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NOVEL PARTICULATE AIR-FILTRATION MEDIA: MARKET SURVEY

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The next generation of respiratory protective masks is expected to have lower burden filters with increased protection for the Warfighter. A market survey was conducted to identify novel commercial filtration media with low-pressure drop and high efficiency. Performance requirements for the filtration media included a pressure drop of ≤ 5 mmH_2O and a particulate filtration efficiency of high-efficiency particulate air (99.97%) or better. Three companies had products that met the performance criteria, and their representatives will be contacted for samples. Six companies had promising technologies, and their representatives will be contacted for more information. These novel aerosol filtration media and technologies will be characterized in-house to determine if they could be included in the next generation respirator.

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PREFACE

The work described in this report was authorized under Project No. 0R22AX. This work was started in June 2010 and completed in March 2011.

The use of either trade or manufacturers' names in this report does not constitute an official endorsement of any commercial products. This report may not be cited for purposes of advertisement.

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NOVEL PARTICULATE AIR-FILTRATION MEDIA: MARKET SURVEY

1. INTRODUCTION

The U.S. Army Edgewood Chemical Biological Center (ECBC) Respiratory Protection Branch members investigated novel aerosol filtration materials for inclusion in the next generation respirator. Commercial particulate filtration technologies with high-efficiency and low-pressure drop have the potential to provide improved protection to the Warfighter while decreasing breathing resistance and thus reducing physiological burden.

2. BACKGROUND

The M50 series Joint Service General Purpose Mask (JSGPM) is the current respirator system used by the U.S. Joint Services. The M50 is a lightweight, protective mask system that incorporates state-of-the-art technology providing a minimum of 24 h of continuous, above-the-neck, head-eye-respiratory protection from vapor, liquid, aerosol, and particulate chemical, biological, radiological, and nuclear (CBRN) threats. The JSGPM is equipped with two low-profile M61 filters that consist of particulate and gas sorbent air-purifying media.

The performance characteristics of the M61 high-efficiency particulate air (HEPA) filter element were used as a guideline to compare and down-select candidate media identified in the market survey. The airflow resistance requirement of a single M61 filter measured at 42.5 L/min (equivalent to 85 L/min through the pair of filters) is 28 mmH_2O. Current production M61 filters typically range between 22 and 24 mmH_2O. Assuming that roughly half of that resistance was contributed by the sorbent media, a resistance of 12 mmH_2O was considered as the maximum acceptable threshold for screening candidate particulate filtration media found in the open literature search.

However, next generation respirators are expected to include lower burden filters. The target total surface area for future filters is 250 cm^2. The new generation of filters will be expected to meet resistance and penetration targets at a face velocity of 5.67 cm/s, which is equivalent to 50 L/min through the 250 cm^2 surface area. In-house testing of single JSGPM M61 filters was performed with a TSI Model 8130 automated filter tester (TSI Inc., Shoreview, MN) to assess the performance of the filters at the targeted face velocity. Model 8130 is a fully automated instrument designed to measure filtration efficiencies up to 99.999% (0.001% penetration) using two solid-state laser photometers to measure aerosol concentration levels up and downstream of the media simultaneously. Along with measuring the percent penetration, the unit provides resistance and flow rate measurements. The filters were challenged with a poly-alpha olefin (PAO) oil aerosol at a flow rate equivalent to 50 L/min through a 250 cm^2 filter. The average resistance of three different filters was 9.2 mmH_2O. Assuming that roughly half of that resistance was due to the carbon sorbent, a target threshold resistance of 5 mmH_2O was estimated from the JSGPM performance requirement for the HEPA element of the filter.

Therefore, a pressure drop of ≤5 mmH_2O was selected as the goal for the development of next generation lower burden filters.

The aerosol filtration penetration requirement for the M61 filter is ≤0.01% (i.e., 99.99% efficiency) when measured at a constant flow rate of 25 L/min (equivalent to 50 L/min through the pair of filters). Each filter has an effective airflow area of approximately 60 cm^2, which results in a face velocity of approximately 7 cm/s when measured at 25 L/min. The particulate filter element of the M61 filter consists of pleated HEPA media and is roughly 6 mm thick. The market survey was limited to media with the potential of achieving efficiencies ≥99.97% (HEPA quality). While this target is below the JSGPM requirement, efficiencies of 99.99% can be achieved through pleating the media, which reduces the face velocity and increases the collection efficiency of the filter. This reduction in face velocity increases the collection efficiency of the filter. In the case of flat sheet electrets (nonwoven electrostatic charged media), the thickness can be increased to meet HEPA requirements. Efficiency can be improved by other means to maximize the effective surface area, for example, by using larger and more efficient filter designs similar to those being considered for future integrated respirator/helmet systems. To avoid eliminating promising media, the market survey did not take into consideration the thickness of the media; however, a total effective surface area of 250 cm^2 was used as the basis for the 5 mmH_2O pressure-drop goal to take into account the increased surface area realized by the emerging advanced filter designs.

