

# **Nanofibers in Filtration Applications in Transportation**

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## **ABSTRACT**

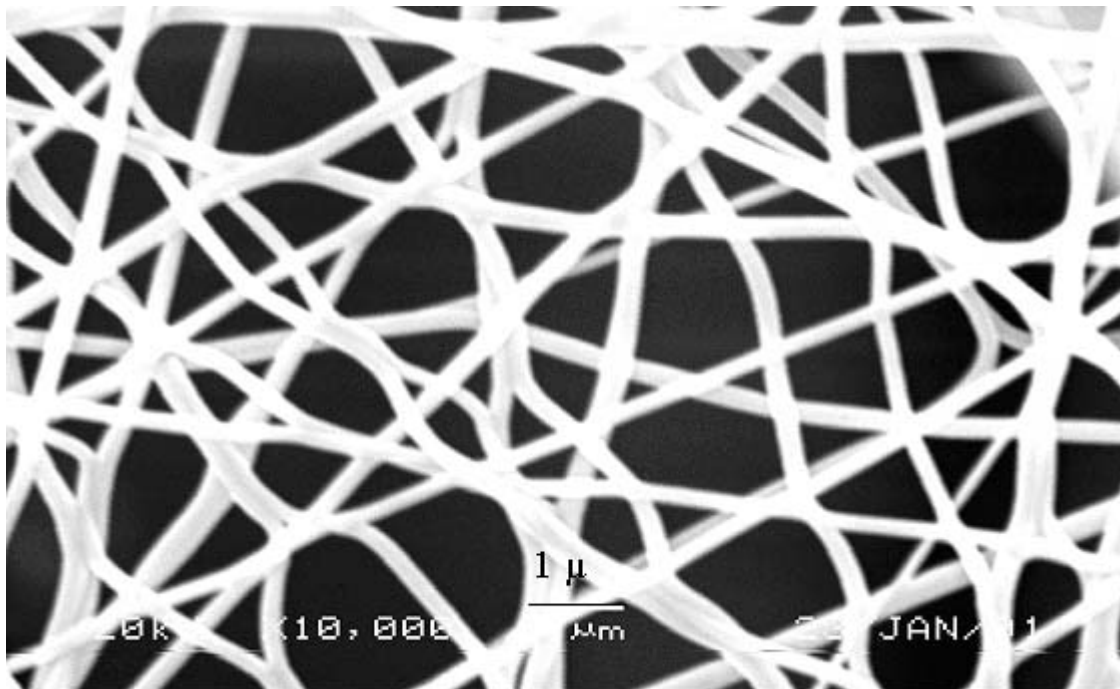
*Nanofiber* is a broad phrase generally referring to a fiber with a diameter less than 1 micron. While glass fibers have existed in the sub-micron range for some time and polymeric meltblown fibers are just beginning to break the micron barrier, Donaldson Company has used Ultra-Web<sup>®</sup> nanofibers with sub-half-micron diameters for air filtration in commercial, industrial and defense applications for more than twenty years. Nanofiber filter media have enabled new levels of filtration performance in several transportation applications including internal combustion engines, fuel cells and cabin air filtration. The broad range of environments and contaminants encountered by engines in various applications illustrates the capabilities of nanofibers.

This paper will discuss the construction and performance of filter media using nanofibers. In particular, nanofibers provide marked increases in filtration efficiency at relatively small (and in some cases immeasurable) decreases in permeability. In many laboratory tests and actual operating environments, nanofiber filter media have longer life and more dust holding capacity than conventional media.

The use of nanofibers will be discussed in three different applications: (A) engine air filtration for heavy and light duty vehicles; (B) air filtration in a self-cleaning air intake system for a gas turbine powered military tank; and (C) cabin air filtration for mining vehicles.

