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MODERN PTFE MEMBRANE BASED HEPA/ULPA FILTERS FOR IMPROVED ENERGY SAVINGS AND RISK REDUCTION

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IMPROVED ENERGY SAVINGS AND RISK REDUCTION

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Abstract. Strict demands are put on HEPA/ULPA filters that are installed as terminal filters in cleanrooms, isolators, workbenches etc. or as last filter stage in air handling units being upstream. They must continuously guarantee safe operation while predefined air quality requirements and energy efficiency are optimized. For that the filter media itself is of major importance.

Standard filter media for HEPA/ULPA filters so far had been fiberglass paper. Being free of boron filter media based on expanded Polytetrafluoroethylene (ePTFE) is used in microelectronics since decades. Based on latest developments in membrane technology, such as PAO compatibility, ePTFE and expanded Fluoro-Resin Membrane (eFRM) based HEPA filters are on their way to replace fiberglass-based filters.

This presentation describes how ePTFE and eFRM membrane media contributes to process safety and low-cost operation.

It sets out structure of modern ePTFE and eFRM membrane media, how these air filters provide significant reduction in energy consumption and risk.

It presents results of several studies on superior stability, durability and performance of ePTFE and eFRM media over traditional fiberglass media. Based on several tests regarding mechanical and chemical resistance as well as soot loading it is demonstrated that ePTFE and eFRM media offer a significant improvement in reducing media failure risk for a retained filter integrity.

PTFE, EXPANDED PTFE (ePTFE) AND EXPANDED FLUORO-RESIN (eFRM) MEDIA

On April 6, 1938 Dr. Roy Plunkett, a scientist with chemicals company DuPont®, accidently discovered polytetrafluoroethylene (PTFE) while looking for better cooling agent. Leaving a batch of tetrafluoroethylene (TFE) gas in a pressure container overnight, he found the next day a layer of a white translucent waxy solid: Polymerized TFE, i.e. PTFE. Poly**te**tra**fl**uor**o**ethyle**n**e was abbreviated to **Teflon**® as registered as trademark in 1945. Today PTFE is available by numerous suppliers under different trademarks.

Its chemical structure is a fluorine saturated carbon chain $(C_2F_4)_n$ of high molecular weight. Fluorine atoms, strongly bond to the carbon atoms, surround the central ethylene carbon chain completely protecting it from chemical attacks.

In Oct 1969 Mr. Bob Gore accidently discovered expanded PTFE (ePTFE). Frustrated with rods breaking when being stretched too slowly, he quickly draws a hot PTFE rod and found he can stretch PTFE 1000-times its original length. First commercial product in 1970 was PTFE pipe tape sealant. Today it's a commodity used in nearly every household. In 1973 industrial filter bag business begun. Here expanded PTFE is used for filtration, pioneering membrane surface filtration to capture contaminants and other particles. Since 1976 ePTFE in apparel is used.

Traditional glass fiber based HEPA-/ULPA-filter media are made of SiO_2 fibers. With progress in microelectronics outgassing issues of boron (Br), an accompanying element of silicon (Si), created quality problems in production of microelectronic components.

In 1994 ePTFE membrane HEPA-/ULPA-filter for deep filtration, made by Japanese Daikin Industries, revolutionized filtration for microelectronic cleanrooms due to ultralow low emission of volatiles, particularly Br.

Nowadays membrane HEPA filters based on expanded Fluoro-Resin Membrane (eFRM) became available from Daikin Industries. These are overcoming some issues with ePTFE filters regarding clogging when leak tested with photometers, which use high concentrations of oily PAO test aerosols, as well as regarding use in pure fresh air applications.

ePTFE AND eFRM MEMBRANE FILTER MEDIA

Figure 1 shows a SEM photo of whole ePTFE HEPA filter membrane media. For comparison a human hair is shown.

The very fine three-dimensional network of PTFE fibrils is bound by small PTFE nodes. Just for stiffening and pleatability ePTFE membrane is supported by a nonwovens layer. That layer doesn't contribute significantly to filtration efficiency.

The whole media has a depth of about 100µm. That's 1000-times the diameter of a 0,1µm particle. Thus, ePTFE HEPA filter membrane media is providing deep filtration – no surface filtration!