Taking these goals into consideration, a market survey was conducted to identify new HEPA quality filtration media with equivalent or greater capture efficiency and lower pressure drop than the particulate media currently used in military air-purifying respirator filters. Only commercial manufacturers were considered.

3. METHODS

Online search engines were researched for the following keywords: *new*, *innovative*, *unique*, *proprietary*, *novel filtration media*, *material*, *filter media*, *air*, *aerosol*, *gas*, or *gaseous*. The searches were initially performed during the summer of 2010 and were later updated in March 2011. Companies and relevant products were identified and described.

Once the products were identified and described, they were objectively and subjectively evaluated. The objective criteria used were a pressure drop of ≤5 mmH_2O and penetration of <0.03%. Subjective criteria included the experience of the researchers and the novelty of the product or technology.

4. RESULTS

Thirty-eight manufacturers with potentially relevant technology were identified using the keyword search. These manufacturers produce a range of filter media including nonwoven, woven, and electret and combinations of media. Some of the manufacturers identified themselves as specializing in biofiltration or nanotechnologies. The companies are listed in alphabetical order along with their product names and brief product descriptions in Table 1.

Table 1. Commercial Filtration Manufacturers Identified in Market Survey

Manufacturer	Products Identified
3M (St. Paul, MN)	AirMate high-efficiency, high-airflow filters and Advanced Particulate Filter 2200 Series
A.R. Medicom, Inc. (Québec, Canada)	SafeMask line
AIM Filtertech Pvt. Ltd. (Pune, India)	Air filter, meltblown, and face mask media
AllergyZone, LLC (Louisville, KY)	High-efficiency electret and mechanical filtration media
American Air Filter International ([AAF] Louisville, KY)	Helior media
AMSOIL Inc. (Superior, WI)	Ea Air Filters technology
Applied Nanoscience, Inc. (Carlsbad, CA)	NanoFense Permaire
Basofil Fibers, LLC (Enka, NC) and Tex Tech Industries (Portland, ME)	BASO-TEX media
Camfil Farr Group (Stockholm, Sweden)	HemiPleat Nano, Absolute Filter, and Megalam, Ultra-Pac
Cerex Advanced Fabrics, Inc. (Cantonment, FL)	SpectraMax
CLARCOR Air Filtration Products, Inc. (Jeffersonville, IN)	Purolator Purolast
Cummins Filtration, Inc. (Stoughton, WI)	StrataPore
Donaldson Company, Inc. (Minneapolis, MN)	Tetratex, Ultra-Web, Spider-Web, Dura-Life, Fiber-Web, and Syntek XP
DuPont (Wilmington, DE)	Spunbond Polypropylene, Nomex KD, and Hybrid Membrane Technology
Fiberweb PLC (London, UK)	Typar/Tekton, Synergex, Reemay, and MasterFlo
Flanders Corporation (Washington, NC)	Permaire
Freudenberg Filtration Technologies, L.P. (Hopkinsville, KY)	Separet 2402 and Viledon filter media
General Electric (GE) Energy (Atlanta, GA)	Aspire, Preveil, Tri-Loft, and Reverse Tri-Loft
Global Finishing Solutions ([GFS] Osseo, WI)	GFS Wave
Hollingsworth & Vose Company ([H&V] East Walpole, MA)	Capaceon, NANOWEB, NanoWave, PerForm, AlphaSeal, AlphaPlus, and Technostat
Irema Ireland (Limerick, Ireland)	Micro2000 Plus

Table 1. Commercial Filtration Manufacturers Identified in Market Survey (continued)

