of the plant.[16,17] The pressure vessel design was selected over a deep-bed sand filter for that application.[16] The initial cost of the steel HEPA filter was also less than the cost for the deep bed sand filter. However, both the steel HEPA and the sand filters cost far more than the conventional HEPA filter.

Another major reason why steel HEPA filters are not selected over glass HEPA filters in the nuclear industry is their high cost. The current steel HEPA filter shown in Figure 2 costs about $70,000 compared to $300 for the glass HEPA filter.[20] The cost for the pressure vessel design shown in Figure 3 is estimated at $109,000.[20] These costs are for current prototype steel HEPA filters. We have estimated that the cost of the panel filter in Figure 2 could be reduced to $5,000 with further development and with production efficiencies.[14]

Despite the much higher costs for the steel HEPA filters compared to the glass HEPA filters, the high cost of disposing of contaminted HEPA filters made the steel HEPA filters appear economically attractive. Our previous cost analysis shows that a $5,000 steel filter would save $54,000 over its life compared to glass HEPA filters.[14] This cost saving is due to the average cost of $4,450 for handling and disposing of glass HEPA filters.[21] Implicit in the cost estimate was that the glass filter had a 3 year life while the steel HEPA filter had a 45 year life.[14] If the assumptions were significantly in error, then the potential cost savings could disappear. Although no additional data on the assumptions was available since our last estimate, we have performed a sensitivity analysis of the potential cost savings as a function of the assumed input parameters.[2] That analysis, which will be summarized in this report, shows that the cleanable steel HEPA filter is still cost effective under a wide range of assumptions.[2]

In order to overcome the identified deficiencies in peformance and the high cost, further development of the steel HEPA filter is required before it can replace the glass HEPA filter. We will summarize the recent developments of the cleanable steel fiber HEPA filter and compare the performance with competing technologies.

## II. Reduction in Pressure Drop Achieved With Smaller Diameter Fibers

The most important parameter that controls the efficiency and pressure drop of fibrous filters is the diameter of the fibers used in the filter medium. To illustrate this point, we have plotted the minimum efficiency and the filter pressure drop in Figure 4 for typical commercial glass fiber filters as a function of the average fiber diameter used in the filter media. The minimum efficiency, pressure drop and fiber diameter for each of the filters identified in Figure 4 represent typical values for each class of filter. The filters are normailized to the same dimensions (2' x 2' x 1') and flow rate (1,000 cfm). As seen in Figure 4, the efficiency increases much faster than the pressure drop with decreasing fiber diameter. Since the filters used to generate the curve in Figure 4 represent typical commercial products, we assume that the filters have been optimized to maximize the efficiency and minimize the pressure drop. Thus filter media with smaller diameter fibers are needed for higher efficiency filters.

Using Figure 4, we can illustrate that reducing the fiber diameter is more effective than alternative approaches such as increasing the amount of fibers or the thickness of the media to obtain filters with the desired efficiency and pressure drop. For a filter medium having a fixed fiber diameter, higher efficiencies are obtained by adding more layers of media. For example two layers of a 95% efficient ASHRAE filter with 1 $\mu$m fiber media will yield a filter with a combined efficiency of 99.75% (E= 1-(1-.95)(1-.95)= 0.9975). The pressure drop for the combined layers is twice the single layer (0.5 inch), or 1.0 inch. Alternatively, Figure 4 shows that by using a filter media with 0.7 $\mu$m diameter fibers, we can reach the same efficiency but only have a pressure drop of 0.7 inches.

We applied the principle of reducing the fiber diameter to improve the performance of the steel filters. The commercially available steel filters shown in Figure 2 meet the HEPA filter efficiency requirement but have a pressure drop of 3 inches of water. In order to reduce the pressure drop to the required 1 inch, the steel fiber media must be made from fibers having diameters about 0.5 $\mu$m instead of the present 2.0 $\mu$m diameter.

We have fabricated and tested a filter cartridge element using steel media obtained from Tomeogawa Inc. that was made from 1 $\mu$m diameter, 316L stainless steel fibers.[1,22,23] An electron micrograph of the sintered media sheet is shown in Figure 5. Tests on the flat sheet are shown in Figure 6 where the penetration is plotted as a function of particle diameter. The face velocity is 3.5 cm/s, which corresponds to the velocity that would be obtained with 150 $ft^2$ of media in a full scale filter. Figure 6 shows that the 1 μm media has a penetration of 0.004% at 0.3 μm aerosol diameter and a pressure drop of 1.05 inches. Thus, the 1 μm media represents the threshold for achieving HEPA filter performance.

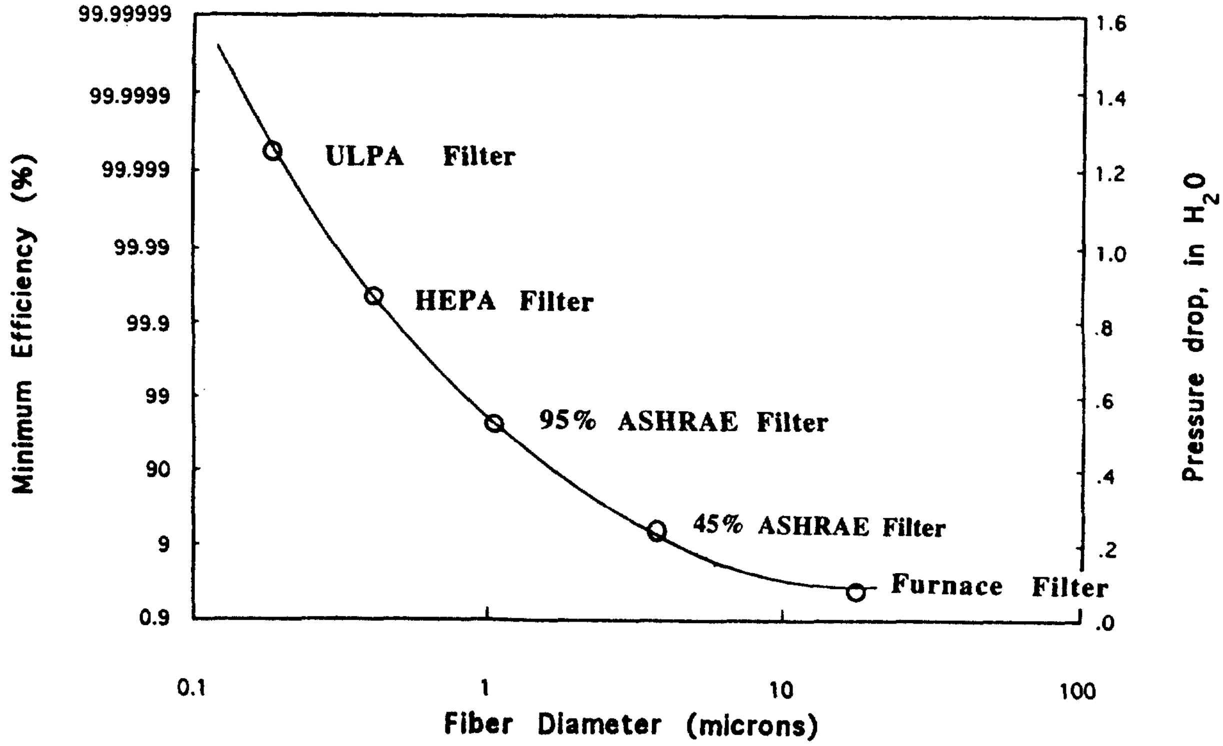



Figure 4. Relationship between the minimum efficiency, pressure drop and fiber diameter in commercial filters.

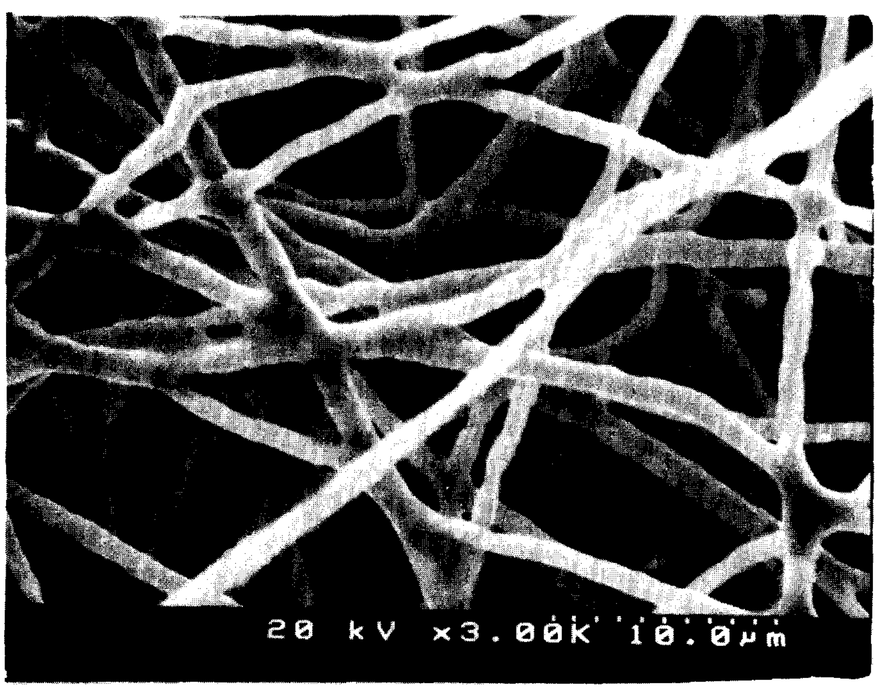



Figure 5. Electron micrograph of Tomeogawa steel fiber media made from 1 μm diameter, 316L stainless steel fibers.[23]

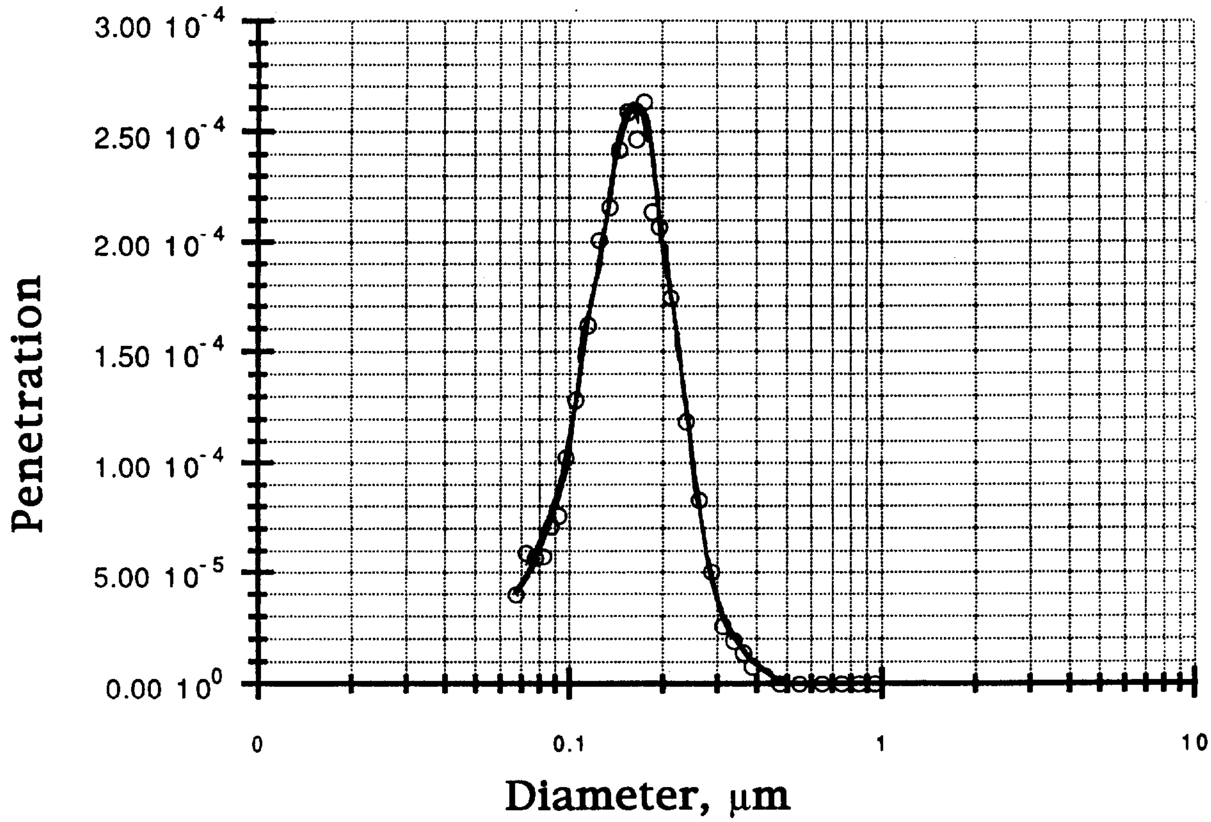



Figure 6. Penetration of DOS aerosols through 1 µm fiber media from Tomeogawa at 3.5 cm/s. Pressure drop was 1.05 inches.