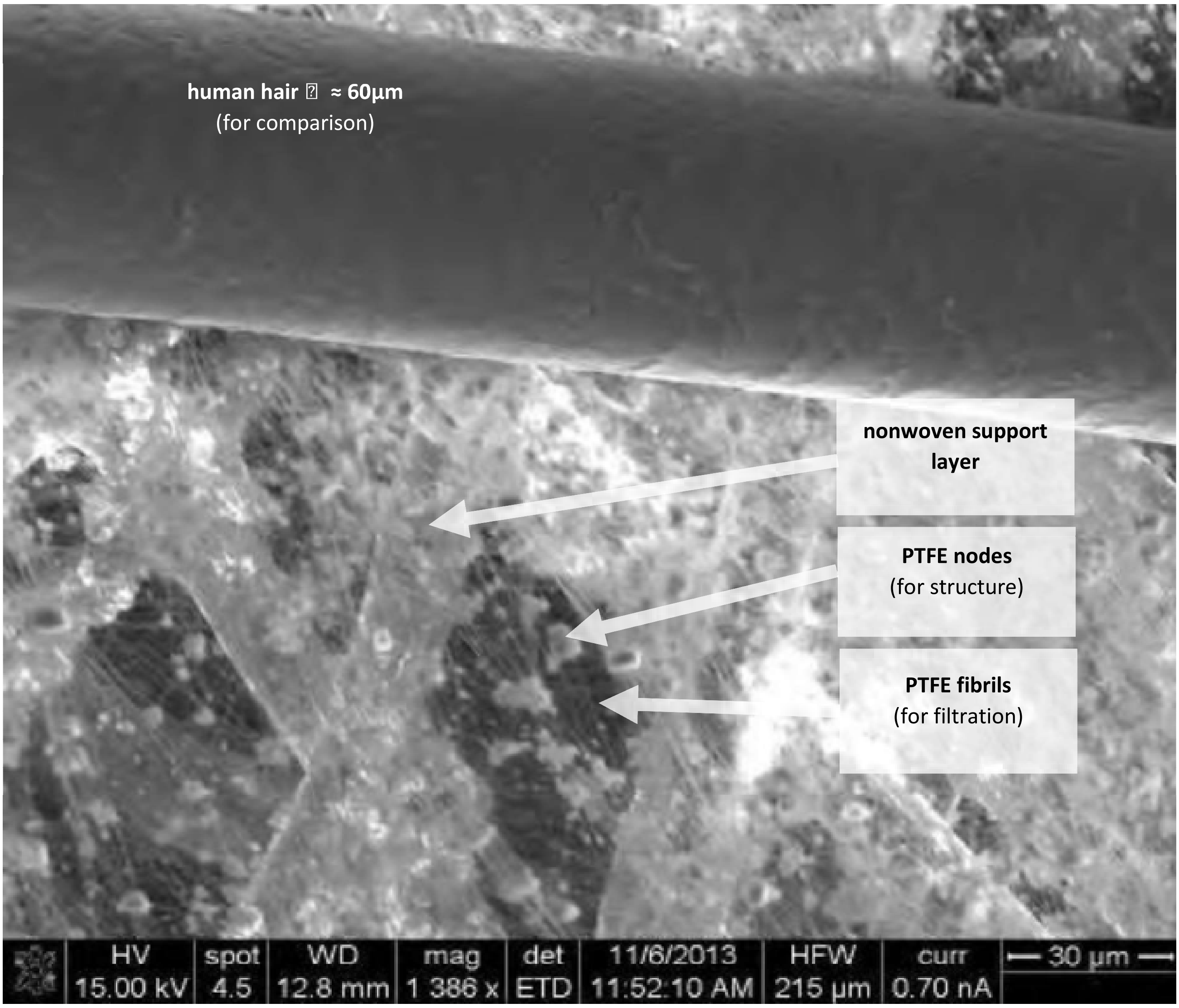

Figure 1: ePTFE HEPA filter membrane media

eFRM media is composed of similar structure but there are two layers of fine-tuned expanded fluoro-resin membrane (eFRM) for improved depth filtration.

Figure 2 shows a SEM photo of ePTFE membrane (left) and traditional glass fiber media (right).

Clear difference in structure can be seen. ePTFE membrane has much smaller pore size than glass media, in average 0,5 - 1µm; i.e. about 100 million pores per cm^2. About 1.000-2.000 of such pores would fit across the tip of a ball point pen.

But more important for filtration is the fiber diameter. Diameter of traditional glass fibers is in the range of 0,5 -1µm; whereas ePTFE fibrils diameter is in the range of 20 - 200nm.

These ultra-thin ePTFE fibrils provide excellent filtration efficiency, particularly for very fine particles but also create an extremely low pressure drop by slip-flow effect.

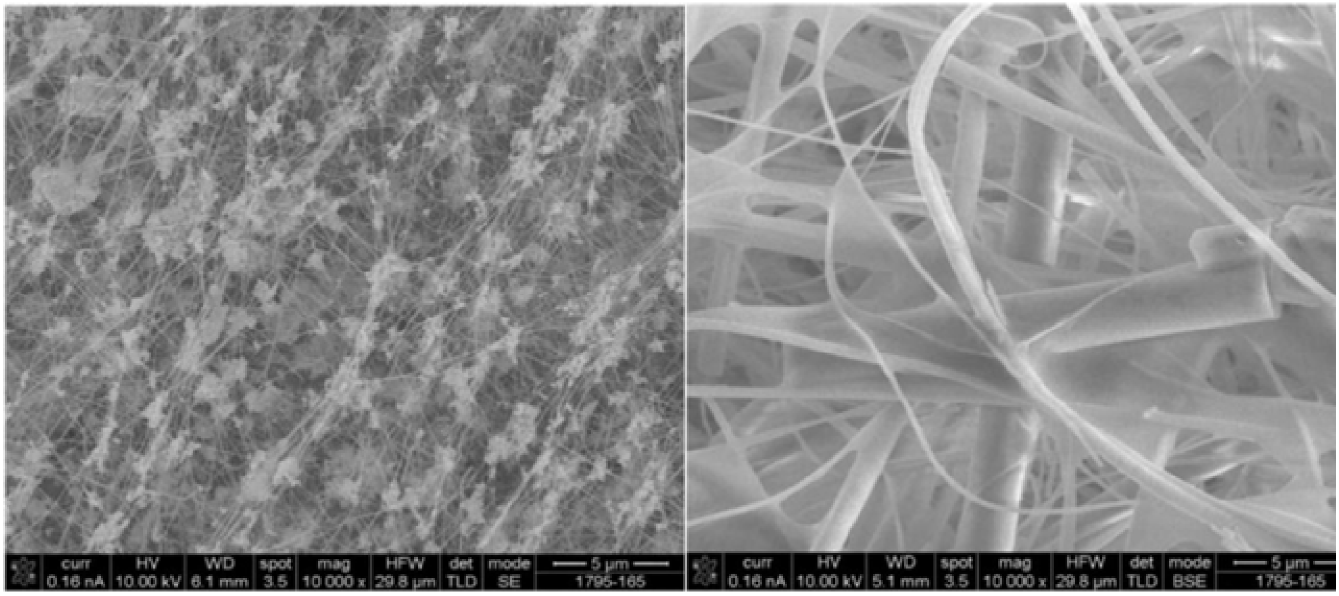

Figure 2: ePTFE membrane (left) and traditional glass fiber media (right)

SLIP FLOW VS VISCOUS FLOW

At typical air flow velocities for HEPA filtration viscous flow regime is formed around traditional glass fibers (Figure 3). The air flowing around the fibers can be seen as a continuum following laws of classical fluid dynamics.