Manufacturer	Products Identified
Johns Manville (Denver, CO)	Assurance
Kimberly-Clark Filtration Products (Kimberly-Clark Corporation, Neenah, WI)	Intrepid
Kolon Industries, Inc. (Gyeonggi-do, Korea)	Heracron
Lydall, Inc. (Manchester, CT)	LydAir line, Arioso line, and ActiPure line
MGF Gutsche GmbH & Co. KG (Fulda, Germany)	Advantex, Microvel, Orotex, and Membratex
Micro-One (Chungnam, Korea)	Microne-Tex
Midwest Filtration Company (Cincinnati, OH)	Unipoly, Unipro, Unilaver, Unifil, Uniblend, Unitherm, and Uniloft
Millipore (Billerica, MA)	Aervent, Aerex, and Durapore
National Nonwovens (Easthampton, MA)	PurusFelt and Filters 29 and 30
Pall Corporation (Port Washington, NY)	Versapore, Versapore TR, Supor R, Emflon *PTFE, Pallflex 40, Pallflex UTF, NEXIS, and POLY-FINE
Texel (Division of ADS, Inc., Québec, Canada)	Tribo
Toray Fine Chemicals Company, Ltd. (Chiba, Japan)	TORAYMICRON, TOYOFLON, TEFAIRE HG, and TEFAIRE X
TWE Dierdorf GmbH & Co. KG (Dierdorf, Germany)	Parafil
Universal Air Filter Company (Sauget, IL)	Quadrafoam and Quadrafoam II
Vokes Air (Svenljunga, Sweden)	Synsafe Reno
W.L. Gore & Associates, Inc. (Newark, DE)	PRISTYNE and RASTEX
Whatman plc (Kent, UK)	*PTFE membrane filters

* PTFE: polytetrafluoroethylene

More detailed descriptions of relevant products for each manufacturer are provided in Section 4.1. The results are organized alphabetically by each company. Only the company products that met the keyword search criteria are described. Product and performance information available on the company websites is included. No companies were contacted for additional information.

4.1 3M

Three of the 3M products[1] were identified in the survey. The first product, the 3M air-mate high-efficiency powered air-purifying respirator (PAPR) systems, provides protection against dusts, musts, fumes, asbestos, radionuclides, and radon daughters. The PAPR filters meet the filtration efficiency requirement, but no pressure drop information could be found on them. The second product is a line of high-airflow (HAF) filters with an antimicrobial agent to help inhibit the growth of mold and mildew on the filter media. The HAF filters, with or without the antimicrobial agent, require a dust cake to form before smaller particles are filtered. Particulate filtration efficiency (PFE) is less than HEPA. A third product produced by the company, the Advanced Particulate Filter 2200 Series disk filters, meets the National Institute of Occupational Safety and Health (NIOSH) P100 standard. These filters use three layers of the

company's advanced electret media (AEM). While these filters meet the filtration performance requirement, their pressure drop is listed in company literature as >10 mmH_2O. However, evaluations conducted at ECBC on various iterations of AEM have yielded promising results. The filtration and pressure-drop characteristics of this media have improved in recent years.

Because 3M researchers are involved in research and development, a search on the company's U.S. operations website was performed to determine if any new technologies were publicized. The search yielded no results for keywords *microfiltration*, *nanofiber*, *nanofilter*, or *nanofiltration*. A search for *nanotechnology* of the U.S. operations resulted in eight items, none of them were related to filters. A search of the term *microfiber* yielded several dental masks as well, as cleaning cloths, but no filter information.

4.2 A.R. Medicom, Inc.

Medicom markets six masks for medical, dental, veterinary, and industrial uses. These masks include the SafeMask Premier Earloop mask, SafeMask Premier Plus Earloop mask, SafeMask Premier Elite Earloop mask, and SafeMask Sof Skin Earloop mask. The Premier for veterinary use (product ID 214)[2] has PFE > 99.4% at 0.3 μm, but the Medicom website does not list the PFE for the Premier for medical use (product ID 123).[3] The biological filtration efficiency (BFE) for the veterinary use of Premier is listed at >99.2%, but the one for medical use lists BFE ≥ 95%. The codes of both products match, so it appears that the product is the same, but the company markets each product with the relevant information for intended use. The Premier Plus (product ID 358)[4] is marketed for dental use and has a PFE ≥ 98% with a resistance of <3.0 mmH_2O/cm^2. The Premier Elite (product ID 359)[5] is intended for the dental market and has a PFE ≥ 99% at a resistance <3.0 mmH_2O/cm^2. The Sof Skin for dental (product ID 350),[6] medical (product ID 351),[7] and industrial (product ID 348)[8] uses does not have PFE listed but has BFE ≥ 95%. The Sof Skin for veterinary use (product ID 216)[9] has PFE > 99.4% at 0.3 μm.

