Multi-Functional Carbon Nanotube Based Filtration Material

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ABSTRACT

As the fibers making up a filter become smaller in diameter, the more efficient the filter is at depth filtration. Seldon Technologies has developed carbon nanotube (CNT) based filtration media (Nanomesh™) that takes advantage of the inherent properties of CNTs (high strength, high surface area, electrical conductivity, etc.). Seldon's Nanomesh™ filters are technically disruptive because the carbon nanotubes they contain represent the ultimate limit in fiber diameter.

Over the past six years, Seldon has demonstrated the feasibility of using its material to clean water, air and fuels. In 2007 Seldon was issued a patent [1] for the filtration of fluids using CNTs. Additionally Seldon has demonstrated that it is possible to produce large quantities of Nanomesh™ on papermaking machines largely using off-the-shelf processing equipment.

Keywords: carbon nanotubes, filtration, water, air, fuel

1 INTRODUCTION

It is understood that due to the hydrodynamics of flow around fibers, the efficiency of depth filters improves as the diameter of the fibers making up the filter element decreases. This is due primarily to two effects: 1) smaller fibers possess larger surface area and can therefore capture and hold more contaminants; and 2) smaller fibers disrupt the fluid stream to a lesser degree – the particles get less "advance warning" that they are about to strike the capturing fiber. However, if the fibers are too small in diameter they may lack sufficient strength to avoid breakage under the stress induced by fluid flow. CNTs possess exceptional mechanical strength (tensile strength ~100 GPa, modulus ~1000 GPa) [2] making breakage nearly impossible. Additionally, due to their very small diameters (on the order of the mean free path of air molecules), carbon nanotubes present a relatively low resistance to the flow of fluids. This, combined with their high surface area, means that highly-efficient, bio-contaminant removals are possible with a thin filtration media possessing a relatively low pressure drop.

For the past five years, Seldon Technologies has focused primarily on developing CNT-based water filtration media. Seldon's water filter material removes bacteria, viruses, spores, cysts, total organic carbons and inorganic contaminants from water using adsorption and sieving. Additionally, the pressure drop across the filter is much less than what is typically seen with nanofiltration and reverse osmosis systems (1 – 2 bar compared to 3 – 20 bar for nanofiltration and 5 – 120 bar for RO [3]) and is capable of working for well over 1,000 gallons of influent. This level of filtration is accomplished passively without the use of chemicals.

More recently Seldon has worked on developing Nanomesh™ that can be used in air and fuel filtration applications. In a 2005 DARPA sponsored project, Seldon demonstrated its air filter Nanomesh™ removed over 99% of an anthrax surrogate. This has lead to a larger research effort that in the past year developed material with near-HEPA filtration performance at a lower pressure drop. In the area of fuel filtration, internal testing showed that Seldon's material was effective at removing bacteria from contaminated jet fuel. Additional testing by a third party has suggested that the Nanomesh™ fuel filter media will be very effective at cleaning contaminated bio-fuels, a market that will be very important in the coming years.

2 WATER FILTRATION

2.1 Background

Over 1 billion people lack access to adequately clean water. Additionally, an estimated 2.5 million people die each year from diarrheal diseases and millions more are chronically ill due to a lack of portable water. In the United States and throughout the world, the number of identified contaminants is increasing, the water distribution infrastructure is aging and the costs of upgrading and repairing it are beyond the capability of many municipalities. Hence, there is a growing concern that the water being delivered to people's houses contains harmful impurities.

Common illness-causing organisms other than viruses are 1 - 5 microns long and can typically be removed by size-exclusion filtration. However, the removal of viruses (on the order of 20 nanometers) by size exclusion is impractical as the material would present a very high-resistance to flow and could not be used in small filtration systems. Seldon's approach uses chemically activated carbon nanotubes as an adsorptive surface for the attraction of viruses and other microorganisms. The very small size of CNTs creates an enormous removal capacity in the Nanomesh™ filtration media which equates to the ability to purify large volumes of water.

2.2 Work to Date

The bulk of Seldon's development work has focused on testing the technology's effectiveness in removing bioburden (i.e. bacteria, viruses, etc.) from water. Seldon's 2" x 9" water filters now reliably remove bacteria and virus from more than 1,000 gallons of water and some tests show that filters can purify up to 3,000 gallons of water.