The filter cartridge, shown in Figure 7, was made by sandwiching the media between support screens, pleating the composite layers, welding the composite sheet ends to form a pleated cylinder, and sealing the two, pleated, cylindrical ends in a potting compound. The pleated, cylindrical ends also could have been sealed by brazing to end caps. We used the test method and apparatus described in our previous report to evaluate the filter cartridge at 15.6 cfm to correspond to a full-scale HEPA filter.[14] Figure 8 shows the penetration of dioctyl sebacate (DOS) aerosols as a function of aerosol diameter. Although the penetration at 0.3 µm diameter is satisfactory at 0.002% , the pressure drop is 1.5 inches of water and exceeds the maximum allowable 1 inch. The major reason for the higher pressure drop in the cartridge than in the filter media shown in Figure 6 is the variablitiy in the media properties. The cartridge in Figures 7 and 8 was made from a different media batch having 50% higher pressure drop than the media in Figure 6. This variation was due to the small sample size in the media production and should not occur with larger samples. Thus, we have approached the threshold for achieving a HEPA filter using 1µm media. Steel media having fiber diameters less than 1 µm is needed for making steel HEPA filters with production variability.

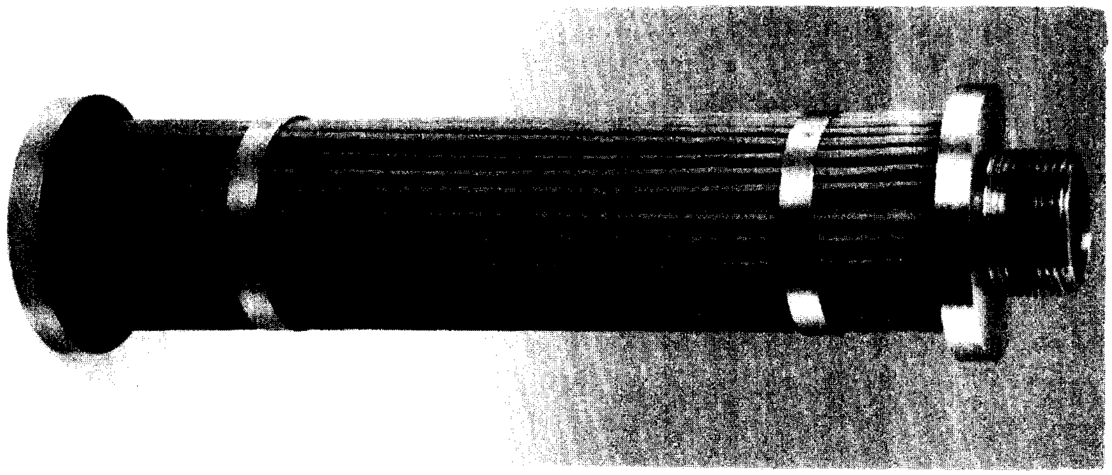


Figure 7. Pleated filter cartridge made from 1 μm steel fiber media.

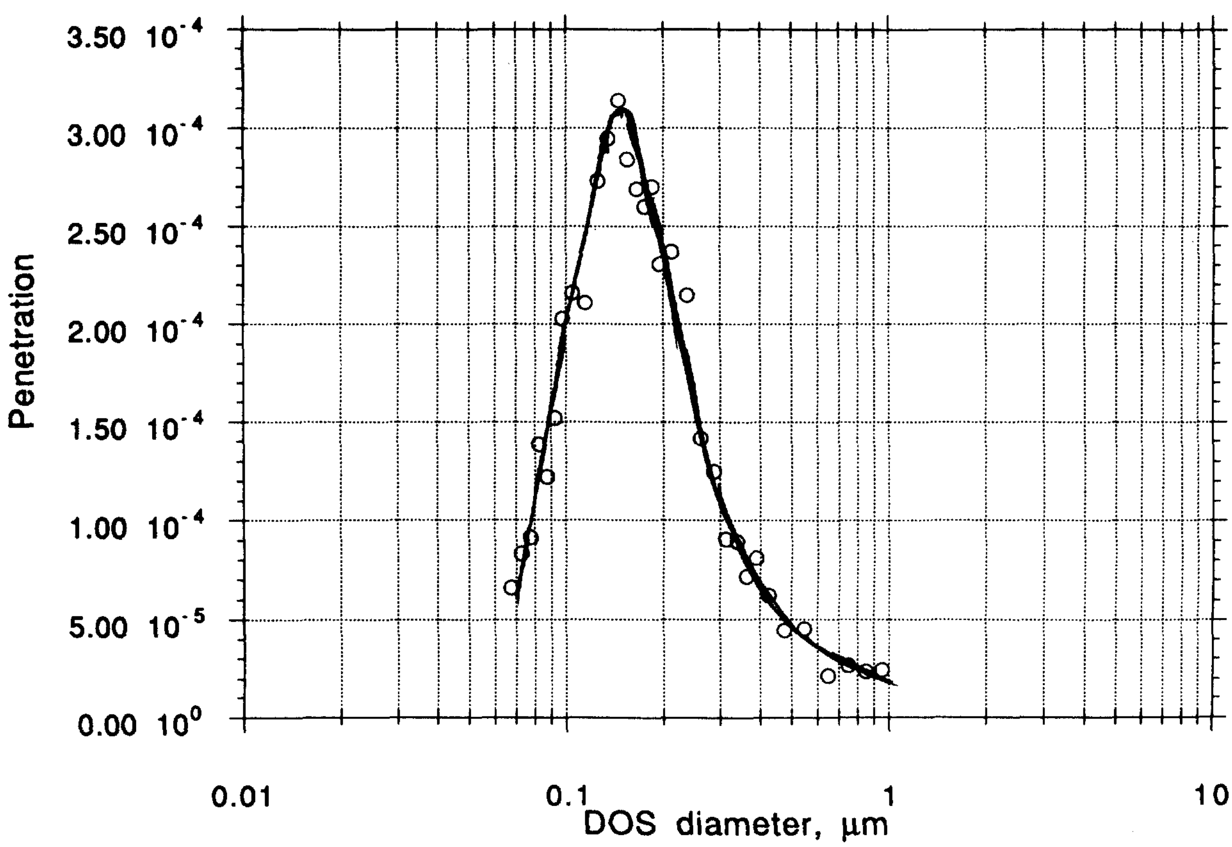



Figure 8. Aerosol penetration through filter cartridge shown in Figure 7 as a function of aerosol diameter. Pressure drop is 1.5 inches at 15.6 cfm flow.

Since the ability to clean and reuse the steel HEPA filter is an important property of the cleanable steel HEPA filter, we conducted a series of filter clogging and cleaning tests on the filter cartridge shown in Figure 7. We used AC Fine dust (Powder Technology Inc, Burnsville, MN) to load the filter and compressed air pulses to remove the particle deposits. The test system is described in our previous publication.[14] Figure 9 shows the results of loading and cleaning the filter cartridge 10 times. The test shows that the filter can be repeatedly cleaned and reused. Note that there is a small increase in the baseline pressure from 1.5 to 2.0 inches up to the fifth cleaning. Beyond that point the residual deposits in the filter remain constant.

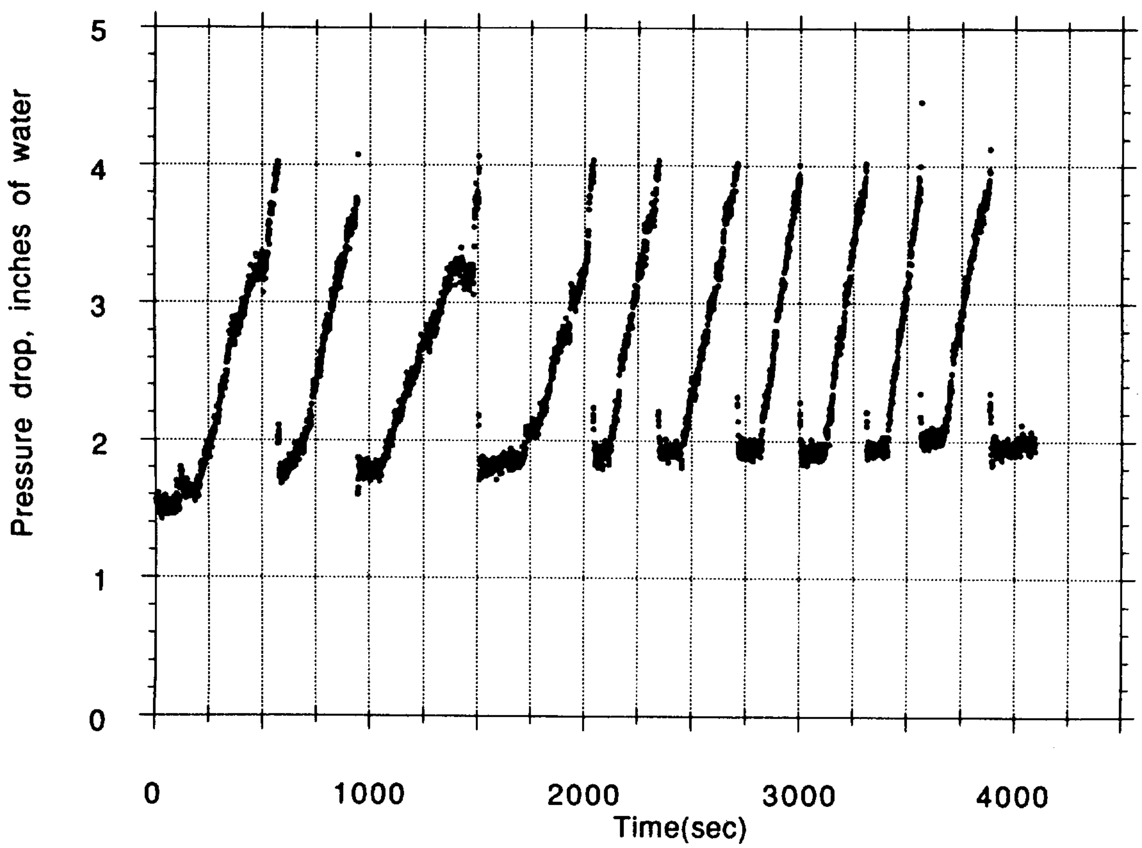



Figure 9. Filter loading and cleaning cycles using AC Fine test dust and compressed air pulses on the filter cartridge in Figure 7.

Since there are no commercial sources that can make 0.5 µm steel fibers, we used fundamental laboratory techniques based on the wire bundling and drawing process to make a small quantity of these steel fibers. The process, which is extremely labor intensive and not suitable for prototype development, involves a series of repetitive steps in which wires are bundled together into a rod and then reduced in diameter by drawing through progressively smaller dies. The starting point is a stainless steel rod that is snugly fitted inside a copper tube. We then reduced the diameter of the rod by swaging until the resulting rod could be drawn through a standard wire drawer for further size reduction. The wire drawing process was periodically interrupted to heat treat the rod to reduce the hardness induced by the drawing process. The reduced wire was then cut into fixed lengths which were then inserted into a new copper tube and the process repeated. Figure 10 shows a rod consisting of a bundle of wires being reduced in diameter through progressively smaller dies. The individual wires have a copper coating from the initial cladding operation to prevent sticking to the other wires. Figure 11 shows a cross section of the rods, starting with the original rod and going through the first, second and nth bundling. When the desired fiber diameter is reached, the copper cladding is dissolved in nitric acid and the fibers dispersed.

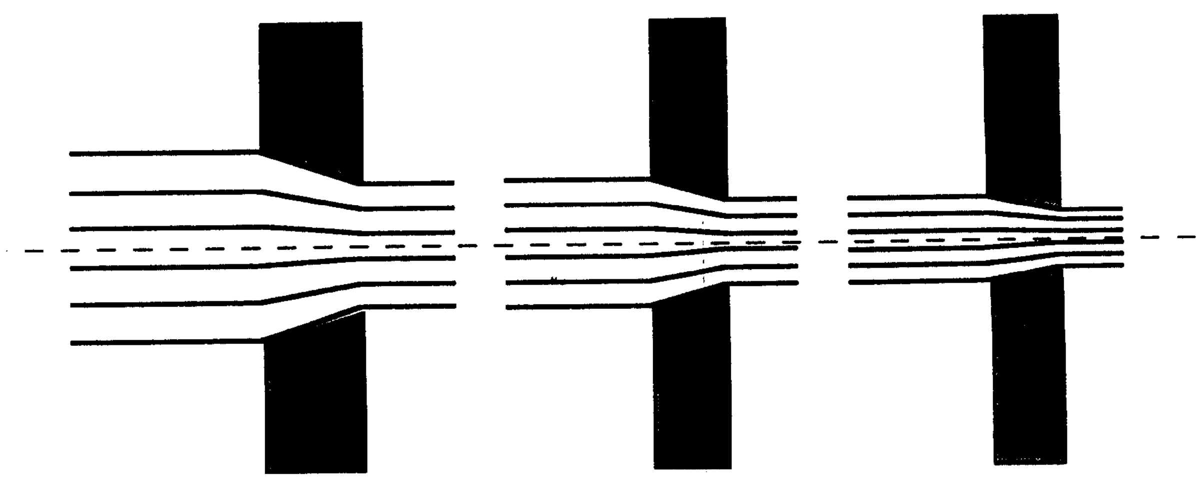


Figure 10. Wire drawing is used to produce smaller diameter steel fibers.