4.3 AIM Filtertech Pvt. Ltd.

Three types of media from AIM Filtertech[10] met the search criteria. These were air filter media, meltblown media, and face mask media. The air filter media are composite microfiber fabrics with low-pressure drops and efficiency classes from F5 to F9 (minimum efficiency reporting value [MERV] 9 to 15). Specific efficiency curves for the products were not provided on the company website. However, from the standard curves provided, it was estimated that the F9 class had approximately 98% efficiency for 0.5 μm particles. The lower numbered classes have PFE <90% for 0.5 μm particles. The AIM Filtertech meltblown filters, ACCOMPLISH MEDIA, use micro and nanofiber technology. The meltblown textiles can be manufactured using polypropylene, polyamides, polylactic acid and biodegradable polymers, polyester, polybutylene tephthalate (PBT), and polyethylene terephthalate (PET). The applications include air filtration, medical disposables, automotive, and various consumer products. Performance data were not provided on the company website. The final product identified was a meltblown media that is intended for face masks. It is sold as flat sheet media or molded into face masks. The media meets the European standard, Europeen de Normalisation

(EN), for filtering face pieces (FFP) FFP1, FFP2, and FFP3. The company website states that the media have high BFE, but no performance data were provided.

4.4 AllergyZone, LLC

One technology from AllergyZone was identified.[11] The company produces a pleated, high-efficiency panel furnace filter that uses electret and mechanical filtration. The filter has a MERV rating of 12, which does not meet the HEPA filtration efficiency requirement.

4.5 AAF

AAF manufactures the MEGAcel I filter with Helior media.[12] The proprietary Helior is a high-efficiency expanded polytetrafluoroethylene (ePTFE) media with low resistance. The filters are intended for heating, ventilation, and air conditioning (HVAC) systems. They have tapered aluminum separators. There are HEPA and ultra-low penetration air (ULPA) versions of the filter. The HEPA has a minimum 99.99% filtration efficiency for 0.3 μm particles. The ULPA exceeds 99.99995% at the most penetrating particle size ([MPPS] about 0.1 μm) at 100 ft/min flow rate for a 35 mm filter. Pressure drop was advertised at approximately 0.1 inH_2O gauge (2.5 mmH_2O) at a flow rate of 500 cfm (14,160 L/min) through a 24 × 24 × 11.5 in.^{3} filter (61 × 61 × 29 cm^3). While the media is primarily for use in HVAC systems, it may possibly be useful for other applications.

4.6 AMSOIL, Inc.

AMSOIL Ea vehicle air filters[13] are made of synthetic nanofibers. The company website states that the filters remove five times more dust than traditional air filters, but no data were provided on the company website.

4.7 Applied Nanoscience, Inc.

Applied Nanoscience, Inc. does not make a filtration product. However, its members have developed a system of enhancing existing filters by combining them with nanoparticles. This capability is called Nanoparticle-Enhanced-Filtration Technology (NEFT). A U.S. Patent is pending on the company's Applied Nanoscience NanoFense Permaire formulation.[14] Nanoparticles are used in powder or pellet form that are either known or engineered to destroy or inactivate bacteria, fungi, viruses, or toxins. The powdered particles can be coated on the filter or impregnated in the fibers, and the pellet particles are placed next to the filter. The nanoparticles are customized for the organism that the customer wishes to target. Efforts are underway to develop a disposable face mask called the NanoFense Permaire Protective Face Mask. The company website states that the NEFT filter media achieves 99.99% PFE with 0.03 μm particles. Information on pressure drop was not provided on the company website.

4.8 Basofil Fibers, LLC and Tex Tech Industries

Basofil produces high-temperature, dry filter media for pulse-jet baghouses, and Tex Tech produces woven and nonwoven filtration fabrics. The two companies partnered together to create BASO-TEX Filter Media,[15] which is a nonwoven combination of Basofil and meta-aramid fibers with inherent triboelectric properties. BASO-TEX filter media is heat and flame resistant.[15] It is used in high-temperature, dry filtration pulse-jet baghouses for industrial applications such as aluminum manufacturing. The media has an efficiency of 99.8% and has a lower pressure drop than 100% meta-aramid fibers.