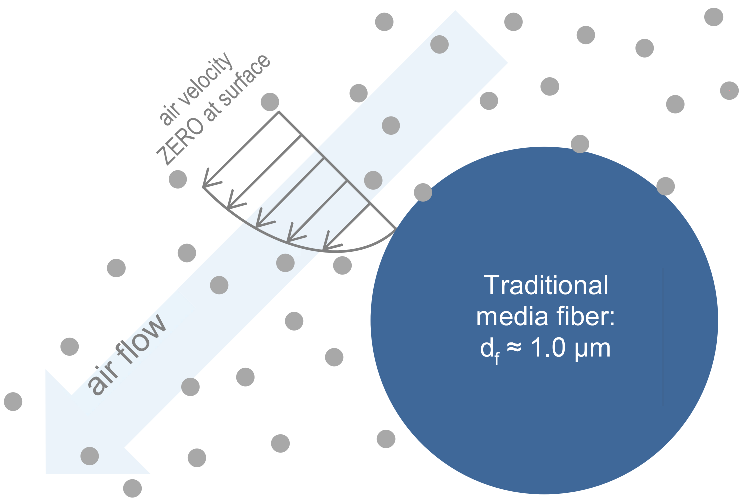

Figure 3: Boundary layer at viscous flow around traditional glass fiber

With viscous flow regime air velocity at the very surface is equal to zero. With increasing distance from the surface, the velocity increases up to velocity of free flow field; forming so called boundary layer. Velocity gradient within the boundary layer leads to internal friction resulting in energy dissipation, which is causing significant pressure drop.

With ultra-thin ePTFE or eFRM fibrils air cannot be seen as continuum anymore. Furthermore, discrete air molecules and their behavior based on kinetic gas theory have to be considered. According kinetic gas theory, gas molecules do randomly move around their flow lines. They collide within a characteristic distance, called mean free path □, with each other. That behavior is also called Brownian motion of gas molecules.

Under ambient conditions mean free path of air molecules is about 68nm. With diameter of ePTFE or eFRM fibrils of 20 – 200nm these are in the same range of size than mean free path of air. Under these circumstances a different flow regime, called slip flow is formed.

With slip flow regime air velocity at the very surface is not equal to zero. Thus a boundary layer is not fully formed resulting in less internal friction and less energy dissipation (Figure 4). Result is dramatic decrease of pressure drop up to 50%.

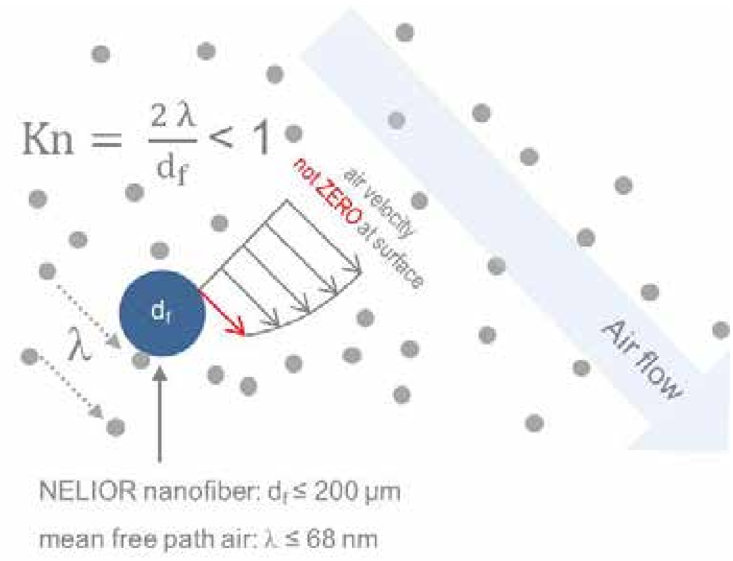

Figure 4: Slip flow regime around ultra-thin PTFE fibril

Slip flow regime and its effect on air filtration is already known since decades (Brown, 1993; Kirsch et al.,1973) and was just recently experimentally confirmed (Bao et al., 2016).

Significant effect of slip flow regime can be seen at Knudsen numbers above around 1:

$$Kn = \frac{2\,\lambda}{d_f} \gtrsim 1. \tag{1}$$

With above mentioned diameters for ePTFE fibrils and mean free path of air under ambient conditions, range of Knundsen number is:

$$0{,}68 \leq \; Kn \; \leq 6{,}8. \tag{2}$$

Mean free path of air at ambient conditions is given the under real world conditions. Thus, slip flow regime can only be formed when fiber resp. fibrils are ultra-thin. As glass fibers cannot be spun with necessary ultra-fine diameters, formation of fibrils by expanding PTFE or FRM membrane is an excellent way for manufacturing highly filtration effective and energy efficient HEPA filter media.

MECHANICAL STABILITY OF ePTFE MEMBRANE FILTER

Traditional glass fiber HEPA media is mechanically not very stable. It's brittle and fragile therefore, sensitive and easy to damage. That can happen during filter installation, filter validation, cleaning of filter ceiling, cleanroom modifications and other working activities in the cleanroom.

Consequences can be cleanroom downtimes, unscheduled replacements, costly recovery action and/or cross contamination as well as uncontrolled release of harmful substances.

Thus, beyond filtration performance and energy efficiency mechanical stability is crucial for modern HEPA filters. Figure 5 compares results of tensile strength test of flat and folded ePTFE membrane and traditional glass fiber media.