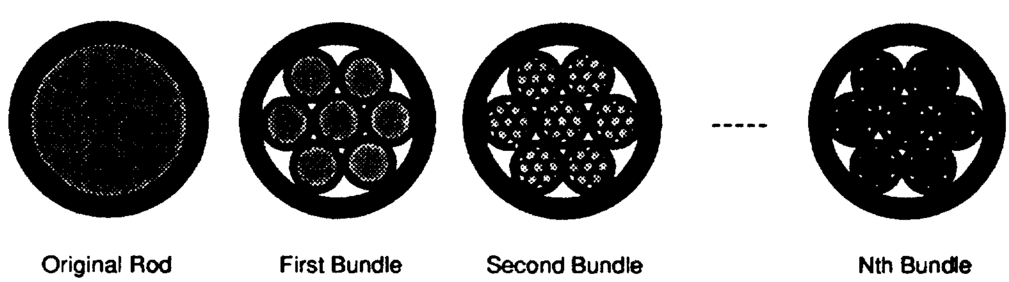



Figure 11. Cross section of steel rods from the original to increasing iterations of bundling and drawing

We then made a small sample of stainless steel fiber media from the 0.5 μm steel fibers using the paper making process followed by sintering.[1] Figure 12 shows an electron micrograph of the media. Laboratory tests at 3.5 cm/s face velocity yielded an efficiency of 99.998% for 0.3 μm dioctyl sebacate (DOS) aerosols.

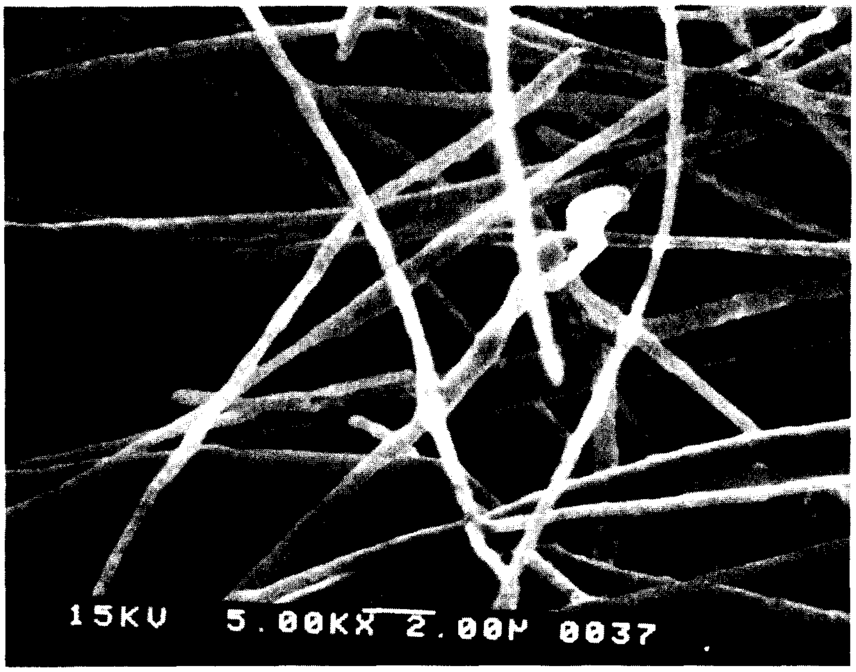



Figure 12. Electron micrograph of the steel fiber media made from 0.5 μm steel fibers.

Figure 13 shows the penetration (1-efficiency) measurement of the media as a function of particle size. The pressure drop was 1.15 inches. The media had a greater quantity of fibers than was needed to achieve the desired efficiency value. We estimate that reducing the quantity of fibers to yield an efficiency of 99.97% will result in a media pressure drop of 0.8 inches. Unfortunately, we did not have sufficient fibers to optimize the media formulation. Nevertheless, our tests have demonstrated that filter media made from 0.5 μm steel fibers will yield the desired HEPA filter performance.

We have shown the feasibility of developing a steel HEPA filter that meets the efficiency and pressure drop requirements for HEPA filters. However, the laboratory bench scale process must be scaled up in order to produce a sufficient quantity of fibers and media to make several prototype HEPA filters. This represents the next step in the development of the cleanable steel HEPA filter.

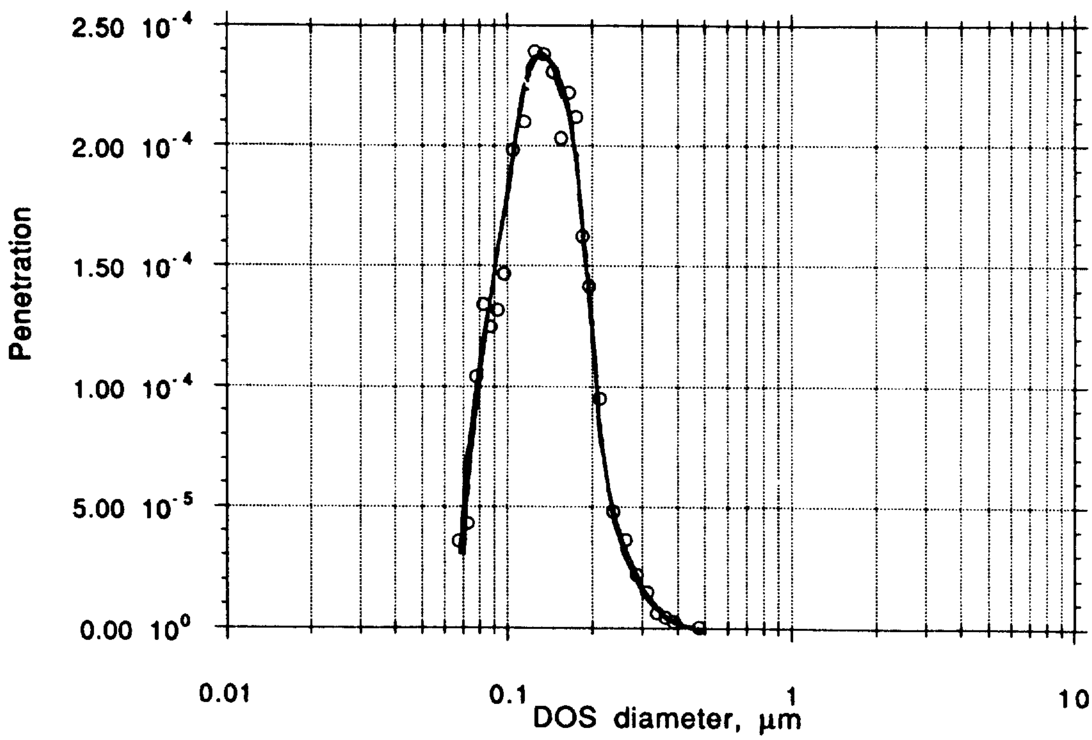



Figure 13. Aerosol penetration measurements at 3.5 cm/s face velocity through steel fiber media shown in Figure 12. Pressure drop was 1.15 inches.

## III. Reduction in Weight Achieved by Using Conventional HEPA Design

Since the filter media for the steel HEPA is expected to weigh about 10 pounds for 200 square feet (glass fiber media would weigh 3.3 pounds), most of the weight is due to the support structure. The filter design that consists of multiple pleated cylinders as shown in Figure 2 would require a considerable amount of heavy metallic support elements and end plates on which to attach the cylinders. This design can not be used to fabricate a steel HEPA filter that has a comparable weight to the steel-framed HEPA with glass fiber media. To achieve the weight objective, it will be necessary to use a similar design as used for glass fiber HEPA filters. Figure 14 shows a design using corrugated separators. Since the steel media is much stronger than the glass media, it also is possible to eliminate the separators. Other designs such as the mini-pleat and Dimple Pleat™ design are also possible.(14,24) The assembly of such filters is very similar to that used for the present glass HEPA filters except that organic sealants would be replaced with a brazing compound. Any of a variety of different brazing or welding techniques can be used to seal the pleated media pack into a steel frame. The final weight of the filter is expected to be less than 60 pounds, compared to the 200 pounds for the commercial units.

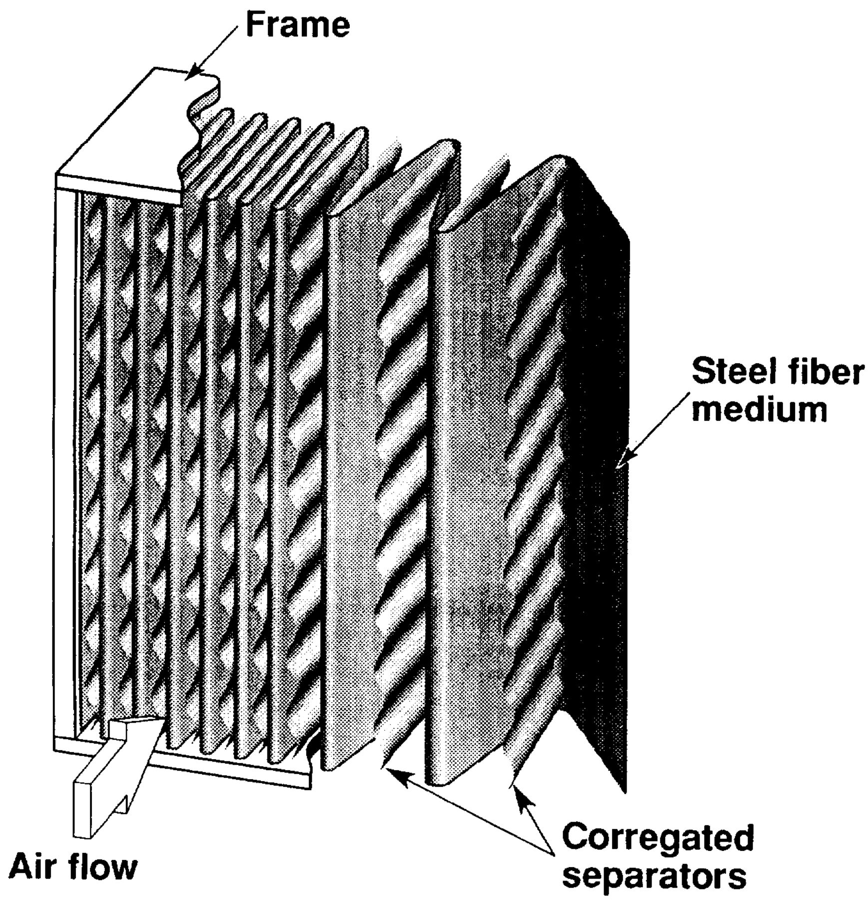



Figure 14 Cleanable steel HEPA filter with the deep pleat and separator configuration.

## IV. Sensitivity Analysis Shows Cleanable Steel HEPA Flatters Are Cost Effective

The initial driver that was responsible for the early development work of the filter was the cost saving that resulted from reducing the large waste disposal costs by cleaning the filter and reusing it.[13,14] We found that during the 1987-1990 period, DOE facilities used an average of 11,478 HEPA filters per year and had an annual estimated cost of $55 million.[21] We estimated that replacing all of the glass HEPA filters with steel HEPA filters would reduce the annual costs to $13 million and save $42 million per year.[14]

Since the number of HEPA filters used by DOE facilities have decreased dramatically in recent years and the parameters used in the cost estimates are uncertain, we have performed a sensitivity analysis of the cost parameters to reevaluate the potential cost savings.[2] The annual number of HEPA filters used by DOE facilities dropped from about 12,000 in 1990 to 4,000 in 1995 as a consequence of the end of the Cold War.[2] The other major factors that determine the total cost savings from using cleanable steel HEPA filters are the average filter life for the glass and steel HEPA filters, the initial purchase price for the glass and steel HEPA filters, the installation, test, removal and disposal cost for a glass or steel HEPA filter, and the cost for cleaning the steel HEPA filter.

The average filter life for the glass-paper HEPA was estimated to be 3 years from a study of filter usage during 1977-1979.[21] If we assume that the number of facilities and operations remain constant during this period, then it is possible to estimate the total number of filters in DOE facilities by multiplying the number of filters tested each year by the average life. For the period between 1977-1979, DOE tested an average of 10,352 filters and therefore had 31,055 filters in its facilities.