4.9 Camfil Farr Group

Camfil Farr has four products that are advertised as having both high-filtration efficiency and low-pressure drop. The company's HemiPleat Nano adds nanofiber media to its other product, HemiPleat media, to increase the MERV rating from 10 to 14.[16] The company's website states that it also produces a high-efficiency media with a MERV of 16, indicating 99.999% filtration efficiency of 0.5 μm particles. The ePTFE absolute filter contains an ULPA-grade pleated media with depths of 45 or 68 mm.[17] The filters have a minimum filtration efficiency of 99.99995% at the MPPS and an initial resistance of <7.6 mmH_2O for the 45 mm depth at a flow rate of 51 cm/s. The pleated Megalam panel filter is available with efficiencies from 95% for a particle size of 0.3 μm and 99.99995% at MPPS.[18] Pleated thicknesses are 53, 70, and 100 mm. The pressure drop of the 53 mm thick filters for the 95% HEPA and ULPA versions are 5.3, 12.4, and 17.3 mmH_2O at 51 cm/s. The Ultra-Pac is a microfiber all-glass media that is available in efficiencies of 95 and 99.99% for a 0.3 μm particle.[19] The respective pressure drops were reported as 12.7 and 25 mmH_2O at 51 cm/s.

4.10 Cerex Advanced Fabrics, Inc.

Cerex Advanced Fabrics manufactures a range of nonwoven nylon spunbond fabrics such as SpectraMax.[20] The company's website proclaims that SpectraMax has superior filtration efficiency, but no data were provided.

4.11 CLARCOR Air Filtration Products, Inc.

CLARCOR makes Purolator Purolast, a bonded polyester fiber air-filtration media.[21] The media is too thick (1.3 to 5 cm), and the efficiency is too low (50–65%) to be useful for the current application.

4.12 Cummins Filtration, Inc.

Cummins Filtration designed the StrataPore synthetic media.[22] The company's researchers used a meltblown process to create multiple layers of polymeric filter material. The individual media sheets can be optimized for the removal of specific particle sizes, increasing the media filtration efficiency. However, the media is intended for fuel filtration in vehicles.

4.13 Donaldson Company, Inc.

Donaldson's Tetratex ePTFE membranes[23] and Ultra-Web[24] and Spider-Web[25] submicron polymeric nanofiber materials met the search criteria. The nanofibers are created using an electrospinning process that generates fibers with diameters <0.5 μm. Nanofiber filter media is used in the Ultra-Web filters for dust collection, in the Spider-Web filters for gas turbine air filtration, and in the EnduranceTM air filters for heavy-duty engines. The Tetratex line consists of hydrophobic ePTFE membranes, available by themselves, or bonded to spunbond polyester, polypropylene, and polyethylene substrates. Additional substrates include Aramid, fiberglass, pleatable polyester antistatic (PPS), P84, and PTFE. Pore sizes for the membranes range from 0.05 to 7.0 μm with thicknesses of 0.005 to 0.25 mm. Particulate filtration efficiency is shown on a graph on the company website to be >99.5% for 0.3 to 0.5 μm particles.

Donaldson's Dura-Life line[26] uses Durapex media that is created by using a hydroentanglement process to blend the fibers. The company website states that this results in a media that is more efficient at capturing 2.5 μm or smaller dust particles compared to standard polyester bags. No filtration efficiency or pressure-drop data were provided. Ultra-Web technology is used in cartridge filters for cabin air filters and in mining haul trucks and military vehicles to protect engines. The product literature shows that the media removes 99.99% of dust particles after exposure to 1 kg of dust during approximately 100 h of operation for a typical off-road application. An electrospinning process is used to create 0.2 to 0.3 μm diameter fibers that are formed into a web. These fibers are available in efficiencies of MERV 13 to 15, so they do not meet the HEPA level.

Donaldson's Spider-Web media is made from a web of submicron fibers that are bonded onto cellulose or synthetic substrates. Spider-Web XP places the submicron fibers on both sides of the substrate. Initial particulate filtration efficiency of 0.5 μm particles is 87% for Spider-Web XP and 74% for Spider-Web. The Fibra-Web product line consists of cartridges with synthetic nanofibers (average 0.2 μm diameter) bonded onto a synthetic fiber substrate (average diameter 12 μm).[27] The filtration efficiency rating is MERV 14. The company's Synteq XP filter media has a PFE of 99.81%.[28] The media is intended for oil-moisturized conditions.