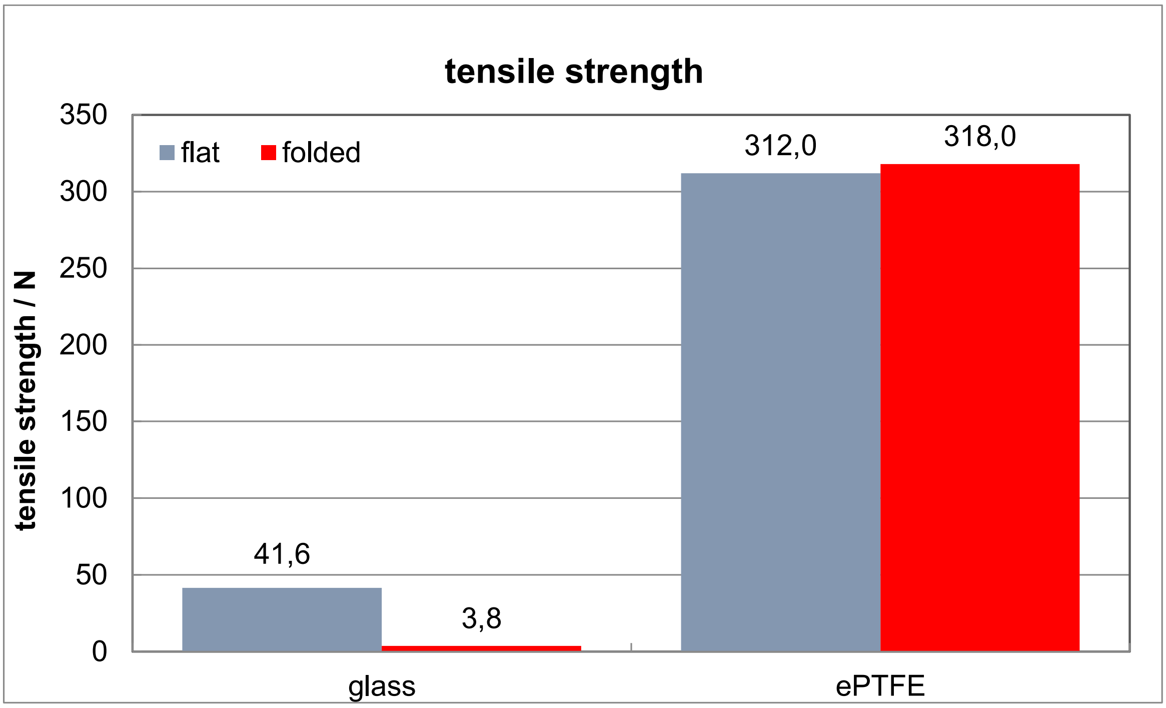

Figure 5: Tensile strength of flat and folded ePTFE membrane and glass fiber media

Significant differences between ePTFE membrane and traditional glass fiber media can be seen. Flat ePTFE membrane is around 8-times stronger than traditional glass fiber media. Folding resp. pleating is weakening traditional glass fiber media because glass fibers are breaking. That reduces tensile strength by more than factor 10. In contrast tensile strength of folded ePTFE membrane stays at the same level than flat media. Compared to traditional glass fiber media ePTFE membrane stronger by factor 84.

CHEMICAL STABILITY OF ePTFE MEMBRANE FILTER

Beyond mechanical stability also chemical stability of filter media is important. HEPA filters can get in contact with water and chemical agents during cleaning operations, droplet loaded process air or condensation of humid air.

Water resistance

It's known that traditional glass fiber HEPA filters, after having been wet and dried, are losing filtration efficiency or are leaking due to changes of fibrous structure. Checking behavior of ePTFE membrane HEPA filters two tests have been carried out.

As a first test an U16 ePTFE membrane HEPA filter was sprayed with 500ml of deionized water and dried for 72h. Table 1 shows the results.

	MEGAcel LPD 1220x610x69			
	before water spray	water spraying	72h after water spray	comment
efficiency	99,999952%@0,1μm	500ml deionized water	99,999974%@0,1μm	✓
pressure drop	70Pa@0,45m/s		73Pa@0,45m/s	✓
DIN Scan Test	no leak		no leak	✓

Table 1: Efficiency, pressure drop and leak test of U16 ePTFE membrane HEPA filter before and after wetting and drying.

Not efficiency nor pressure drop are showing significant changes. Filter remained leak free.

As a second test an U17 ePTFE membrane HEPA filter was exposed during operation in a test duct to water spray (450 ml/min for 1 h, totally 27 l). Afterwards the filter dried naturally for 1 week and was again check in operation. Table 2 shows the results.

Also, in this test not, efficiency nor pressure drop are showing significant changes. Filter remained leak free.

	MEGAcel 610x610x65 (ePTFE)			
	before exposure (@600m3/h)	exposure	after exposure (@600m3/h)	comment
visual appearance	✓	operation 1h@245Pa while spraying 450ml/min for 1h (total 27l), afterwards natural drying for 1 week	✓	✓
efficiency	99,999995%		99,999999%	✓
pressure drop	85		85	✓
leak test	no leak		no leak	✓

Table 2: Efficiency, pressure drop and leak test of U17 ePTFE membrane HEPA filter before and after wetting in operation and drying.

Both tests are confirming that ePTFE membrane HEPA filters are nonsensitive regarding wetting with water. The structure remains unchanged and with-it filtration performance and energy efficiency what makes them unique for applications when water droplets are carried by the air or high humidity can lead to water condensation.

Resistance to hydrogen peroxide (H_2O_2)

In pharmaceutical industry clean environments like cleanrooms, isolators etc. are often disinfected by fumigation with H_2O_2. That's normally done in recirculation mode of HVAC system to ensure that also these components are disinfected. Hereby HEPA filters are flushed by gaseous H_2O_2.

H_2O_2 is a very aggressive oxidant in gas phase and even more in liquid phase. That can create problems with chemical resistance of traditional glass fiber HEPA filter media particularly when condensation on the filter surface or micro-condensation with micro-pores of filter media occurs. As result, the binder in traditional glass fiber HEPA filter media (often acrylic resin) is oxidized and the media is becoming even more brittle and fragile therefore, even more sensitive and easier to damage.

Checking resistance to H_2O_2 ePTFE membrane media was exposed to 36% aqueous H_2O_2 solution. Results are shown in Table 3.

Not efficiency nor pressure drop or weight are showing significant changes. The tests are confirming that ePTFE membrane HEPA filters are resistant to H_2O_2. The structure remains unchanged and with-it filtration performance and energy efficiency.

	sample	before exposure	after 24h exposure in H_2O_2 solution	notes	result
efficiency @ 0,1~0,2µm	#1	99,9998%	99,9999%	efficiency test at 5,3 cm/s	✔
	#2	99,9999%	99,9998%		✔
pressure drop	#1	255 Pa	276 Pa		✔
	#2	257 Pa	286 Pa		✔
weight	#1	2,729 g	2,738 g	135x200 mm	✔
	#2	2,603 g	2,609 g		✔

Table 3: Efficiency, pressure drop and weight test of ePTFE membrane HEPA filter media before and after exposure to H2O2 solution.

Resistance to chlorine dioxide (ClO_2) and formaldehyde (CH_2O)

Whereas in pharmaceutical industry H2O2 is dominating disinfection agent for fumigation, in veterinary or bio-safety labs chlorine dioxide (ClO2) is often still in use. Checking resistance to ClO2 ePTFE membrane media was exposed for 24 hours to 0,2% aqueous ClO2 solution. Results are shown in Table 4.

	before exposure	after 24h exposure in 0,2% ClO_2 solution	notes	result
efficiency @ 0,3µm PSL	99,9995%	99,9992%	at 5,3 cm/s	✔
pressure drop	119 Pa	119 Pa	at 5,3 cm/s	✔
weight	98 g/m^2	99 g/m^2	-	✔

Table 4: Efficiency, pressure drop and weight test of ePTFE membrane HEPA filter media before and after exposure to ClO2 solution.