Seldon has successfully completed third party testing of its Nanomesh™ filter at the University of New Hampshire's Water Treatment Technology Assistance Center. Using specific protocols from NSF P231, UNH demonstrated that while there was a very high biological challenge upstream of the filter, none of the contaminants made it through the filter. The third party test of Seldon's Nanomesh™ filter was terminated at 600 gallons. At Seldon, duplicating the third party's test conditions as closely as possible, the filter testing continued to operate up to 1,000 gallons.

2.3 Large Scale Production

Since May 2007 Seldon has conducted ten large scale production runs of its water filtration material (this includes producing both Nanomesh™ and pre-filtration material). It has been an on-going process at Seldon's facility in Vermont to evaluate this material's biological removal performance. While not all runs of the material have shown a high level of performance (filtration of 3000^+ gallons), the material does perform relatively well and shows a higher level of consistency than batch processes used previously. As a result of this work, Seldon has demonstrated it is possible to produce large quantities of a product incorporating a nanoscale material on a papermaking machine (see Figure 1).

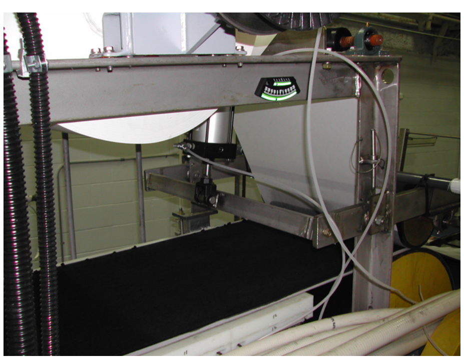


Figure 1: Wet lay deposition of Seldon's Nanomesh™ water filtration media.

2.4 Water Filtration in the Field

Throughout 2007, a Dian Fossey Gorilla Fund International field project located in Bisate, Rwanda used prototypes of Seldon's water purification products. Users from the NGO have provided valuable feedback to Seldon on how the units operate in the field. Additionally, all users have regularly commented on how good the water tastes when filtered through Seldon's system as compared to other water purification methods.

3 AIR FILTRATION

3.1 Background

There is a widespread pressing need for the effective filtration of airborne biological and chemical agents. Applications range from building ventilation systems, public transportation to personal health protection. While some very efficient air filtration technologies exist (e.g., HEPA and ULPA) they typically are restricted in their use by their bulk and/or the energy required to achieve adequate flow rates.

Air filtration presents challenges that are somewhat different than those for liquids. Because of the inherent limitations in air handling systems and human lung performance, air filtration must be carried out at a considerably lower pressure drop than liquid filtration. The most significant technical concern, then, is being able to achieve sufficient biological and chemical removal levels at the required flow rates without undue pressure drops. Fortunately, the low density/viscosity of air leads to higher levels of diffusion and easier deflection of small particles allowing for a thinner material and lower pressure drops as compared to liquid filtration media. Further, because of the absence of surface tension issues it is easier for contaminants to interact with the fibers within the filter.

Early air filtration tests showed that several non-optimized designs operated in the performance range of HEPA filters for bio-contaminants (see Figure 2). Samples of Seldon's candidate air filters achieved a log 2 reduction (~98%) for a weaponized form of *Bacillus subtilus*, the common surrogate for the bio-warfare agent, *Bacillus anthracis*. This level of removal is comparable to the early results achieved in the development of a water filtration product that currently has log 7 bacteria and log 6 virus reductions in water (99.99999% and 99.9999%, respectively).

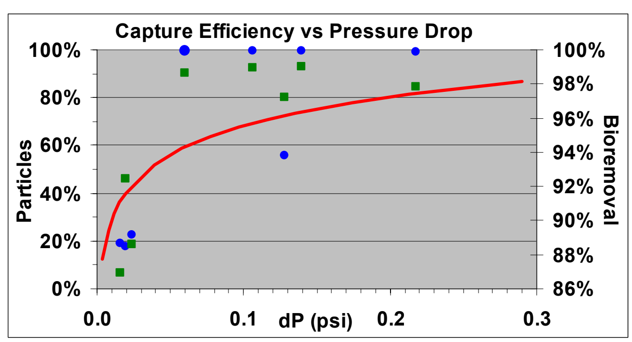


Figure 2: Neutral particle (circles) and surrogate bio-warfare agent (square) removal efficiency for several Seldon air filters. Solid curve is typical filtration relationship.