4.14 DuPont

The search identified several products from DuPont. Nomex KD is a blend of Nomex and Kevlar fibers.[29] The resulting media has an increased surface area that can improve filtration efficiency up to 60% without adding media weight. On the other hand, filter weight can be reduced while maintaining the same efficiency level. DuPont hybrid membrane technology (HMT) is created using a proprietary spinning process. HMT is a membrane-like nonwoven sheet of polymeric filaments between 200–600 nm. Filtration efficiency and pressure drop were not provided on the company website. DuPont Spunbond polypropylene is a nonwoven fabric made of thermally bonded polypropylene fibers. Filtration efficiency and pressure drop data were not provided for any of the technologies.

4.15 Fiberweb

The search identified four Reemay filtration products: Typar/Tekton spunbonded polypropylene,[30] Synergex flat-bonded nonwoven,[31] Reemay spunbond polyester,[32] and MasterFlo depth filtration media for liquid and gas filtration.[33] Little information was available on the company website, although Synergex was identified as high-efficiency.

4.16 Flanders Corporation

Flanders produces Permaire,[34] a passive electrostatic filter medium constructed from resin-treated synthetic fibers. The filters are intended for air filtration for furnaces, paint spray booths, and room and central air conditioners. No filtration efficiency or resistance data were provided on the company website.

4.17 Freudenberg Filtration Technologies, L.P.

Freudenberg Filtration Technologies produces Viledon filter media,[35] which is used for particulate filtration in half-mask respirator applications. While multiple products that are customizable for specific uses are available, only the Separet 2402 meets FFP3 standards. This media is foldable and can be used with additional support structures. The characteristics of the material are

- weight: 210 g/m^2
- thickness: 2.4 mm
- composition: polypropylene and polyacrylonitrile fibers
- sodium chloride penetration: $\leq$0.9% at 8 cm/s flow rate
- flow resistance: <2 mmH_2O at 8 cm/s flow rate

4.18 GE Energy

The Aspire filtration media[36] and membrane solutions and Preveil membrane[37] from GE Energy met the search criteria. The Aspire line combines filtration with venting capabilities for healthcare, automotive, and packaging applications. With this media, filtration efficiencies >99.99% are possible while allowing adequate airflow. Typical healthcare applications include intravenous venting systems, surgical filtration, and ostomy bags. Preveil is an ePTFE membrane that is bonded to the surface of conventional filter media. Membrane characteristics such as pore size, pore size distribution, and membrane thickness can be customized. The GE Energy website proclaimed that Preveil provides low-pressure drops with high-efficiency (>99.99%) filtration, but the site did not state whether Preveil provides biological or particulate filtration or specify the pressure drops. Preveil can be laminated onto polypropylene, polyester, acrylic polyphenylene sulfide, Aramid, fiberglass, P84, or PTFE filter material. Filter bags laminated with the Preveil membrane do not require a traditional dust cake to build for filtration efficiency. GE also has fabric filtration media such as Tri-Loft and Reverse Air Tri-loft[38] woven filter bags that require a dust cake to collect particulate matter. The company website stated that the Tri-Loft and Reverse Air Tri-loft[38] woven filter bags have maximum efficiency with high airflow, but no data were provided.

4.19 GFS

GFS produces the GFS Wave filter for paint spray booths,[39] which has 99.83% particulate filtration. No pressure-drop information was provided on the company website.