Another disinfection agent for fumigation still sometimes in use is formaldehyde (CH_2O). Checking resistance to CH_2O ePTFE membrane media was exposed for 24 hours to 36% aqueous CH_2O solution. Results are shown in Tab. 5.

In both cases not efficiency nor pressure drop or weight are showing significant changes. The tests are confirming that ePTFE membrane HEPA filters are resistant to ClO_2 as well as CH_2O. The structure remains unchanged and with-it filtration performance and energy efficiency.

	before exposure	after 24h exposure in 36% CH_2O solution	notes	result
efficiency @ 0,3µm PSL	99,9998%	99,9996%	at 5,3 cm/s	✔
pressure drop	125 Pa	124 Pa	at 5,3 cm/s	✔
weight	97 g/m^2	101 g/m^2	-	✔

Table 5: Efficiency, pressure drop and weight test of ePTFE membrane HEPA filter media before and after exposure to CH_2O solution.

PRESSURE DROP REDUCTION BY ePTFE MEMBRANE FILTER

As described above slip-flow is significantly decreasing pressure drop of HEPA filter in comparison to viscous flow. Figure 6 shows pressure drop as function of volume flow for a H14 ePTFE membrane HEPA filter and a traditional H14 glass media HEPA filter.

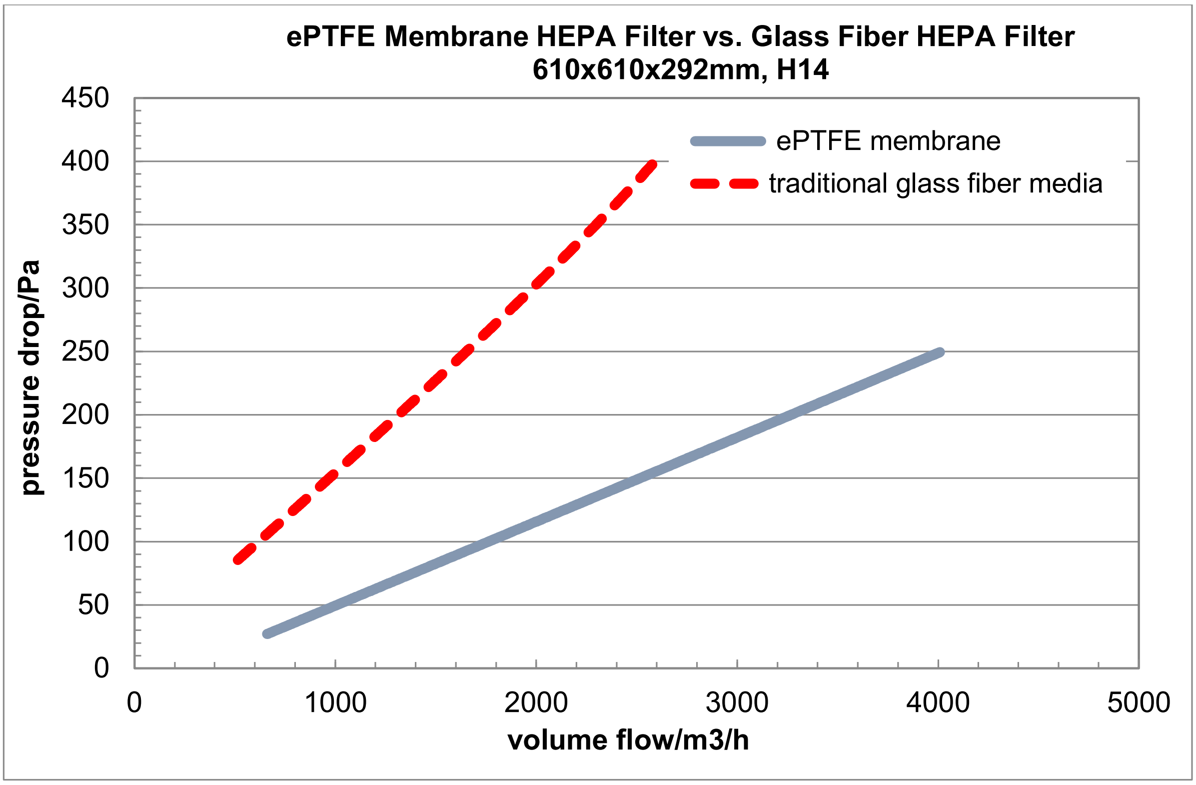

Figure 6: Pressure drop as function of volume flow for an H14 ePTFE membrane HEPA filter and a traditional H14 glass media HEPA filter

ePTFE membrane HEPA filter does not only show significant lower pressure drop than traditional glass media HEPA filter but also slope of the curve is flatter. That means the difference between the two filters is increasing with increasing volume flow. Energy saving potential is even bigger for high volume flow HEPA filters.

Due to their dual membrane composition eFRM HEPA filters are showing little higher pressure drop than ePTFE HEPA filters but still far below micro-glass HEPA filters.

HEPA/ULPA FILTER LEAK TESTING

To prove performance and zero leaks HEPA and ULPA filters are tested by filter manufacturers in the factory before shipment. That's always done using Discrete Particle Counters (DPC) by counting single particles up- and downstream the filter for several classes of particle sizes. European standard for classification and performance test of HEPA/ULPA filters is EN1822. International standard ISO29463 is based on European standard EN1822 and will probably replace this standard in the future.

Once installed HEPA/UPLA filters are leak tested in situ to:

- test for leakage of filter medium and sealant to frame due to transport, installation

mishaps and/or misuse of the filter element and
- test for bypass in the frame, housing, gasket seal and grid system.