Once we have the total number of filters, we can estimate the average filter life by dividing the total number of filters by the annual number tested. Assuming the total number of active filters is still about 31,000, we estimate that the average filter life is (31,000/4,000 = 7.8) 7.8 years. This estimate is reasonable based on the filter age data from Lawrence Livermore National Laboratory as of 10/13/94 that is shown in Figure 15. However, the 4,000 annual filters reflect a relatively idle DOE undergoing a major redirection following the end of the Cold War, and a large fraction of DOE operations, such as environmental clean-up , waste processing and weapons manufacturing are not yet in full operation. The number of HEPA filters used is expected to significantly increase with a corresponding decrease in the average HEPA life as DOE begins to process its radioactive waste and decontaminate and decommission its facilities. For our analysis, we will assume the average filter life will fall within the range of 3 years for full production and 7.8 years for primarily idle operation. The average is 5 years. In addition, there is a growing trend for DOE facilities to impose a 5 year life time on glass HEPA filters because of deterioration with age.[25]

The life of the steel HEPA is another uncertain parameter in the potential cost savings from using steel HEPA filters. The life of the cleanable steel HEPA filter, assumed be 45 years in our original cost savings estimate, is probably much less.[14] The 45 year life estimate assumed that the steel HEPA filter would last the life of a typical facility, hence 45 years. However, the life of the steel HEPA depends on the environment to which the filter is exposed. For a relatively clean, non-corrosive environment, this is probably still a good estimate. However, if 304 or 316 stainless steel filters are exposed to a halide salt or acid environment, then the filter will rapidly degrade due to chemical attack. In fact, these filters should not be used in those environments. For applications in corrosive environments, the fibers should be made from Hastelloy or Inconel. Unfortunately, these fibers are only available in diameters greater than 8 μm, which are not suitable for HEPA filters as seen in Figure 4.

In addition to chemical attack on the fibers, the filter life is also determined by the ability to clean the filter. If the filter cannot be effectively cleaned, then the filter life will be shortened. In our cost analysis, we have assumed a life of 30 years. This is based on having a minimum of six cleanings (i.e. six equivalent glass HEPA filters, each having a 5 year life). In our laboratory tests, we were able to repeatedly clean the steel HEPA for an equivalent of 15 glass HEPA filters.[14]

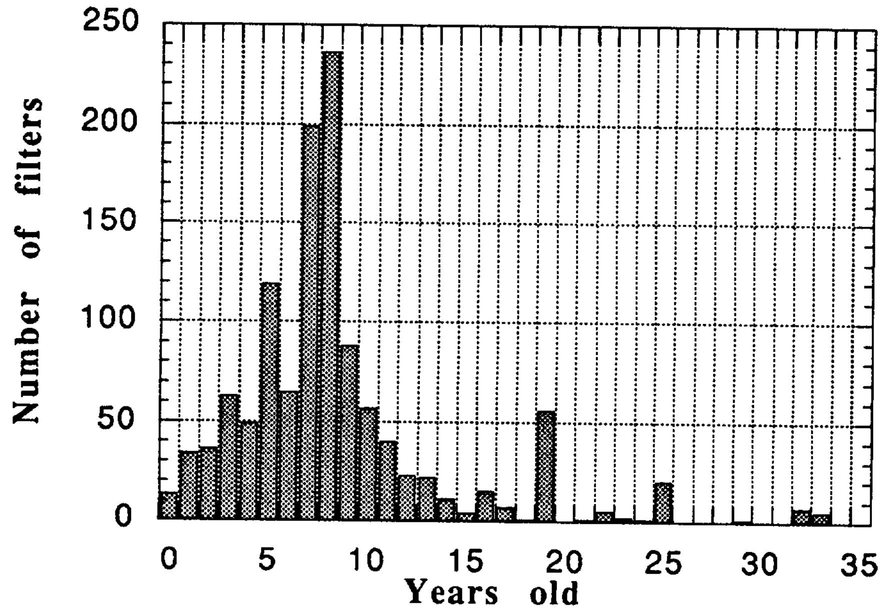



Figure 15. Distribution of HEPA filter age at LLNL as of 10/13/94. The filters are size 5.

Another uncertain parameter in the cost analysis is the final cost of the cleanable steel HEPA filter after it is completely developed and in production. We have assumed that the cost of the steel HEPA filter can be reduced to $5,000 through further development work and with efficiencies in mass production. The present cost of a cleanable steel filter with 3 inches pressure drop and weighing 200 pounds is about $70,000.[20] In contrast a standard glass HEPA filter, which weighs about 40 pounds, costs about $300.

The cost for the installation, test, removal, and disposal was $4,450 as obtained from a survey of life-cycle costs of glass HEPA filters for the period 1987-1990.[21] We assumed that this cost would be the same for both the prototype and the steel HEPA filter. The prototype steel filter would have a slightly higher cost because of its greater weight, but we have ignored that in our analysis.

The final parameter to be considered in our cost analysis is filter cleaning costs. We have assumed reverse pulse air cleaning or filter removal and off-line washing would be the primary cleaning methods. Pall has also developed and successfully tested an on-line water cleaning method for their pressure vessel design.[18,19] We have estimated that each cleaning cycle would cost $500 based on labor costs. The associated capital costs for the cleaning hardware (e.g. blow back tubes) would be lumped into the initial cost for the filter element housing or in the initial cost of the steel HEPA filter.

We have summarized the various costs and parameters for the glass HEPA filter, the commercially available steel filter, and the fully developed cleanable steel HEPA filter in Table 1. We have also computed the total filtration cost for a given HEPA filter installation over 30 years. The total filtration cost for the HEPA filters are given by:

$$C_{GT} = (30/L_{GF})(C_{GF} + C_M) \quad (1)$$

$$C_{ST} = (30/L_{SF})(C_{SF} + C_M) + N_C(C_C) \quad (2)$$

where $C_{GT}$ = total filtration cost for glass HEPA in a single installation over 30 years.

$C_{ST}$ = total filtration cost for steel HEPA filter in a single installation over 30 years.

$L_{GF}$ = Life of glass HEPA filter, years

$L_{SF}$ = Life of steel HEPA filter, years

$C_{GF}$ = Initial cost of glass HEPA filter

$C_{SF}$ = Initial cost of steel HEPA filter

$C_M$ = Maintenance cost of installation, test, removal and disposal

$C_C$ = Cleaning cost of filter

$N_C$ = $30/L_{GF}$ = Number of cleanings

Equation 2 incorporates the assumption that the steel HEPA is cleaned prior to disposal at the end of its useful life. The cost of the cleaning system that is required for retrofit applications is included in the cost of the cleanable steel HEPA because it is small compared to the cost of the filter. The cleaning system would either consist of an in-duct reverse air pulse jet or the filter would be removed for off line cleaning in a liquid bath.

Once the costs for glass and steel HEPA filters are determined from Equations 1 and 2 respectively, a variety of other cost figures can be computed such as annual costs per filter location, total and annual cost savings for steel HEPA filters compared to glass HEPA filters, and total DOE filter costs and total savings. We have made these computations in Table 1.

As seen in Table 1, the commercially available steel filter is not cost effective because of the high purchase cost of $70,000 and the few cleaning cycles for applications having an average HEPA life of 5 years. This explains why these filters are not being used in applications where conventional glass HEPA filters are used. The steel HEPA filter becomes more cost effective with increasing cleaning cycles because of the $4,450 in handling and waste disposal costs that are saved with each cleaning. Table 1 also shows that the steel HEPA filter costing $5,000 is very cost effective for the given assumptions. We believe that this cost reduction is achievable with additional development and improvements in production methods.

To assess the sensitivity of the filtration costs and cost savings to variations in the key parameters in Table 1, we used Equations 1 and 2 to determine the total cost as a function of the glass HEPA life (or cleaning frequency), the purchase cost of the steel HEPA filter, and the service life of the steel HEPA. Details of the sensitivity study are presented in our previous report.[2]

Table 1. Comparison of costs and parameters for glass HEPA and cleanable steel HEPA filters.

| | Glass-paper HEPA | Stainless steel HEPA | |
|---|---|---|---|
| | | Commercial | After Development |
| Filter element (1000 $ft^3/min$) | $300 | $70,000 | $5,000 |
| Installation, test, removal, and disposal | $4,450 | $4,450 | $4,450 |
| Cleaning | $0 | $500/cleaning | $500/cleaning |
| Average filter life | 5 years | 30 years | 30 years |
| life costs for one location(30 years) | $28,500 | $77,450 | $12,450 |
| life savings per location | $0 | -$48,950 | $16,050 |
| cost per location per year | $950 | $2,648 | $415 |
| annual savings per location | $0 | -$1,698 | $535 |
| total DOE cost per year (31,055 filters) | $29.5M | $82.2M | $12.9M |
| total DOE savings per year (31,055 filters) | $0 | -$52.7M | $16.6M |

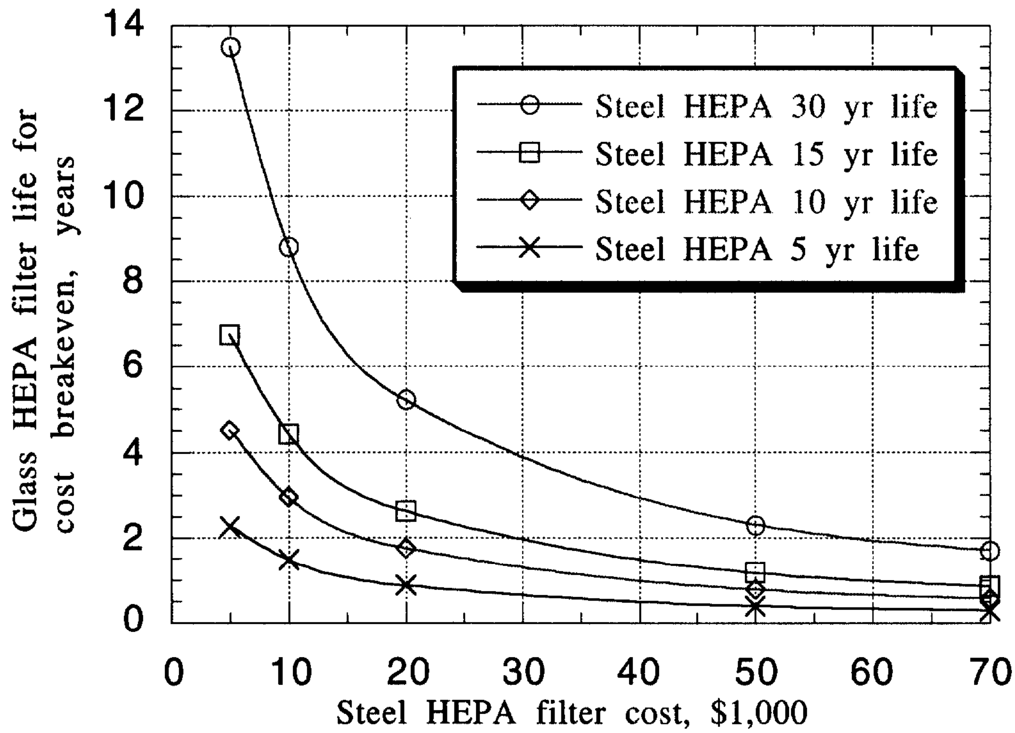



Figure 16 Break-even costs for cleanable steel HEPA filter having different filter lives as a function of purchase cost.

The results of our sensitivity analysis are summarized in Figure 16 which defines the break-even costs as a function of glass HEPA life, steel HEPA cost, and steel HEPA life. Using a cleanable steel HEPA filter will be cost effective for any combination of glass HEPA life and steel HEPA cost that lies below the curve defining a given steel HEPA life. Figure 16 shows that more expensive steel HEPA filters are only cost effective with long steel filter life and short glass HEPA life. Conversely, lower cost steel filters can be cost effective with higher glass HEPA filter lives and lower steel HEPA lives.

In addition to the direct cost savings shown in Table 1, there are additional cost savings due to the increased reliability of the steel HEPA filters. Steel HEPA filters have a much higher reliability than the present glass HEPA filter, which can be damaged or destroyed under a number of operational and accident conditions involving fires, explosions, tornadoes, or water exposure.[(26)] When the HEPA filters are damaged, radioactive contaminants can escape and cause environmental contamination. The typical consequence of a accidental release is a facility shut down and an environmental clean-up operation, both of which are very expensive.

V. Evaluation of Competing Technologies for Cleanable HEPA Filter

The major competitors of the sintered steel fiber filter are the metal and ceramic sintered powder filters and the reinforced glass fiber HEPA filter. In fact, the early high efficiency metal filters used in nuclear air cleaning applications were sintered steel powder filters.[3-5,9] Currently, both steel and ceramic sintered powder filters are used extensively in high efficiency filtration applications in which the filters are repeatedly cleaned and reused. Most of the applications involve filtering gas and liquid process streams at relatively low flow rates and have high pressure drops across the filters.