## **NANOFIBER FILTER MEDIA**

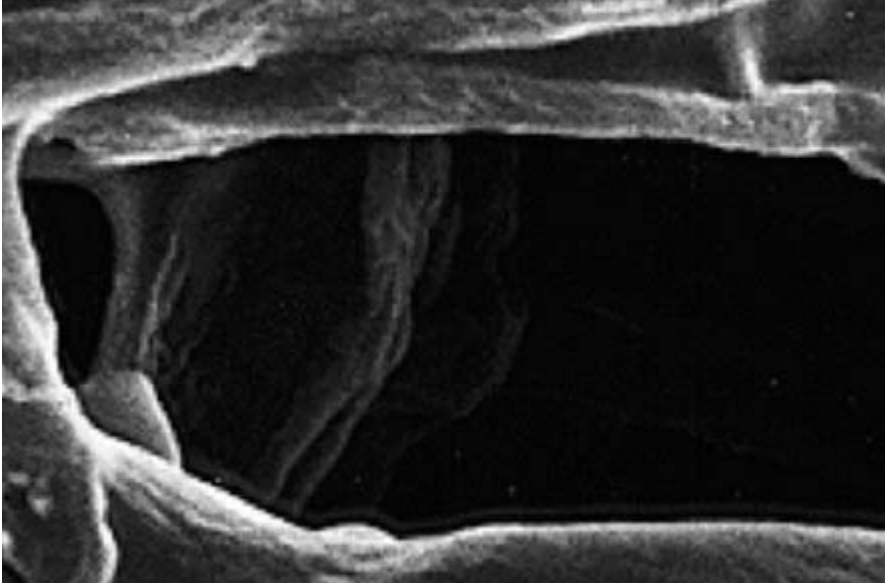
Polymeric nanofibers have been made with fiber diameters less than 0.5 microns (Figure 1). These nanofibers can be formed into a web (sometimes called a nanoweb). In many cases, it is desirable to have a very thin web consisting of just a few nanofiber diameters thick. The thickness of the nanoweb can be less than 1-5 microns. While the thinness of the nanoweb provides high permeability to flow, the nanoweb has limited mechanical properties that preclude the use of conventional web handling and filter pleating equipment.



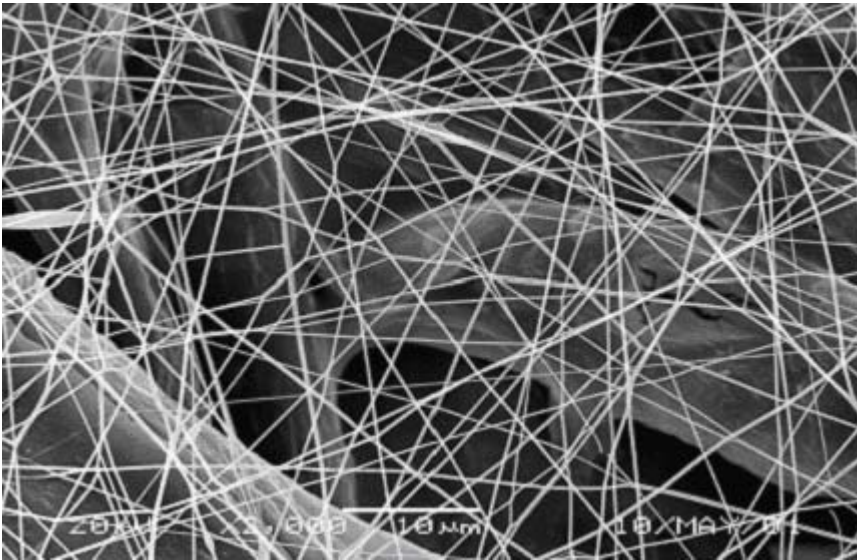
*Figure 1 Nanofiber filter media shown at 10,000 times magnification. Fiber diameter ranges from 0.3 – 0.4 microns.*

Nanofiber webs have been applied onto various substrates. These substrates can be selected to provide appropriate mechanical properties to allow pleating, filter fabrication, durability in use, and in some cases, filter cleaning. In many cases, substrates have been selected which resemble conventional filter materials. This allows the use of conventional filter media pleating equipment. In addition, the substrate can serve as a safety filter in case of inadvertent damage to the nanofiber layer during use.

The following scanning electron microscope (SEM) photographs show conventional cellulose filter media manufactured using a wet-laid process (Figure 2) and a nanofiber filter media consisting of polymeric nanofibers on a cellulose substrate (Figure 3). In both cases the filter media has a basis weight of about 70 lbs. / 3000 ft<sup>2</sup> (110 grams / m<sup>2</sup>). While the nanofibers add a nearly imperceptible amount of mass to the substrate, the filtration characteristics are notably changed.