That's just a leakage test no performance test re-approving filter class! International standard ISO14644 is (among others) classifying air cleanness of cleanrooms describing in part 3 methods for in-situ leak test. For that two methods are allowed:

- **Discrete Particle Counter (DPC) method:** As described above its function is based on counting of single particles. Besides factory performance test and in-situ leak test it's also used in pharma for cleanroom monitoring and the only method used in ultra-clean environments for microelectronics. DPC method is allowed for all filter classes from H14 up to U17. It uses a very low concentration of test aerosol (≈ 0,03 - 0,3 mg/m^3).
- **Photometer method:** It's function is based on light absorption of a cloud of particles. It requires a much higher test aerosol concentration (≈ 5 - 40 mg/m^3) than DPC and therefore it's not used at all for cleanroom monitoring nor ultra-clean environments for microelectronics. Photometer method is only allowed for leak testing of H14 HEPA filters in pharma applications. ULPA filters from U15 up to U17 always (also in pharma applications) have to be tested by DPC method.

Although both methods are allowed for leak testing of H14 filters in pharma applications, users in German speaking countries (Germany, Austria, Switzerland) are traditionally and solely using DPC method whereby majority of users in other countries is using photometer method.

COMPARISON TRADITIONAL ePTFE AND ADVANCED eFRM MEMBRANE FILTERS

Oil loading behavior of traditional ePTFE membrane HEPA filters

As described above leak testing causes oil loading of HEPA/ULPA filters at which photometer testing is much more critical than DPC testing due to its much higher concentration of test aerosol (PAO oil).

In a recent work of Devine et al. (2013) pressure drop increase as function of oil load was investigated for different HEPA filter media, see Figure 7.

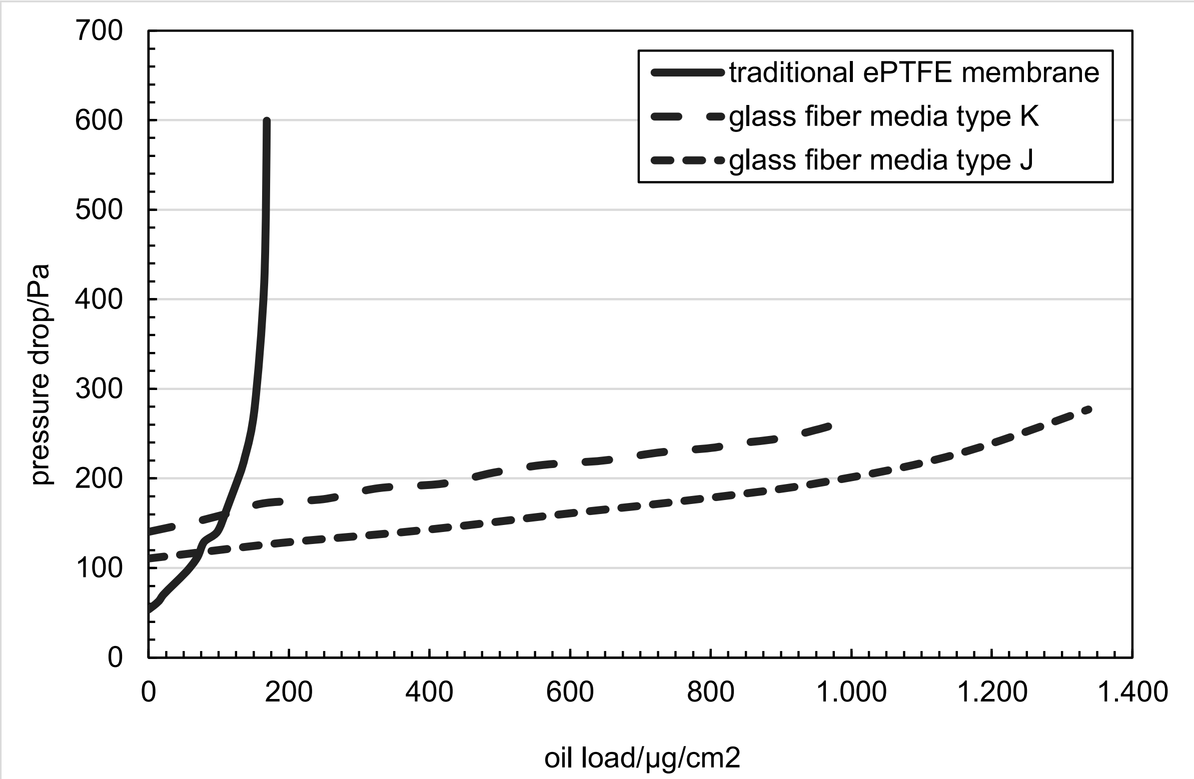

Figure 7: Pressure drop as function of oil load for traditional H14 glass media HEPA filter and traditional ePTFE membrane HEPA filter (see Devine at al.).

Both traditional glass media show pressure drop increase with increasing oil load as captured oil droplets are loading the filter. Even if initial pressure drop of traditional ePTFE membrane is significantly lower than glass media's (by roughly 50%), its increasing rapidly with oil load. That's why in the past traditional H14 ePTFE membrane HEPA filters could only be leak tested using DPC (low test oil concentration) what was limiting their use in pharmaceutical industry in non-German speaking countries.

Oil loading behavior of advanced eFRM membrane HEPA filters

Advanced membrane technologies known as FRM (Fluoro-Resin Media) in critical applications are beginning to be adopted for three reasons. Extreme durability (including hydrophobic benefits), lower resistance than glass and today comparable to glass fiber from a Total Cost of Ownership standpoint. The lower unit cost now comparable to glass fiber media and the lower resistance will also see the eFRM media installed in terminal and exhaust housings.

One of the challenges that had existed with traditional ePTFE membrane filters was how they are tested in the field. Oil based aerosols (PAO) remains the standard in the industry for field certification in most parts of the world. The aerosol concentrations historically utilized through thermal generating techniques caused the membranes to clog and see a steep increase in pressure drop. Today, this problem is solved. There are two solutions. Decrease the aerosol challenge and utilize a dilution system with DPC for conventional PTFE membranes which is more accepted in German speaking countries; or utilize the FRM membrane technology which is 100% compatible with current field testing methodologies when higher concentrations of PAO are generated.

Figure 8 shows comparative results of PAO oil loading tests of micro-glass HEPA, PAO tolerant eFRM HEPA and conventional ePTFE HEPA filters. For that a 592x592mm HEPA filter, at nominal air flow, was loaded with an PAO aerosol stream of 45µg/l.