We have evaluated sintered metal and ceramic powder filters and concluded that these filters have much higher pressure drops than fibrous filters with the comparable efficiency. Figure 17 illustrates the general structure of a sintered powder filter which consists of several layers of different size powders that are sintered together.[27] The layer having the smallest size particles performs the basic filtration, while the intermediate layers and substrate provide structural support to the filtration layer. In order to minimize the pressure drop, the thickness of the filtration layer is made as small as possible.

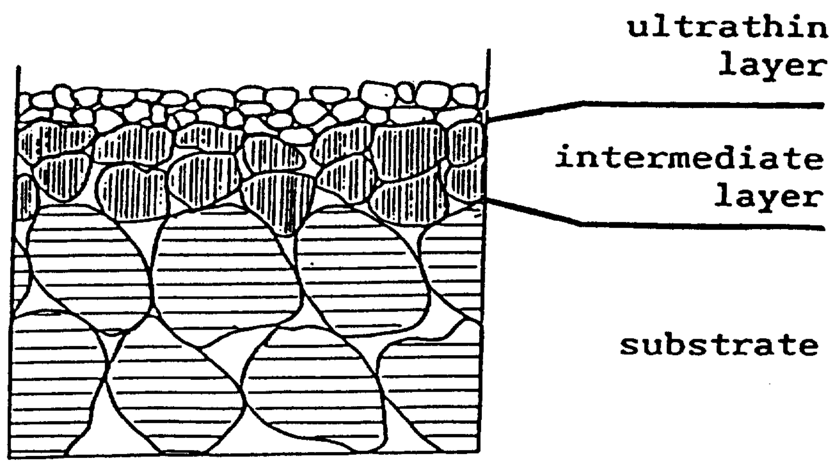
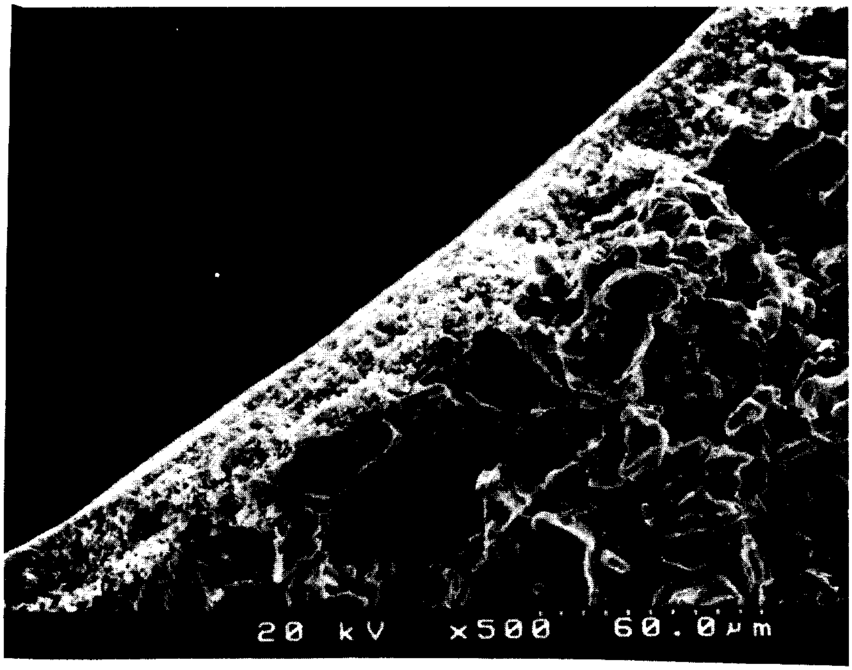
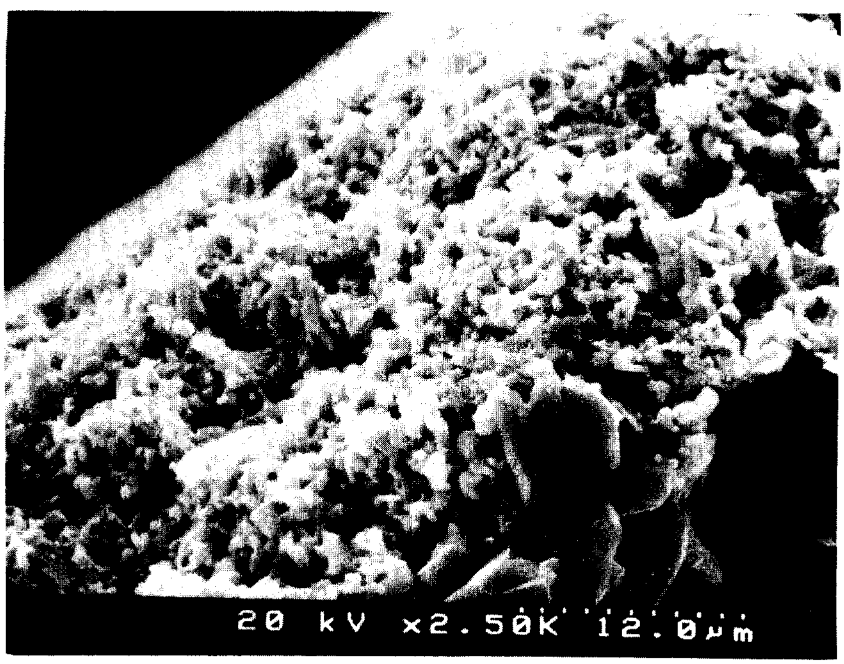



Figure 17. Typical structure of a ceramic powder filter having multiple layers of different size powder.[27]

An example of a typical ceramic powder filter is illustrated in Figure 18 which shows electron micrographs of the cross section of the French KERASEP filter.[28] The substrate layer of 5 $\mu$m aluminum and titanium oxide powder and the surface layer of 0.8 $\mu$m zirconium or titanium oxide powder are seen in the two photographs. In addition to the filter with a surface layer of sintered 0.8 $\mu$m powder, we also obtained KERASEP filters with a surface layer of 1.4 $\mu$m powder and one filter having only the substrate with no surface layer. This filter was used by the French Atomic Energy Agency for isotope separation.




(A)




(B)

Figure 18. Electron micrographs of the cross section of the KERASEP ceramic powder filter having a surface layer of 0.8 μm powder. B is a magnification of A.

We measured the penetration of DOS aerosols and the pressure drop of the three different KERASEP filter elements at 1.3 cfm, which corresponds to a flow rate of 1,000 cfm if the maximum number of KERASEP elements were packaged into the standard HEPA frame of 2' x 2' x 1'. The KERASEP filter elements are cylinders with multiple interior channels that are parallel to the cylindrical element. Figure 19 shows the KERASEP filters have an excessive pressure drop, even with only the pure substrate. The filter with a layer of 1.4 µm powder meets the HEPA penetration requirements but has an excessive pressure drop of 25 inches of water.

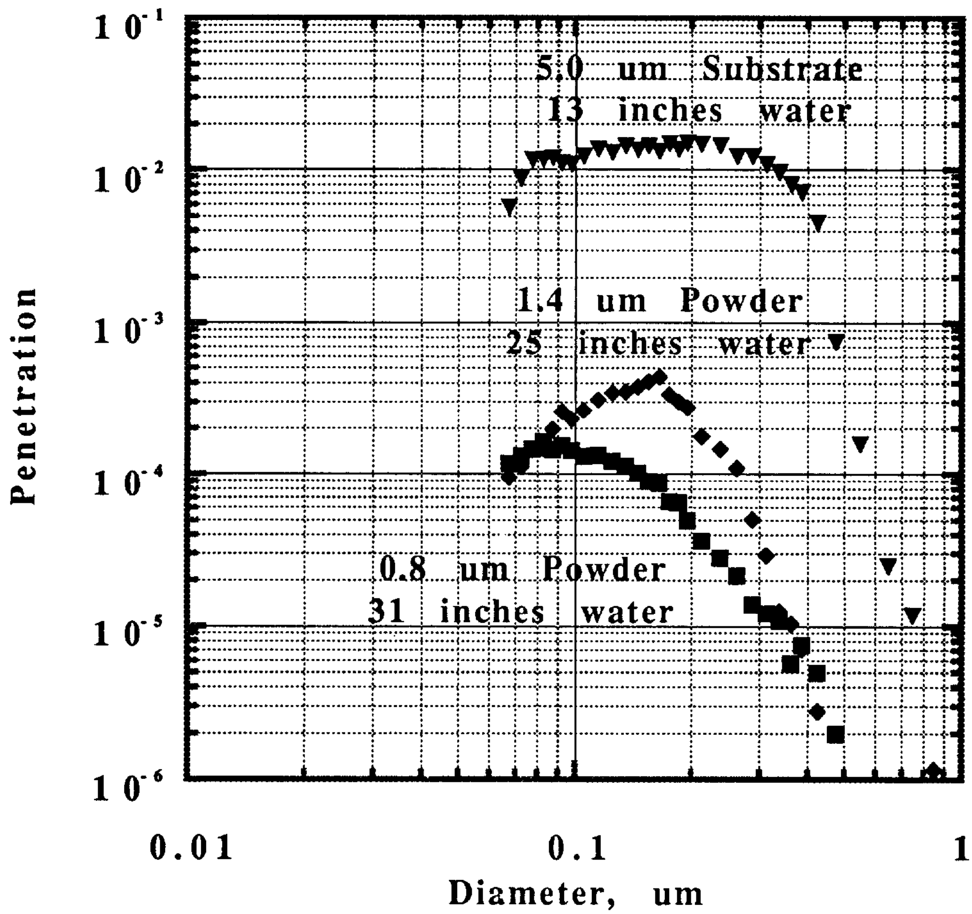



Figure 19. Penetration of DOS aerosols as a function of diameter for three different KERASEP ceramic powder filters.

Another multi-layer ceramic filter that we evaluated was a honeycomb ceramic monolith with a surface layer of fine ceramic powder deposited by a slurry and sintered.[29] This filter element from the CeraMen Corporation had high efficiency and relatively low pressure drop. We tested the filter sample at 50 cfm to correspond to the 1,000 cfm flow for a 2' x 2' x 1' standard HEPA filter. Figure 20 shows that the penetration at 0.3 µm was 0.06, and the pressure drop was 4.0 inches. These values are not close to the HEPA filter requirements.

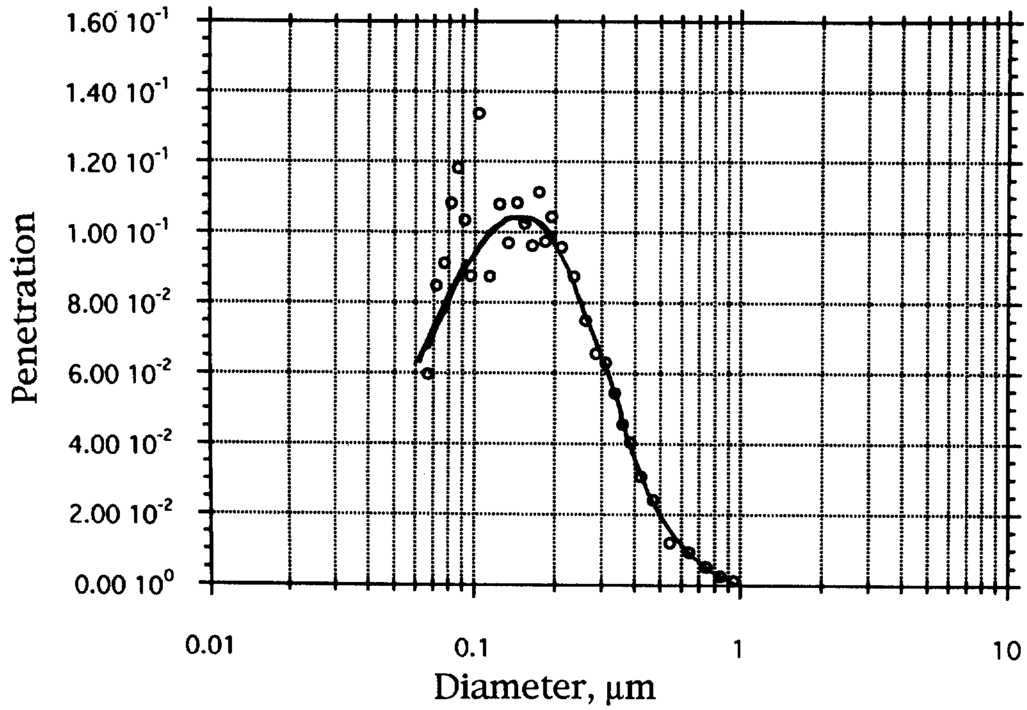



Figure 20. Penetration of DOS aerosols through CeraMen ceramic filter at 50 cfm. The pressure drop was 4.0 inches.