*Figure 2. SEM micrograph of conventional filter material for engine air cleaner applications. Material is wet laid cellulose with a basis weight of 70 lbs. / 3000 ft<sup>2</sup> (110 grams / m<sup>2</sup>).*



*Figure 3. SEM micrograph of nanofiber filter media. The nanofibers are deposited on a wet laid cellulose substrate. The material has a basis weight of 70 lbs. / 3000 ft<sup>2</sup> (110 grams / m<sup>2</sup>).*

## THE EFFECT OF NANOFIBERS ON FUNDAMENTAL FILTRATION PROPERTIES

It is well known that particle filtration occurs via multiple collection mechanisms including sieving, direct interception, inertial impaction, diffusion and electrostatic collection.[1] For practical purposes, sieving is not an important mechanism in most air filtration applications. Commercially available nanofibers are electrically neutral. As a result, the remaining mechanisms of importance in mechanical filtration are direct interception, inertial impaction and diffusion. The mathematical description of filter media is complex. However, reasonable approximations of media performance have been made using single fiber filtration theory.

The single fiber efficiency for *direct interception*  $E_R = (D_P/D_F)^2 / Ku$

Where  $D_P$  is the particle diameter,  $D_F$  is the fiber diameter and  $Ku$  is the Kuwabara constant. As can be seen, filtration efficiency due to direct interception  $E_R$  is inversely proportional to the square of the fiber diameter.

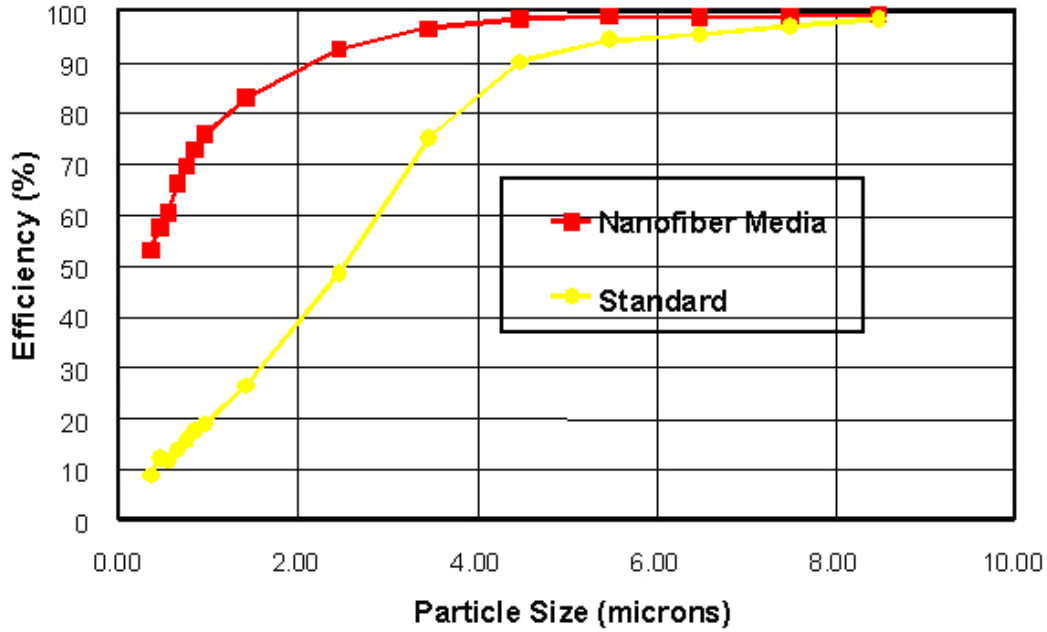
The single fiber efficiency for *inertial impaction*  $E_I \propto St / (2Ku^2)$

Where  $St$  (Stokes Number) =  $S_D / D_F$  and where  $S_D$  is the Stopping Distance. As can be seen, filtration efficiency due to inertial impaction  $E_I$  is inversely proportional to the fiber diameter.