Traditional glass media HEPA filter shows pressure drop increase with increasing oil load as captured oil droplets are loading the filter. Even if initial pressure drop of traditional ePTFE membrane is significantly lower than glass media's, it's increasing rapidly with oil load. Initial eFRM HEPA filter pressure drop is significantly lower than ePTFE HEPA filter pressure drop and increases only slowly as oil droplets are captured. The slope of pressure drop curve is even flatter than the one of micro-glass HEPA. The eFRM HEPA filters blocks due to oil load much later than the conventional ePTFE HEPA filter and even much later than the micro-glass HEPA, at levels that are irrelevant for field applications.

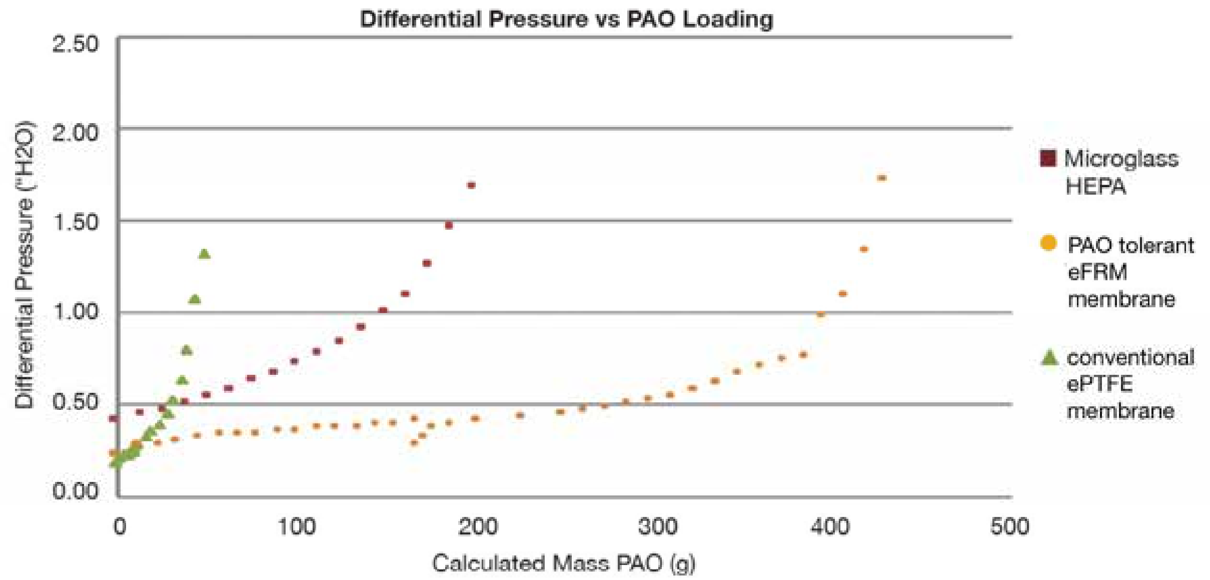

Figure 8: Pressure drop as function of oil load for H14 micro glass media HEPA filter, traditional ePTFE membrane and advanced PAO tolerant eFRM membrane HEPA filter.

COMPARISON SOOT LOADING BEHAVIOUR OF GLASS FIBER HEPA AND ADVANCED eFRM MEMBRANE FILTERS

To evaluate performance of HEPA filters in air handler unit applications, soot loading has been identified as a method that will relate to real-life particle loading for these filters. The goal is to have an eFRM filter media that meets or exceeds the performance of glass filter media in these applications.

For that soot loading behavior of two glass fiber HEPA filters was compared to behavior of two eFRM HEPA filters.

The filters were tested at their rated flow (3400 m^3/h) with the stopping condition of 249 Pa pressure drop rise over initial resistance. Soot was generated according to the ISO 12103-3 test standard. This test method calls for soot generated at an average diameter of 95 nm ± 10 nm. Soot was generated from the combustion of ultra-low-sulfur diesel with a soot generator, constructed using a camp stove inside of a stainless-steel chimney quenched by nitrogen introduced 30,5 cm up the chimney pipe at 68 m^3/h to control the particle size. Particle size distribution as shown in figure 9 was measured using a by a TSI Condensation Particle Counter (CPC) and Scanning Mobility Particle Sizer (SMPS) spectrometer.

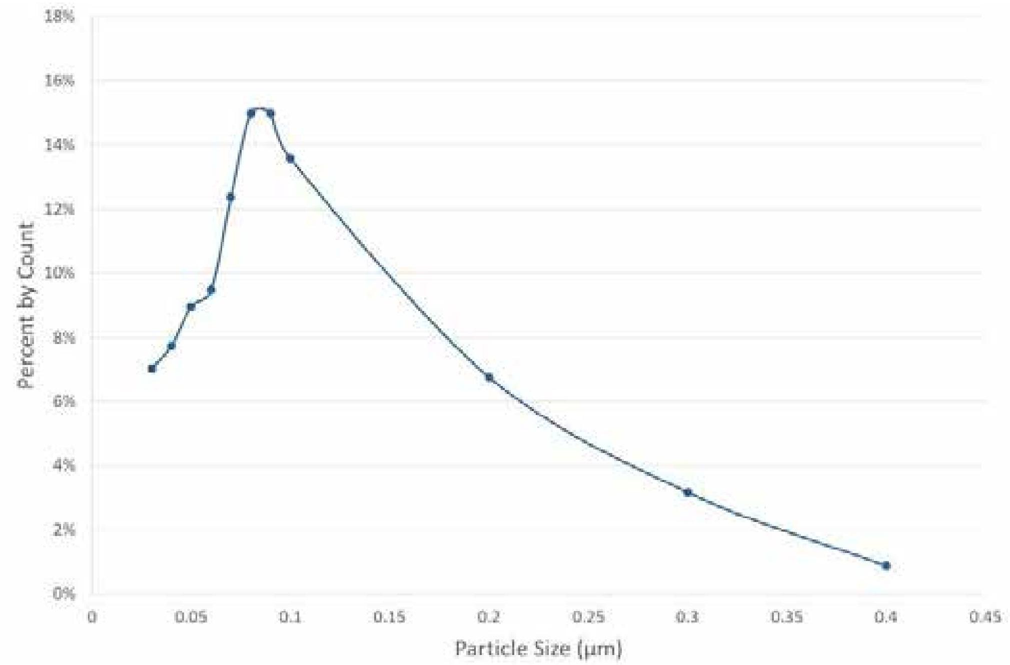

Figure 9: Particle size distribution of soot generated.