Sintered powder metal filters have a similar performance as the powder ceramic filters because the basic structure of the medium is the same. The powder metal filters are made with either multiple layers of graded powder as in Figure 17 or with uniform size powder throughout. The configuration of the powder metal filters is generally as tubes or other rigid shapes because once the powder is sintered, the filter medium cannot be bent sharply, as required for making filter pleats, without cracking. This is true even for relatively thin sheets. An example of a powder steel filter (Mott Metallurgical, Farmington, Conn.) having 85 tubes with a nominal pore size of 0.2 µm mounted together is shown in Figure 21. We attempted to determine the aerosol penetration through the multi-tube filter, but the pressure drop was too high for our test equipment. The pressure drop across the filter at 1.9 cfm was 8 psi (222 inches). This flow corresponds to the equivalent flow through the small element that a full-scale HEPA filter would see. The full scale filter would have more than 3,800 tubes within the 2' x 2' x 1' filter housing.

Fain has developed a powder nickel filter using the tube design for potential applications as a HEPA filter.[30] The filter has 4 layers of decreasingly smaller powder diameter arranged as in Figure 17: a substrate layer of 55 µm powder, first intermediate layer of 15 µm powder, second intermediate layer of 5µm powder, and a top layer of 0.5 µm powder. The filter technology for making the multi-layer filter was used in the U.S. gaseous diffusion process for separating radioactive isotopes (analogous to the French using the KERASEP filter in the French isotope separation process). We evaluated a prototype module consisting of 10 tubes approximately 11 inches long and that represented 1/64 the capacity of a standard HEPA filter. The full scale HEPA filter would have 676 tubes.

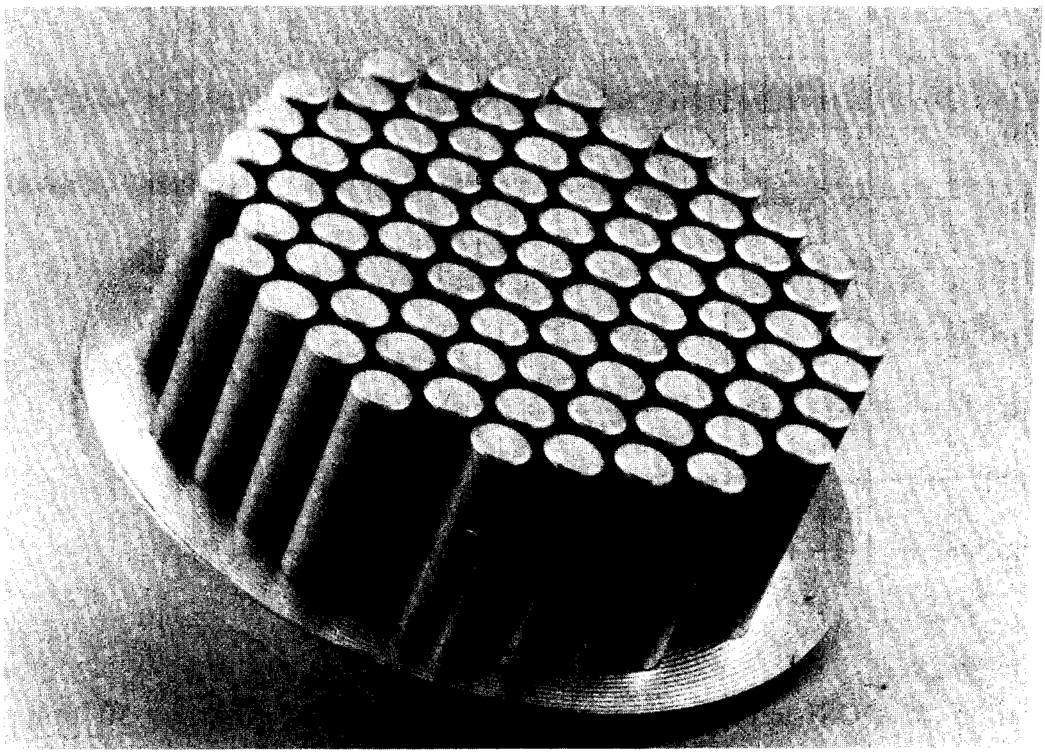


Figure 21. Photograph of sintered stainless steel powder filter from Mott Metallurgical consisting of 85 tube elements. Each tube has a diameter 0.31 inches and is 1.2 inches high.

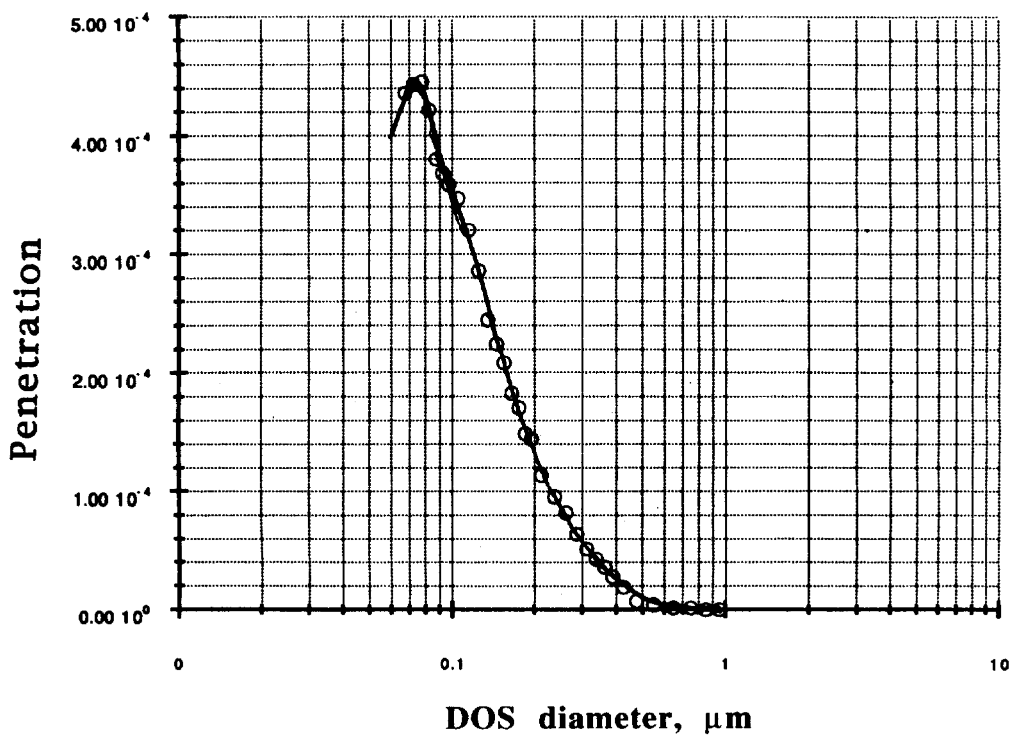



Figure 22. Penetration of DOS aerosols through sintered nickel power filter consisting of 10 tubes. Pressure drop at 15.6 cfm was 38 inches.[30]

Our test results showed the powder nickel filter had very high pressure drop and plugged rapidly with aerosols. Figure 22 shows the penetration of DOS aerosols through the filter as a function of particle size. The penetration at 0.3 µm is 0.00006, which meets the requirements for a HEPA filter. However the pressure drop at 38 inches greatly exceeds the maximum 1 inch. Since the filter pressure drop increased from 38 to 45 inches within 5 minutes of aerosol exposure, we were careful to measure the aerosol penetration for the clean filter within the first 60 seconds before the particle loading could affect the filter penetration. Attempts to reduce the pressure drop by reducing the powder layers is futile as seen with the French KERASEP filter in Figure 19 because the aerosol penetration will increase beyond the maximum 0.0003 at 0.3 µm. Thus we conclude that the sintered powder filters are not a viable competitor of the steel HEPA filter.

The reason why the sintered powder filter cannot compete with the sintered steel fiber filter is the more restrictive structure of the powder filter. Figures 23 and 24 show cross sections of a steel fiber and a steel powder filter respectively. These cross sections are perpendicular to the air flow and represent the environments particles would see at the fixed depth within the filter. Figure 23 shows the fibers occupy a small volume fraction of the filter and result in relatively open region for air and particles to pass. In contrast, Figure 24 shows the powder occupies a large volume fraction and results in a relatively closed region for air and particles to pass.

This difference in fraction of occupied space accounts for the observed differences in filtration performance between the fibrous and powder filters. Because of the open space in a fibrous filter, the average internal air velocity is not much greater than the external air velocity. Particles therefore have a long residence time within the filter and result in high particle capture due to Brownian motion. The relatively few restrictions to the air flow also result in a low pressure drop for the fibrous filter. In contrast, the small volume of open space in the powder filter forces the air to flow at very high velocities through the powder filter matrix. The high velocity forces the particles through the filter very quickly with little residence time for Brownian motion to capture the particles. A high pressure drop is also required to force the air flow through the small open areas of the filter.

We have measured the aerosol penetration and the pressure drop through a sintered powder and fiber filter having the same powder or fiber dimension to illustrate the difference between the two filters. Figure 25 shows the resulting penetration of DOS aerosols and the pressure drop through a sintered powder filter made from 5 µm steel powder and a sintered fiber filter made from 5 µm steel fibers. We see that the powder filter has a much higher aerosol penetration and a higher pressure drop than the fiber filter. Note also that the peak aerosol penetration occurs at 0.17 µm for the fiber filter and at 0.11 µm for the powder filter. The shift in maximum penetration to smaller particle sizes with increasing filtration velocity is well known in the field and occurs because of lower residence time and the resulting decrease in Brownian capture.

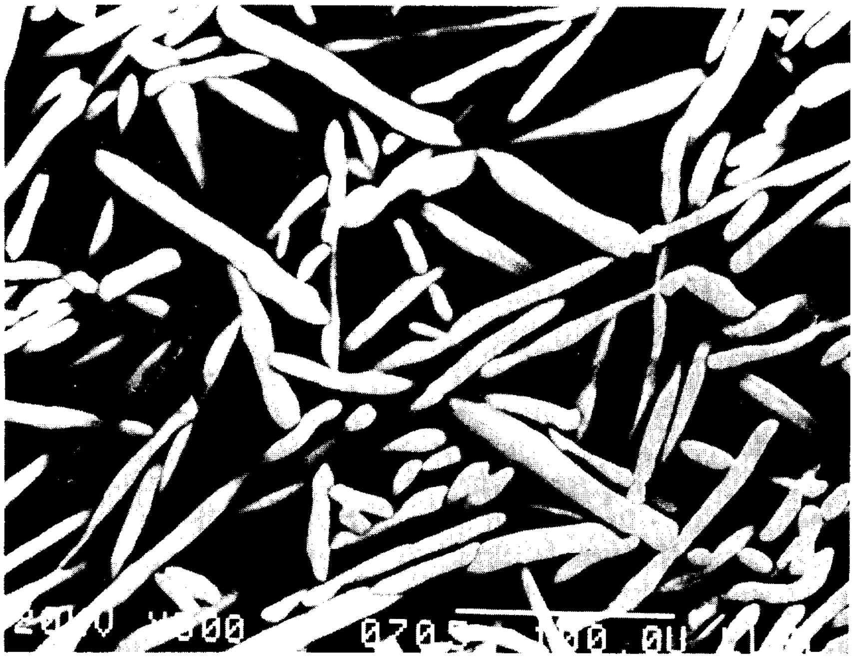


Figure 23. Electron micrograph of a cross section of a steel fibrous filter in a plane perpendicular to the air flow.

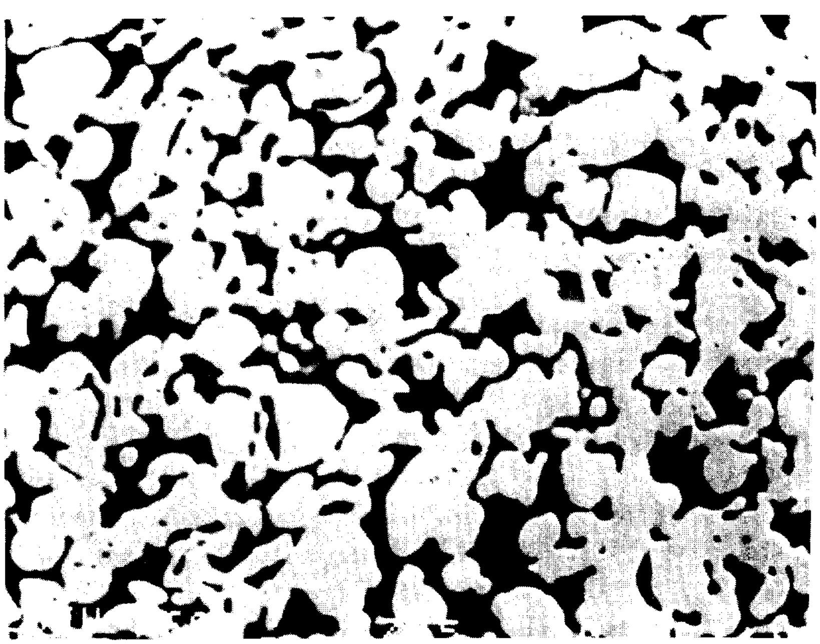


Figure 24. Electron micrograph of a cross section of a steel powder filter in a plane perpendicular to the air flow.