The single fiber efficiency for *diffusion*  $E_D$  is  $E_D = 2.7 / (Pe)^{2/3}$

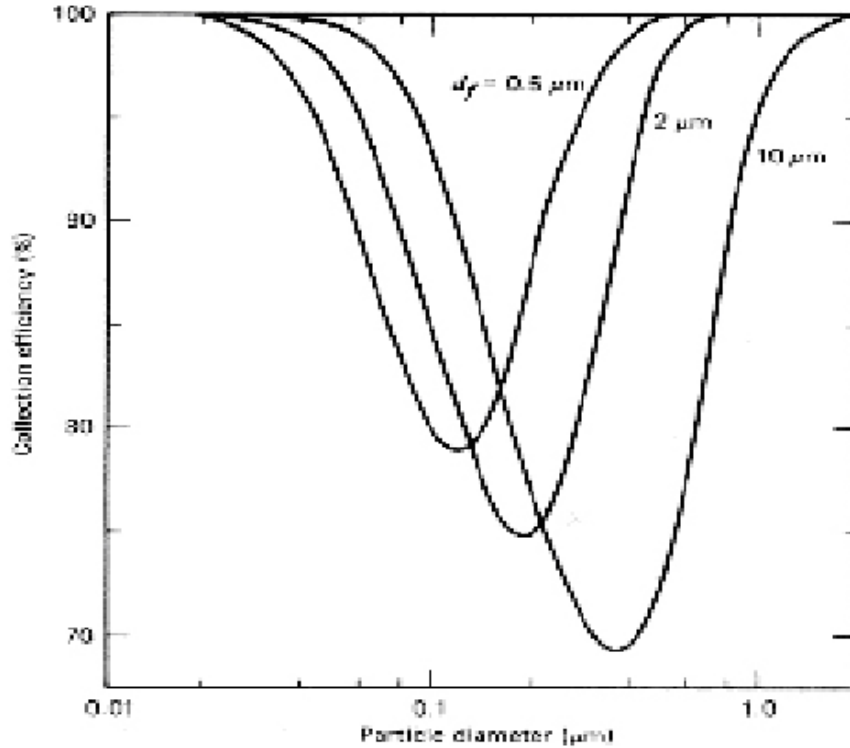
Where  $Pe$  is the Peclet number and is defined as  $Pe = D_F U / D$  and where  $U$  is velocity and  $D$  is the coefficient of diffusion. As with the other filtration mechanisms, decreasing fiber diameter increases filtration efficiency due to diffusion.

These effects of increasing filtration efficiency can be observed experimentally by measuring filter efficiency as a function of particle size (Figure 4).



*Figure 4. Fractional efficiency (Filtration Efficiency vs. particle size) for a standard cellulose media and nanofiber filter media.*

Combining the 3 dominant filtration mechanisms and plotting results in a graph of Efficiency versus Particle Size illustrate that there is a most penetrating particle size (MPPS). As Figure 4 illustrates, decreasing fiber size in a filter media (designed for the same pressure drop) provides for improvement in the MPPS situation. The use of nanofiber filter media shifts the MPPS to smaller sizes while simultaneously increasing the efficiency for all particle sizes.

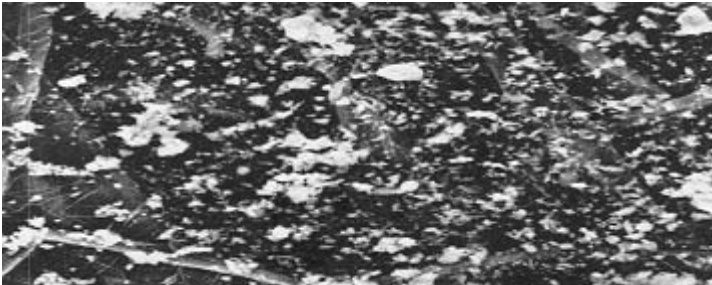


*Figure 5. Fractional Efficiency and Most Penetrating Particle Size (MPPS) for various filter media constructed with various fiber diameters. Filter media permeability is the same in all cases. The use of smaller fibers leads to a reduction in MPPS and a general increase in efficiency for all particle sizes.*

The increased filtration efficiency due to nanofibers has been shown from classical filtration equations and fractional efficiency testing. The filtration merits of nanofibers can also be shown visually using scanning electron microphotographs. The following microphotographs show conventional cellulose filter media (Figure 6) and a nanofiber filter media with a cellulose substrate (Figure 7). Both media samples were loaded with the same amount of ISO fine test dust. (ISO fine test dust is commonly used for testing engine air cleaners, and contains particles in size ranges from 0.7 – 70 microns.)