3.2 Recent Work

Following a typical design of experiment (DOE) methodology, researchers tested over 300 individual filters in the past 18 months. Careful analysis of early results suggested that the properties of the carbon nanotubes were not being fully leveraged to optimize a filter's performance. The key element was that the CNTs significantly contributed to the pressure drop across the filter, but did not lead to a concomitant improvement in the particle removal efficiency. This is typically indication that the specific fibers are not being adequately dispersed and exist in the media as tight agglomerations that block flow but do not effectively capture contaminants.

By closely examining the processing and mixing of each component fiber, Seldon's team managed to ease the constraints driving the efficiency-permeability relationship. SEM images show that the CNTs span the large pores created by the scaffold fibers effectively capturing particles but causing very little impediment to the flow of air. As a result, the overall media performance has significantly improved. Comparing the performance of Seldon's media to that of a flat sheet of HEPA media under the test conditions used in Seldon's lab, researchers have shown that several of Seldon's media designs achieve higher capture efficiency than HEPA media at nearly *three times* the permeability (Figure 3). Researchers are in the process of getting the comparison of Seldon's materials to HEPA media validated by a third party lab to confirm the improved performance.

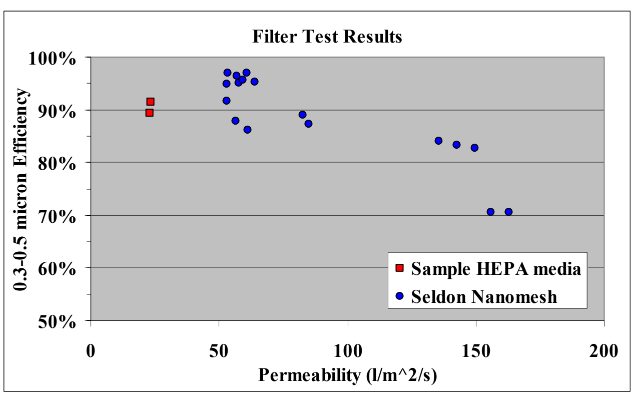


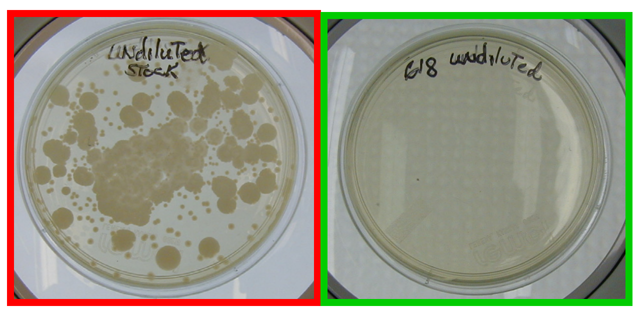
Figure 3: Filter performance comparison between several of Seldon's improved Nanomesh™ air media (circles) and a sample of HEPA media (squares) received from a third party supplier.

4 FUEL FILTRATION

4.1 Background

Although freshly refined oil is pure, bacterial growth can occur at the interface layer of fuel and water in storage tanks. (The water needed for the growth of microorganisms can enter the fuel tank by condensation due to temperature changes.) When disturbed, this growth enters vehicles and can quickly clog fuel filters and interfere with engine operation. The importance of microbial contamination in fuels was realized in 1958 when a B-52 crash was directly related to the plugging of an in-line fuel filter. Together with improved housekeeping, toxic chemicals like ethylene glycol monomethyl ether (EGME) and di-ethylene glycol monomethyl ether (di-EGME) were used as icing inhibitor additives to reduce the microbial infestation in the fuel. Although these measures reduced biological contamination, a complete reduction of microbial growth in aviation fuel was never achieved. A recent microbial study [4] shows that there is a variety of microbial organisms found in aviation fuel tanks throughout the United States. Moreover, the high toxicity [5] to mammals and aquatic animals of the chemicals used to treat this problem demands an alternate solution.