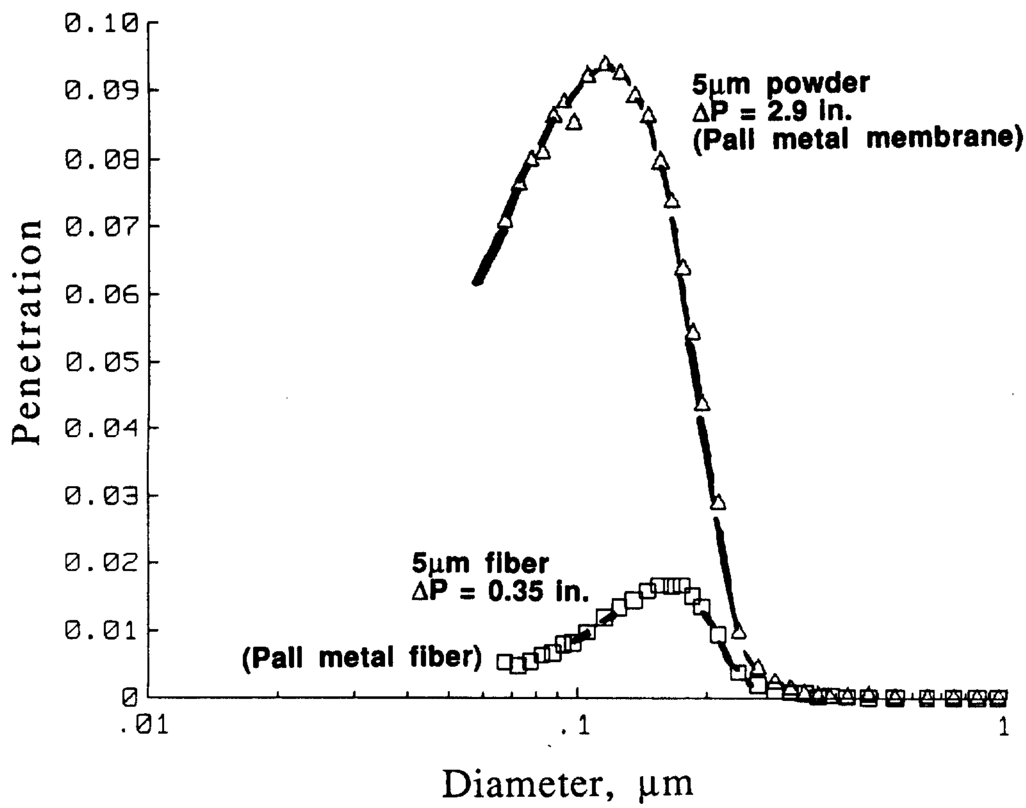



Figure 25. Penetration of DOS aerosols through sintered fiber filter made from 5 µm steel fibers and sintered powder filter made from 5 µm steel powder tested at 1.25 cm/s.

Another technology that we reviewed for potential application as a cleanable HEPA filter was ceramic fiber filters. These filters would have the same geometry advantages as the steel fiber filter. However ceramic fiber filters do not appear promising as a candidate for cleanable HEPA filters for several reasons. One of the major problems is the large diameters of most ceramic fibers. As seen in Figure 4, it is necessary to have fibers substantially less than 1.0 µm diameter to be considered for use as a HEPA filter. One of the smallest diameter ceramic fibers are the Saffil (ICI, England) aluminia fibers shown in Figure 26. These fibers range from 2-4 µm and are available in felts, although sheets could be made in the wet paper making process. We measured the penetration of DOS aerosols on the Saffil felt and found the filter has an unacceptable high penetration for consideration as a HEPA filter. Figure 27 shows the penetration at 0.3 µm is 0.33 and the pressure drop is 0.49 inches at a velocity of 4 cm/sec. Even with two layers, the penetration would only drop to 0.10 while the pressure drop increases to 0.98 inches.

Assuming that ceramic fibers smaller than 1 µm become available, the resulting filter media would be too brittle to be used as a cleanable HEPA filter. The fibers would have to be either sintered together or bonded together with a ceramic glue, both of which would result in easilv fractured media. Using an organic binder as done with glass HEPA filters would allow the media to be flexible for pleating, but would not withstand the high temperature. We do not believe that the ceramic fiber media in flat sheets would have the required strength to survive repeated cleanings.

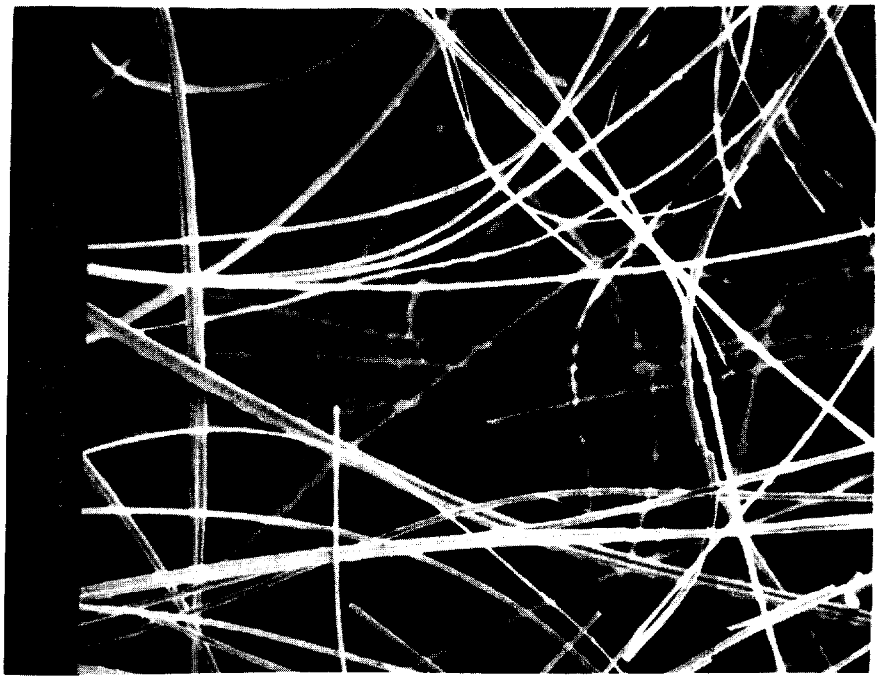


Figure 26 . Electron micrograph of Saffil alumina fiber media.

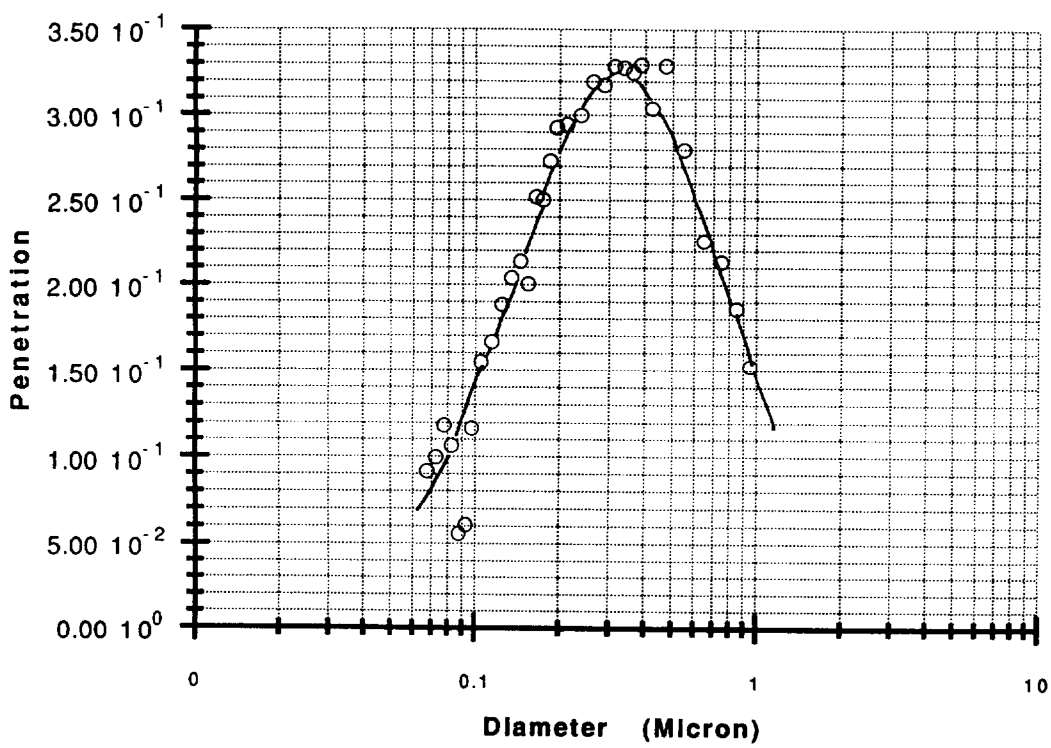



Figure 27. Penetration of DOS aerosols through Saffil alumina fiber medium at 4 cm/s. Pressure drop was 0.49 inches.

The final potential candidate for a cleanable HEPA filter that we reviewed is the reinforced glass fiber HEPA filter.(31) This filter has a glass scrim laminated on the back of the HEPA media to provide extra strength to the medium. Test results have shown the reinforced media is very effective in preventing filter blow out during heated air and water exposure tests.(31) However, the filter was designed to withstand a single accident condition and not for repeated cleanings by reverse air pulses. To survive repeated reverse air pluses, the glass HEPA medium should have glass scrim laminated on both sides of the medium. Without this reinforcement, the glass fiber medium could be blown out. Although a HEPA filter with a single layer of reinforced medium can meet the one inch pressure drop requirement, it is not known whether the same holds for two layers. In addition, tests need to be conducted to establish that the reinforced glass fiber filter can be repeatedly cleaned as was demonstrated for the steel fiber filter in Figure 9 for the single cartridge and in our previous report for the full scale HEPA filter.(14) Other cleaning methods such as liquid washings also have to be evaluated for those applications where reverse air pulses are not effective. Since a cleanable glass HEPA filter is expected to cost about $500 compared to $5,000 for a cleanable steel HEPA filter, the reinforced glass HEPA filter has the potential to be a viable candidate for the cleanable HEPA filter.

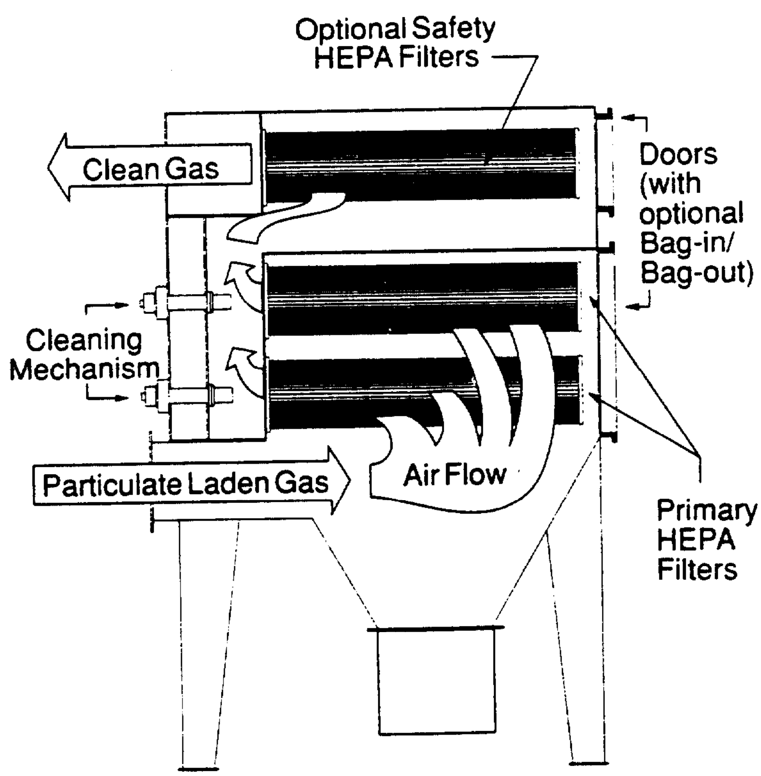



Figure 28. Cleanable HEPA filter using reinforced glass HEPA medium and manufactured by MAC Environmental.(33)

Cleanable HEPA filters using the standard and the reinforced glass fiber HEPA medium and a gentle reverse air pulse are being developed for various applications.[32,33] Leibold et al have described the use of reverse air flows in the pockets of deep pleated HEPA filters to dislodge particle deposits for renewing clogged HEPA filters.[32] They were able to clean standard, deep-pleated HEPA filters using several different dusts. Morgan described a cleanable HEPA filtration system using HEPA filters with reinforcement scrim on both sides of the HEPA media.[33] The commercially available unit uses cylindrical cartridge HEPA filters in a conventional blow-back air cleaning unit. Figure 28 shows the commercially available cleanable HEPA filter system manufactured by MAC Environmental (Kansas City, MO). This system functions in a similar to the cleanable steel HEPA filter system shown in Figure 1.