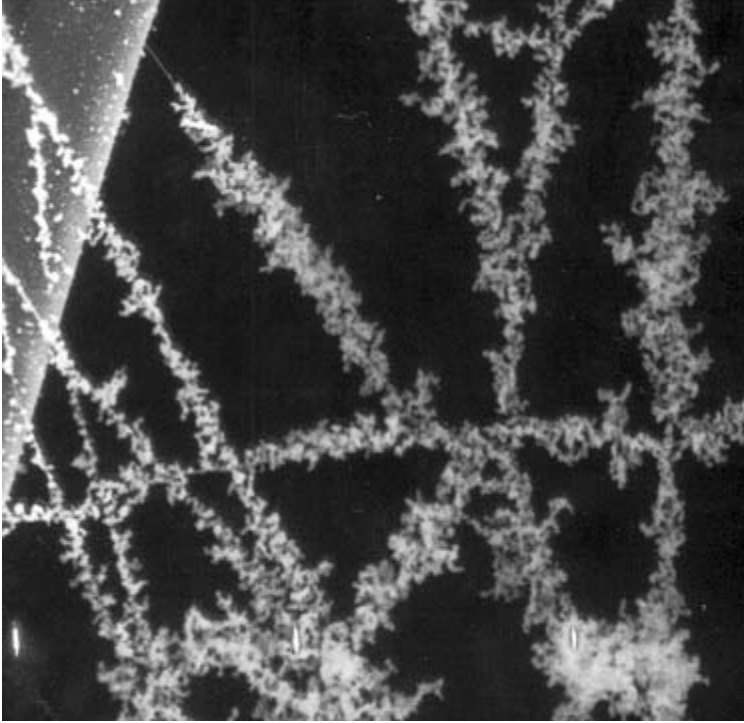


*Figure 6 SEM micrograph of conventional filter material for engine air cleaner applications loaded with ISO fine test dust.*



*Figure 7 SEM micrograph of nanofiber filter media for engine air cleaner applications loaded with ISO fine test dust. Note the retention of small particles on the nanofiber layer.*

The particle removal capability of nanofibers versus larger fibers is shown in the following microphotograph (Figure 8).



*Figure 8. SEM photograph showing the collection of sodium chloride crystals sized from 0.01 to 0.50 microns collected on sub-half-micron nanofibers. For reference, the diameter of the large synthetic fiber in the upper left corner is about 15 microns.*

## FILTRATION APPLICATIONS IN TRANSPORTATION USING NANOFIBERS

Nanofiber filter media has been used in several applications. Three applications will be discussed that illustrate the range of nanofiber usage.

### A. Engine Filtration: Heavy duty and light vehicle engines

For most engine air filters, the function of the filter and the corresponding engine wear are based largely on dust cake filtration. The formation of a dust cake on the filter media changes many important factors in the function of a filter media, including filtration efficiency and pore size distribution.[2] Engine wear rate has been shown to be significant during the early portion of an air filter's design life (Figure 9).

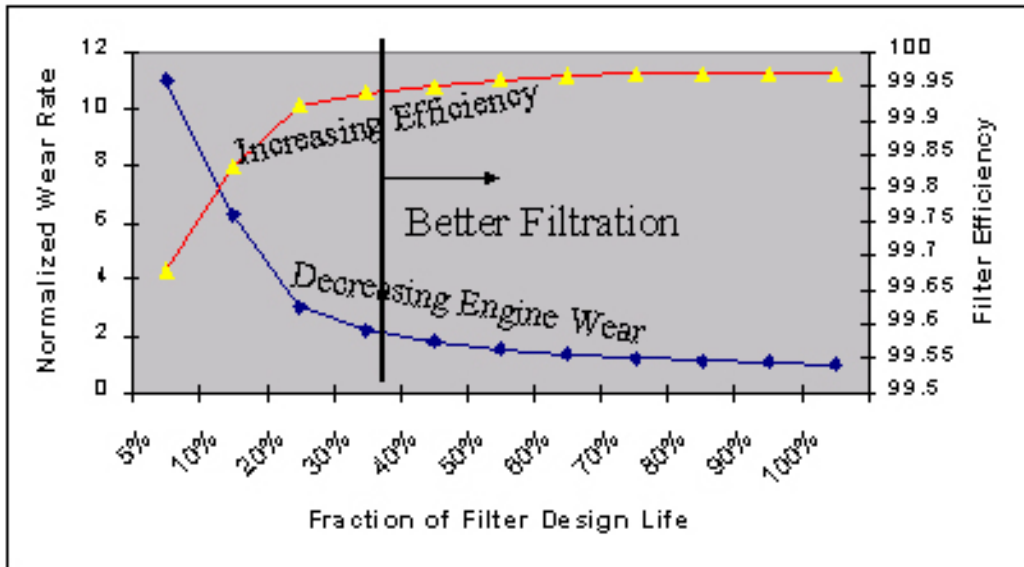


Figure 9. Engine Wear Rate and Filter Efficiency as a fraction of filter life obtained.