In 2004, at the request of the AFRL, Seldon tested the feasibility of its Nanomesh™ filtration media in removing bacteria from contaminated JP-8 jet fuel. Figure 4 shows a result from these feasibility tests. Figure 4a shows a culture of a sample taken from the fuel-water interface of contaminated JP-8. Figure 4b is a culture of the fuel after it has been passed through a Nanomesh™ filter. The Nanomesh™ was clearly capable of removing the bacteria from the fuel.



(a) (b)

Figure 4: (a) Culture of sample from fuel-water interface showing considerable bacterial growth. (b) Culture of sample filtered through Seldon's Nanomesh™ showing total absence of bacteria

4.2 Recent Work

An outside laboratory has conducted numerous tests showing the feasibility of using Seldon's fuel filtration material in a variety of applications. In a qualitative test, Seldon's Nanomesh™ fuel filtration media was shown to significantly reduce the amount of fuel degradation products (FDPs) from biodiesel as well as commercial diesel products. Figure 5 compares a samples of biodiesel

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and regular diesel before and after filtration. The clarity of the post-filtration samples indicates the removal of fuel degradation products. For diesel fuel (based on the clarity of the filtrate), Seldon's sample appears to outperform the commercial filter.

Figure 5: (a) Image of thermally degraded biodiesel fuel before and after removal of FDP using Seldon's Nanomesh™ filter; (b) Image comparing the effect of a traditional filter against the effect of Seldon's Nanomesh™ filter for the removal of FDP from commercial diesel fuel.

In another test, the laboratory demonstrated the removal of small particulate matter using Seldon's media. In this measurement, test filters were placed upstream of a sacrificial "filter patch" (see inset in Figure 6) and the change in pressure across the patch was then monitored. Figure 6 shows the results of flowing ultra-low sulfur diesel fuel containing 0.14% of dimethyl-phenanthrene (DMP) particulate (less than 3 μm) through a traditional fuel filter, a sample of Seldon's Nanomesh™ fuel filter and when no test filter is in place. As seen in the figure, with no test filter in place, the sacrificial patch quickly becomes clogged. No increase in pressure drop was observed in both the Nanomesh™ and the traditional filter; indicating that they work with similar removal efficiencies. However, because Seldon's Nanomesh™ fuel filter media is slightly electrically conductive, it has superior electrostatic discharge capabilities as compared to the traditional filter. At high flow rates, the build up of large electrostatic charges causes electrical sparks within the filter. These discharges cause damage to the filter and hence reduce filter efficiency and life.

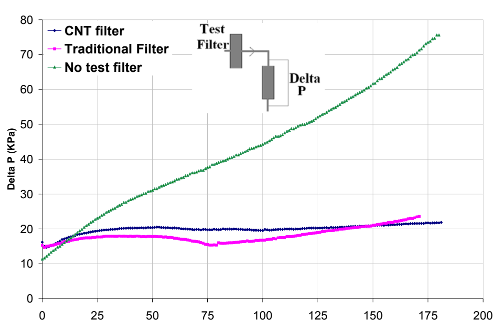

Figure 6: Plot depicting change in pressure drop across a downstream filter when Seldon's Nanomesh™ pre-filter, a traditional pre-filter and no pre-filter is used for removal of 0.14% (DMP) fine particulates (< 3 micron) from ultralow sulfur diesel(ULSD).

Internal testing has shown that swatches of Seldon's fuel filtration media is capable of removing over 7 logs of bacteria from emulsions of made from 85% fuel surrogate and 15% bacteria laden water.

5 CONCLUSIONS

Seldon Technologies has successfully applied its concept of filtration using nanoscale particles (specifically carbon nanotubes) to the areas of water, air and fuel filtration. Seldon's water filtration technology has matured to the point where a single filter cartridge can potentially clean 3000 gallons of water heavily contaminated with bio-burden. Seldon's air filtration media appears to perform on par with some types of HEPA media in terms of efficiency but at a lower pressure drop. Finally, fuel filtration media produced by Seldon could prove very useful in the remediation of contaminated fuel stocks greatly reducing waste.

6 ABOUT SELDON TECHNOLOGIES

Founded in 2002, Seldon Technologies has received $15 M in government sponsored funding from AFRL, DARPA and NASA. Additionally, Seldon has entered into collaborative research agreements worth $2.4 M with corporate sponsors. In addition to its patent for the purification of fluids using carbon nanotubes, Seldon has 11 patents pending. The company currently employees 35 people in eastern Vermont.

REFERENCES

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