## VI. Conclusion

We have made further progress in developing a cleanable steel fiber HEPA filter. We fabricated a pleated cylindrical cartridge using commercially available steel fiber media that is made with 1 μm stainless steel fibers and sintered into a sheet form. Test results at the DOE Filter Test Station at Oak Ridge show the prototype filter cartridge has 99.99% efficiency for 0.3 μm dioctyl phthalate (DOP) aerosols and a pressure drop of 1.5 inches. Filter loading and cleaning tests using AC Fine dust showed the filter could be repeatedly cleaned using reverse air pulses. We also produced 0.5 μm steel fibers using the fiber bundling and drawing process and sintered the fibers into small filter samples. Test results on the sample showed a penetration of 0.0015 % at 0.3 μm and a pressure drop of 1.15 inches at 6.9 ft/min (3.5 cm/s) velocity. Based on these results, steel fiber media can easily meet the requirements of 0.03 % penetration and 1.0 inch of pressure drop by using less fibers in the media.

A cost analysis of the cleanable steel HEPA filter shows that, although the steel HEPA filter costs much more than the standard glass fiber HEPA filter, it has the potential to be very cost effective because of the high disposal costs of contaminated HEPA filters. We estimate that the steel HEPA filter will save an average of $16,000 over its 30 year life. The additional savings from the clean-up costs resulting from ruptured glass HEPA filters during accidents was not included but makes the steel HEPA filter even more cost effective.

We also present the results of our evaluation of competing technologies with metallic and ceramic powder filters, ceramic fiber filters, and reinforced glass fiber filters. In general, the metallic and ceramic powder filters have pressure drops in excess of 25 inches of water for HEPA grade efficiencies and are therefore not viable candidates. The ceramic fiber filters cannot meet the HEPA efficiency because the fiber diameters are too large. The reinforced glass fiber filter is a promising candidate for the cleanable HEPA filter but requires additional development and testing to confirm its potential to be repeatedly cleaned.

## VII. References

1. Bergman, W, Larsen, G, Lopez, R, Wilson, K, Witherell, C, and McGregor, M, “Feasibility demonstration of a steel HEPA filter,” in Mixed Waste Integrated Program, Mid-Year Technical Review, Volume 5, Off-Gas Treatment, Available from DOE, EM-50, 1000 Independence Ave, Washington, DC 20585, Document WPI.94-0159-5, April 21, (1994).

2. Bergman, Werner “Requirements for a cleanable steel HEPA filter derived from a systems analysis” Lawrence Livermore National Laboratory Report UCRL-ID-125048, Available from NTIS, 5285 Port Royal Rd, Springfield, VA 22161, June (1996).

3. Ziegler, D.L., and Johnson, A.J., “Disposal of HEPA filters by fluidized bed incineration” in Proceedings of 15th DOE Nuclear Air Cleaning Conference, CONF-780819, NTIS, Springfield, VA 22161, pp.111-116, (1979).

4. Kirstein, B.E., Paplawsky,W.J., Pence,D.T., and Hedahl, T.G., “High efficiency particulate removal with sintered metal filters” in 16th DOE Nuclear Air Cleaning Conference, CONF-801038, pp. 719-744, (1981).

5. Bergman, W., “Comments to paper by Kirstein” in 16th DOE Nuclear Air Cleaning Conference, CONF-801038, pp. 742-744, (1981).

6. Dillmann, H.G., and Pasler, H., “Experimental investigations of aerosol filtration with deep bed filters” in Proceedings of 17th DOE Nuclear Air Cleaning Conference, pp. 1160-1174, CONF-820833, (1983).

7. Dillmann. H.G., and Pasler, H., “ A filter concept to control airborne particulate release due to severe reactor accidents and implementation using stainless-steel fiber filters” in Proceedings of 18th DOE Nuclear Air Cleaning Conference, pp. 1417-1428, CONF-840806, (1985).

8. Klein, M., and Goossens, W.R., “ Aerosol filtration with metallic fibrous filters” in Proceedings of 17the DOE Nuclear Air Cleaning Conference, pp 504-522, CONF-820833, (1983).

9. Randhahn, H., Gotlinsky, B., and Tousi, S., “The development of all metal filter for use in the nuclear industry” in Proceedings of 20th DOE/NRC Nuclear Air Cleaning Conference, CONF-880822, pp 726-748, (1989).

10. Bergman, W.,” Evaluation and modification of commercial sintered metal filters” LLNL memorandum, July 7, (1989).

11. Kaercher, M.V., “Design of a prefilter to improve radiation protection and filtering efficiency of the containment venting system” in Proceedings of the 22nd DOE/NRC Nuclear Air Cleaning and Treatment Conference, pp 443-452, CONF-9020823, (1993).

12. Bergman, W., Conner, J., Larsen, G., Lopez, R., Turner, C., Valha, G., Violet, C., and Williams, K., “High efficiency steel filters for nuclear air cleaning” , in Proceedings of 21st DOE/NRC Nuclear Air Cleaning Conference, CONF-900813, pp. 733-761, (1991).

13. Bergman, W., “Cleanable steel HEPA filters” in Environmental Technology Program Annual Report FY90, pp.44-47, Lawrence Livermore National Laboratory report UCRL-LR-105199, January 2, (1991).

14. Bergman, W., Larsen, G., Weber, F., Wilson, P., Lopez, R., Valha, G., Conner, J.. Garr, J., Williams, K., Biermann, A., Wilson, K., Moore, P., Gelner, C., Rapchun, D., Simon, K., Turley, J., Frye, L., and Monroe, D., "Development and Evaluation of a Cleanable High Efficiency Steel Filter" in Proceedings of the 22nd DOE/NRC Nuclear Air Cleaning Conference, CONF-9020823, PP586-616, July (1993).

15. Bergman, W., Larsen, G., Lopez, R., Wilson, K., Simon, K., and Frye, L., "Preliminary field evaluation of high efficiency steel filters" in Proceedings of the 23rd DOE/NRC Nuclear Air Cleaning and Treatment, CONF-940738 , pp 195-213, February , (1995).

16. Kruger, O.L., “Hanford Waste Vitrification Plant Applied Technology Plan”, WHC-EP-0417, January (1992).

17. Procurement Specification, Filter, High Efficiency Metal, W-320-P3, January 24, (1995).

18. Weber, L., “Pall Technical Brief: HEMF-5, Demonstration of efficiency measurements and in-situ cleaning”Pall Corporation report, December 31, (1992).

19. Weber, L., “Pall Technical Brief: HEMF-6, Study to investigate backwash regenerability and maintenance of integrity by ASHRAE test”, Pall Corporation report, December 31, (1992).

20. Dittman, P., “Cost estimate for steel HEPA filters”, Pall Corporttion, Cortland, NY, May 28, (1996).

21. Moore, P., Bergman, W., and Gilbert, H., "Survey of Life-Cycle Costs of Glass-Paper HEPA Filters" in Proceedings of the 22nd DOE/NRC Nuclear Air Cleaning Conference, Denver, Co, August 24-27, 1992. UCRL-JC-109768, December, (1992).

22. Stepuszek, D and Hirose, J “High performance functinal paper for use as filter media” in Advances in Filtration and Separation Technology, Vol. 7, System Approach To Separation and Filtration Process Equipment. W.W-F Leung, Editor, pp. 111-114, The American Filtration Society, P.O. Box 6269, Kingwood, Texas 77325, April (1993).

23. Tomeogawa High-Performance Sheet, SS, Specification brochure for sintered stainless steel sheeet, Tomeogawa (U.S.A.) Inc., 742 Glenn Avenue, Wheeling, IL 60090 (1993).

24. Flanders Filters Catalog showing separatorless filters likethe Dimple Pleat™ and Super-Flow™ HEPA filters. Bulletins 812 and 871.

25. Air Filter Specifications, Manual No. 5Q1.10, Section 7, Westinghouse Savannah River Company, Savannah River Site, Health Protection Department, (1995).

26. Bergman, W., First, M.W., Anderson, W.L., Gilbert, H., and Jacox, J.W., "Criteria for calculating the efficiency of deep-pleated HEPA filters with aluminum separators during and after design basis accidents" in Proceedings of the 23rd DOE/NRC Nuclear Air Cleaning and Treatment Conference, NTIS, Springfield, VA, CONF-940738 , pp 563-598, February , (1995).

27. Gerster, D. "State of mineral membranes in the world" in the 1986 Fourth Annual Membrane Technology/Planning Conference, W. Shoemaker, Editor, Business Communications Co., Inc,. Norwalk, CT 06855, pp152-159, (1986).

28. Kientz, G "Industrial use of inorganic membranes in the food industry" in Advances in Filtration and Separation Technology, Vol. 8, Filtration and Separation Processes and the Environment, S.K. Sharma, Editor, American Filtration and Separations Society, PO Box 1530, Northport, AL 35476, pp 49-55, (1994).

29. Abrams, R, "High temperature filtration using ceramic membranes" in Advances in Filtration and Separation Technology, Vol. 8, Filtration and Separation Processes and the Environment, S.K. Sharma, Editor, American Filtration and Separations Society, PO Box 1530, Northport, AL 35476, (1994)

30. Fain, DE "Inorganic membrane cleanable HEPA filter" in Mixed Waste Integrated Program, Mid-Year Technical Review, Volume 5, Off-Gas Treatment, Available from DOE, EM-50, 1000 Independence Ave, Washington, DC 20585, Document WPI.94-0159-5, April 21, (1994).

31. Gilbert, H., Bergman, W., and Fretthold, J. "Development and evaluation of a HEPA filter for increased strength and resistance to elevated temperature." in Proceedings of the 22nd DOE/NRC Nuclear Air Cleaning Conference, Denver, Co, August 24-27, 1992. LLNL report UCRL-JC-110582, January, (1993).

32. Leibold, H., Doffert, I., Leiber, T., and Wilhelm, J.G., "The application of HEPA filter units in gas streams of high dust concentrations" in Proceedings of the 22nd DOE/NRC Nuclear Air Cleaning Conference, Denver, Co, August 24-27, 1992, pp 540-553, CONF-9020823, NTIS, Springfield, VA, July, (1993).

33. Morgan, L, "Ultra high efficiency dust collection" pp 30-32, in Filtration News, Vol, 12, No. 4, July/August (1994).

## DISCUSSION

**WILHELM:** Who is producing 1$\mu$m diameter metallic fibers and what is the form in which it is delivered?

**BERGMAN:** Tomeogawa, a Japanese firm, produces the 1 $\mu$m stainless steel fiber media in sintered sheets. We obtained our supply from Tomeogawa (USA), Inc., Wheeling, IL.

**TSENG:** With any fiberized material there will be a lower limit to diameter based on practical considerations of material stability. What would be the smallest diameter in stainless steel, and how would you compare it to glass?

**BERGMAN:** I thought that when we had reached 2$\mu$m that we were getting close to the limit, but at this point I do not know the lower limit. We made 0.5$\mu$m fibers, and 0.1$\mu$m is not unreasonable. Glass fibers are commercially available at 0.1 - o.2$\mu$ diameters.

**TSENG:** With metals there is a crystalline structure and once you get down to a fiber diameter of the order of a grain boundary, you have problems. I do not know where the limits are, I was hoping you could enlighten me.

**BERGMAN:** I do not have the answer. As far as I am concerned, there is no limit except for time, money, and effort.

**WEBER:** What about glass fiber diameter?

**BERGMAN:** You can buy glass fibers down to 0.1$\mu$m.

**BLACKLAW:** What are the other important parameters in development of alternatives; for example, strength and corrosion?

**BERGMAN:** The strength of the steel media is due to inherent strength of the steel fibers plus the fiber-to-fiber bonds from sintering. In contrast, glass fiber media is not as strong because the fibers are held together with an organic binder, which is not only weaker, but also subject to more failure modes. However corrosion in the 300 series steels is a serious concern and one of the areas we have not studied. Corrosion resistant steels such as Hastalloy and Inconel would work, but they are only available in diameters greater than 8$\mu$m. The diameter of the Hastalloy and Inconel fibers would have to be reduced to less than 1 $\mu$m for use as HEPA filter media.

**ENGELMANN:** How flammable is it?

**BERGMAN:** The loose steel fibers are extremely flammable and will ignite spontaneously when dispersed in air. However, the sintered steel fiber media will not burn even with a flame directed on it. Direct flames will destroy the media by converting the steel alloy to oxides, which flake and crumble.