While vehicle manufacturers are specifying longer life air cleaners and longer maintenance intervals, the actual service interval for air filters varies widely depending on the sophistication of the vehicle end-user and the maintenance staff. The most sophisticated end-users are large fleet operators with several thousand vehicles. Air cleaner maintenance is typically performed based on filter restriction using a restriction indicator on the vehicle. Maintenance decisions are largely made based on economic factors, and trained personnel provide oversight on maintenance intervals and filter

selection. The decisions are based on a complex interaction of factors, including filter design and efficiency, filter maintenance interval, filter and service cost, and engine wear rate.[3]

The use of nanofiber filter media has provided extended service life in a variety of on-road and off-road applications. In mining applications, nanofiber filters have provided 4 times the filter life.[4] In on-road applications, nanofiber filters are available with twice the filter life of conventional cellulose filters.[5] The life increases observed with nanofiber filters are more pronounced in applications with sub-micron contaminants from engine exhaust and industrial processes.

Consumers must also make maintenance decisions about the air filters in their cars. This user group is relatively unsophisticated in their knowledge of filter maintenance and function. Air filters are perhaps the most easily serviced but least understood parts on a vehicle. Other common replacement parts on a vehicle such as tires, wiper blades, oil and oil filters work best when new. However, this is not the case with conventional air filters. Since most air filters rely on the formation of a dust cake to improve the performance of a filter media, over-servicing can lead to dire consequences from inadequate engine protection. [6]

Air filter over-servicing is common for light vehicles. Light vehicles are generally not equipped with filter restriction indicators. Air filters are often inspected by maintenance personnel during oil changes. In spite of the typical manufacturer's recommendation of at least a 30,000-mile change interval, it is common for dealers, service stations and quick lube businesses to recommend more frequent air filter changes. Given the frequency of oil changes and air filter replacements at quick lubes, it is expected many light vehicle air filters are changed much more frequently than manufacturers recommend. [7]

While this over-servicing phenomenon is frustrating to those who understand filter media performance, the filter industry has not sufficiently educated customers how air filters function. Not surprisingly, filter manufacturers, distributors, dealers, service stations, and quick lubes have economic incentives to change and sell more air filters. It is also understandable that consumers believe air filters work best when they are new (like other parts) and have a clean appearance.

In spite of the best intentions of automotive mechanics and consumers, typical automotive air filters are notably inefficient at capturing particles less than 5 microns in size. Several studies have shown that particles between 1-5 microns cause engine wear, which will lead to increased engine emissions and shorter engine life. [2,8,9] Because many car engine air filters are over-serviced, a typical automotive filter may operate for most of its life without the protective benefits of a well-developed protective dust cake. As the filter becomes dirty by visual appearance (and the dust cake finally starts working) the filter is often exchanged.

The use of nanofiber filter media in engine air filters can solve the problems of over-servicing and can provide the customer a filter which works well (i.e., is satisfactorily efficient at removing particles greater than 1 micron) when new. The nanofiber layer acts to improve initial efficiency as a surrogate for a dust cake. The low additional pressure drop of the nanofiber layer does little to impair engine power or fuel economy. A nanofiber filter works as a customer intuitively expects: it provides full protection with maximum engine performance when new. A filter with nanofiber media also works in concert with the economic incentives of filter suppliers and maintenance providers to service air filters frequently (i.e. over-servicing does not lead to dire consequences).

#### B. Nanofibers in Pulse-Jet Air Cleaner systems for turbine engines

Nanofiber filter media has been also applied to air cleaners for gas turbines. A gas turbine engine is used on the M1 Abrams tank (Figure 10). Turbine engines require more combustion air per horsepower than piston engines. The combination of high air flow rates, high dust loading conditions in environments that include deserts, and the reliability requirements of military vehicles, have led to development and use of self-cleaning systems using pulse-jets and nanofiber filter media for several years.



*Figure 10. M1 Abrams tank with pulse-jet air cleaner and nanofiber filter system for filtration of the turbine combustion air.*

The previously discussed benefits of nanofiber filter media (higher filtration efficiency with minimal pressure drop increase) are also important in this application. However, the

nanofiber layer provides another important benefit in self-cleaning applications. When positioned on the upstream face of the filter, nanofibers significantly enhance the ability of the pulse-jet cleaning system to dislodge dust from the filter surface (Figure 11). This same combination of surface loading nanofiber media with pulse-jet cleaning has been successfully used in several industrial filtration applications such as dust collection.