The soot concentration upstream of the HEPA filters was monitored with a photometer and pressure drop across the filter was continuously monitored until a 249 Pa rise was detected.

The weight of the filter was measured before and after the test to determine the amount of soot held, and filter efficiency according to EN 1822-5 post-loading to ensure no loss of efficiency after soot exposure.

Table 6 and figure 10 are showing the soot loading results.

filter	air flow m^3/h	pressure drop Pa	pressure drop Pa	soot held g	soot concentration $\mu g/m^3$
glass fiber HEPA #1	3.400	316	565	21,4	525
glass fiber HEPA #2	3.400	319	568	20,8	528
eFRM HEPA #1	3.400	192	441	21,5	542
eFRM HEPA #2	3.400	177	423	20,9	559

Table 6: Soot loading test results.

The average soot holding capacity of the glass fiber HEPA filter was 21,1 grams over a 707,5 min (11,8 hour) test time compared to 21,2 grams over a 680 min (11,3 hour) test time for the eFRM HEPA filter.

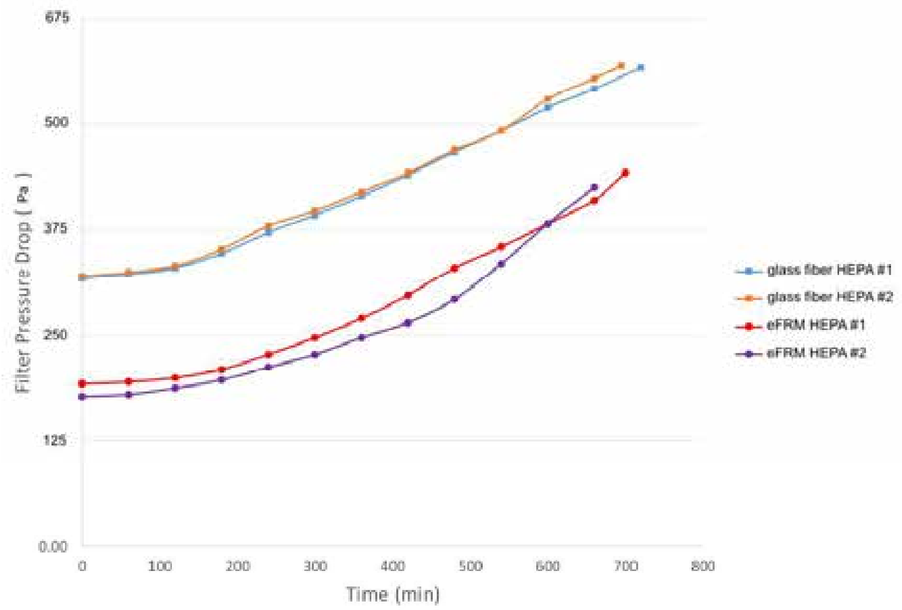

Figure 10: Pressure drop vs time during soot loading test.

The soot loading test results show that the glass fiber HEPA filters and eFRM HEPA filters had similar soot loading performance. The eFRM membrane did not clog even under the harsh conditions of soot loading.

After soot loading, the filters were tested for efficiency and MPPS per the EN1822-5 test to show that the soot exposure didn't cause a drop in efficiency. The results of this testing showed that the filters maintained their rated efficiency, summarized in table 7.

filter	MPPS nm	mean penetration at MPPS %	mean efficiency at MPPS %
glass fiber HEPA #1	100	0,016	99,984
glass fiber HEPA #2	100	0,017	99,983
eFRM HEPA #1	79	0,0011	99,9989
eFRM HEPA #2	79	0,0012	99,9988

Table 7: Efficiency and penetration at MPPS for soot loaded filters.

These test results clearly show that eFRM filters outperform conventional glass HEPA filters as the eFRM filter media provides a lower initial resistance media with similar soot holding capacity to glass HEPA filter media when challenged with soot.

ENERGY AND COST SAVINGS BY ePTFE AND eFRM MEMBRANE FILTERS

Low pressure drop of membrane filters has significant economic and ecologic implications as shown in Table 8.

As pressure drop is reduced by more than 50% yearly energy consumption, its CO_2 equivalents (acc. IEA 2011) and in the end energy cost are reduced by same ratio.

The values shown above are only valid for one filter and operation time of one year. For installations with multiple HEPA filters and an operation time of several years, the savings scale by the product of number of HEPA filters times operation time in years.

	operating resistance @0,45m/s	per filter and year		
		energy consumption	CO_2 equivalents	energy cost
traditional glass media	110 Pa	548 kWh	175 kg	52 €
ePTFE membrane	50Pa	249 kWh	79 kg	23 €
savings by ePTFE membrane	>50%	299 kWh	96 kg	29 €

Table 8: Comparison of energy and cost savings of ePTFE H14 HEPA filter vs. traditional H14 glass fiber filter (610x1220mm, 50mm filter pack, operation 8760h/a, 58% fan efficiency).

BENEFITS OF ePTFE AND eFRM MEMBRANE FILTERS

Energy and cost savings by ePTFE and eFRM membrane filters aren't there only advantages. Unmatched mechanical stability and chemical resistance are nearly completely eliminating risk of uncontrolled particle release, cross-contamination etc. Therefore, ePTFE and eFRM HEPA filters significantly reduced particle release related risk of operations in clean environments.

Superior mechanical stability and chemical resistance also reduce risk of premature filter replacements, cleanroom downtimes, recovery expenditures, requalification cost and other cost related to filter media failure.

Their low pressure drop allows smaller fan motors which are cheaper, generating less heat as well as less noise. Low pressure drop also allows reduced construction depths of filters and fan filter units, which is of particular interest for reconstruction projects and installations with limited space available.

One of the challenges that had existed with traditional ePTFE membrane filters was how they are tested in the field. The aerosol concentrations historically utilized through thermal generating techniques caused the membranes to clog and see a steep increase in pressure drop. Today, this problem is solved with eFRM membrane HEPA filters.

Today comparable to micro-glass HEPA filters from a Total Cost of Ownership standpoint, the lower unit cost (now comparable to glass fiber media) and the lower resistance will see the eFRM HEPA filters widely spreading.

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