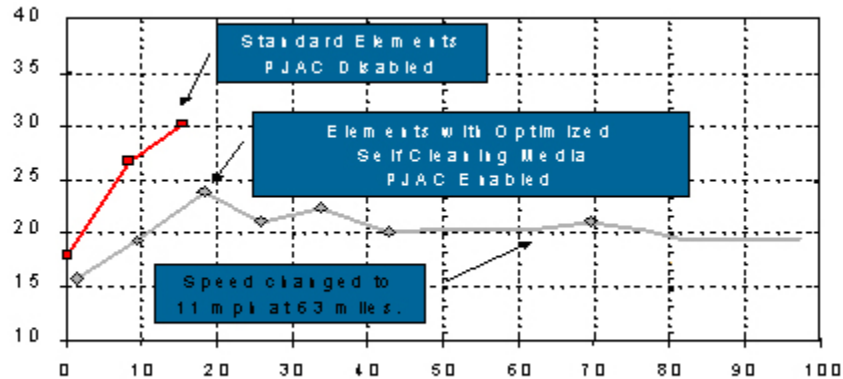


Figure 11 Air cleaner pressure drop versus miles traveled in 20 mph convoy test in desert conditions.

### C. Nanofiber Filter Media in Cabin Filtration of Mining Vehicles

Airborne contamination in the personnel cabins of mining equipment is of concern to mining workers, mining companies and government agencies such as the Mine Safety and Health Association (MSHA). Recent work with mining equipment manufacturers and the MSHA has shown that nanofiber filter media can reduce cabin dust concentration compared to standard (cellulose) filter media. [10]

Nanofiber media has proven beneficial when used in either or both the intake filter and recirculation filter. The use of nanofiber filter media allows for high efficiency filtration at high airflow rates (due to the low additional pressure drop) which makes recirculation of air in the vehicle cabin effective. Figure 12 illustrates the cabin clean-up rate using various combinations of filter media.

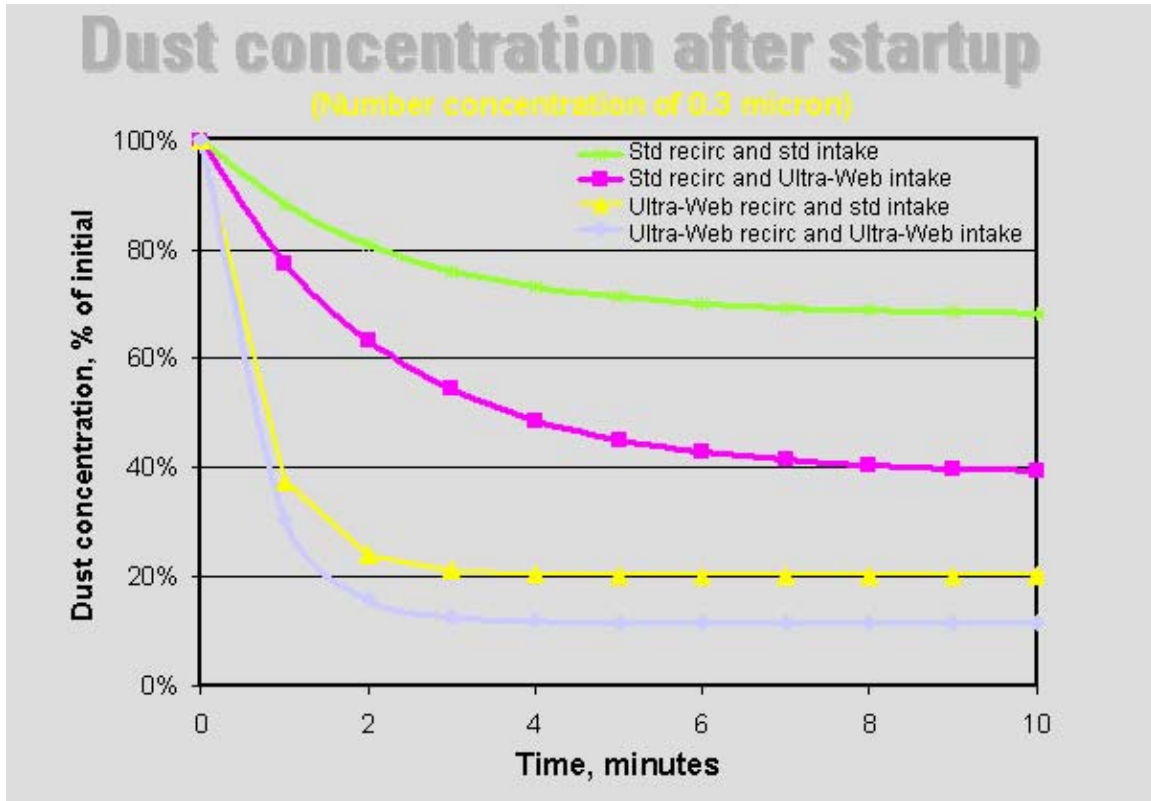


Figure 12. Dust concentration (0.3 microns) in a mining vehicle as a function of time during a cabin cleanup study with various filters.

The boost in filtration efficiency was obtained with no measurable increase in pressure drop and no sacrifice in filter life as shown in Figure 13.

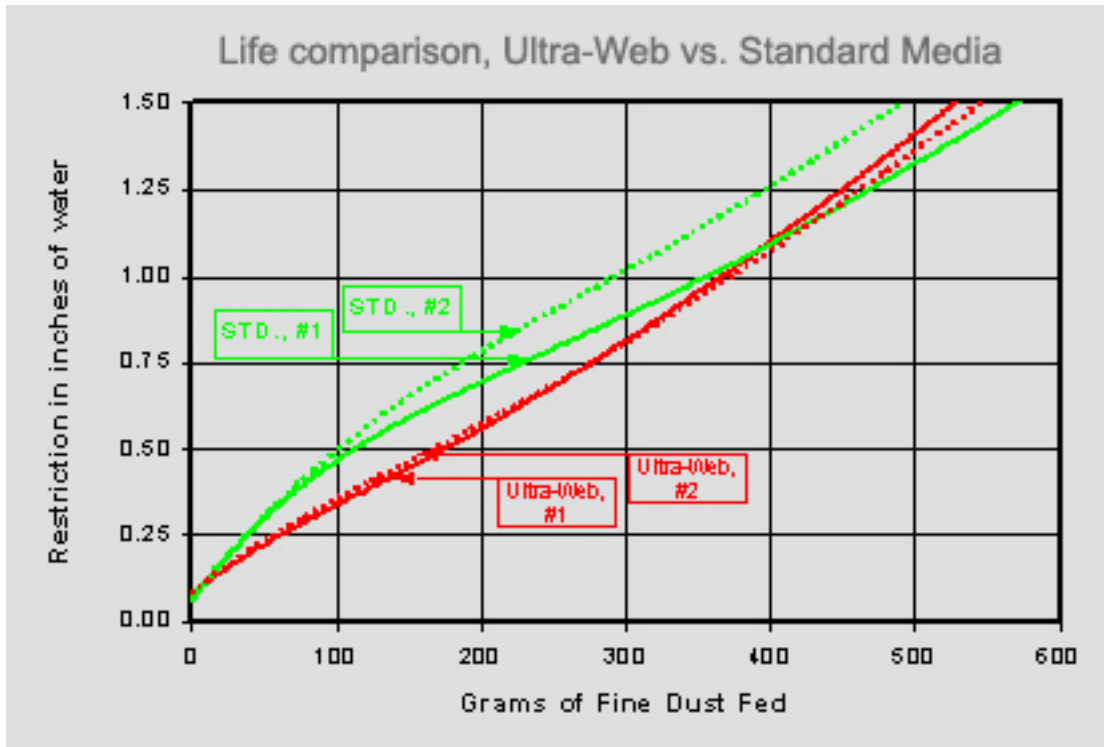


Figure 13. Filter Life in Mining Vehicle Cab: standard media vs. nanofiber media tested using ISO Fine Test Dust

## CONCLUSIONS

Nanofiber filter media has been successfully used in a variety of filtration applications ranging from engine air cleaners to cabin filters for mining vehicles to self-cleaning filter systems for industrial applications and turbine vehicles. Due to the sub-half-micron fiber diameter of nanofibers and the thin nanoweb layer possible, significant boosts in filter efficiency are possible with minimal pressure drop increases.

In both static and self-cleaning filtration applications, nanofiber filter media has demonstrated longer filter life over several conventional filtering materials. Filter engineers are continually balancing the three major technical parameters of filter performance: filter efficiency, pressure drop, and filter life. An improvement in one category generally means a corresponding sacrifice in another category. However, the proper use of nanofibers can provide favorable improvements in both filtration efficiency and life, while having a minimal impact on pressure drop.

It is expected that continued technical development will lead to the use of nanofiber filter media in several new applications including light vehicle engine filters, fuel cells, HVAC filters and liquid filters in the years to come.

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