4.20 H&V Company

The product lines for H&V have many different types of air filters including those designed for respirators. The company maintains an active research and development center. The Capaceon air filter media is intended for automotive and heavy duty applications.[40] It uses nonsynthetic fibers and has a higher initial efficiency than its competitors. However, the initial efficiency is below 97%. NANOWEB Advanced Nanofiber Technology media,[41] another H&V product, has a microporous structure. It can function as stand-alone media, or it can be coated on a nonwoven base such as glass, cellulose, or synthetic fiber. Thickness, fiber, and pore size can be adjusted for a specific application. The company website states that their process leads to a nanofiber coating that is more flexible, controlled, and durable compared to one created using electro-spinning. The nanofibers typically range from 0.3 to 0.5 μm, but can go up to 1 μm. A nanofiber layer has a thickness of 15 to 30 μm, and it is applied to a macrofiltration substrate. A second nanofiber layer can be applied as a coating. Sample filtration efficiencies and pressure drops were not provided on the H&V website. NanoWave Extended Surface Filter Media is a synthetic filter media for HVAC,[42] paint spray booths, and respirators. It is available in F6, F7, and F8 ratings (MERV 11, 14, and 15). Pressure drops are 2.4, 4.6, and 9.2 mmH_2O at 0.11 m/s. PerForm[43] is a pleated HEPA/ULPA filter media. Pressure drop for all varieties is 24 mmH_2O or higher. AlphaSeal and AlphaPerm Plus are the company's two meltblown filter media.[44] Particulate filtration efficiency of NaCl (5.33 cm/s, 0.5 μm challenge particle) is <98% for all models. Technostat electrostatic media filters particulates down to 0.05 μm.[45] It is available in rolls (composite or individual component), sheets, converted filters (cut pads), and pleat pack forms. Versions of this media are available to meet various EN and NIOSH respirator standards including P100. However, resistance increases as penetration decreases and none of the media meets the resistance and filtration efficiency requirements.

4.21 Irema Ireland

Micro 2000 Plus filtration media from Irema was identified as a possible candidate technology.[46] It is a nonwoven meltblown filter media designed for surgical masks and HVAC applications. It is marketed as encompassing high-efficiency and low-pressure drop. The HVAC media is available in grades F5 through F9. Values for mask media efficiency were not provided on the Irema website, but because the material is suitable for surgical masks, it is likely not adequate enough for respirator applications.

4.22 Johns Manville

Johns Manville manufactures Assurance,[47] a nonwoven, mechanical air filtration media. This media is intended for furnace applications and comes in MERV 6 to 8, which does not meet the performance requirements.

4.23 Kimberly-Clark Corporation

Kimberly-Clark makes an electret filter media called Intrepid that has a high filtration efficiency and low-pressure drop.[48] The media is made from hydrophobic polyolefin fibers that are thermally bonded together. It has an engineered gradient structure that increases fiber density from upstream to downstream, concomitantly increasing filter efficiency. However, the filters are reported to have a filtration efficiency <90%.

4.24 Kolon Industries, Inc.

Heracron, an aramid product from Kolon Industries, Inc., is used in protective apparel.[49] Performance data were not provided for this product on the company website.

4.25 Lydall, Inc.

Lydall has an active research and development laboratory and testing facility with rapid prototyping capabilities. The company has a large range of filtration products with efficiencies up to ULPA (99.9995%+). Available media from Lydall include microglass, synthetic composites, membranes, and activated carbon impregnated media. LydAir MG is the company's microglass media.[50] This media uses only mechanical filtration, is pleatable, and is available in a range of efficiencies including ULPA. However, all pressure drops for the media exceed 25 mmH_2O.

The synthetic media include LydAir MB,[51] LydAir SC,[52] and Arioso membrane composite.[53] LydAir MB is a polypropylene meltblown media with low air resistance but with the highest available PFE (95%) for NaCl at 32 L/min. LydAir SC is a composite of polypropylene and polyester that combines mechanical filtration with an electrostatic charge. Lydall's SC 8501 model has an NaCl penetration of <1% with a resistance of 7 mmH_2O at a face velocity of 5.33 cm/s. The basis weight for the SC 8501 model is 98 g/m^2.

Lydall's Arioso composite media consists of a Solupor membrane laminated to a backing layer. Solupor membranes are made from ultra-high molecular weight polyethylene (UHMWPE). The backing material options include wet-laid glass, polyester (wet-laid and spunbond), wet-laid polyester-cellulose, and spunbond polypropylene. The Arioso filtration structure consists of a micro and nanofibrillar multilayer network. Efficiencies for this media range from 99.5 to 99.99993%. The M32 has a particulate filtration efficiency of 99.95%, the M33 has 99.9995%, and the M34 has 99.99993%. No data sheets were provided on the company website for the M33 or M34 series, so the pressure drops are unknown. Pressure drops for the M32 series are around 15 mmH_2O. ActiPure combines activated carbon with a nonwoven media.[54] It can be laminated to most Lydall filter media. The C680 and C688 models are recommended for air filtration. The basis weights for the C680 and C688 are 142 and 212 g/m^2, respectively. Both models are used to remove sand, silt, rust and other sediment particles as small as 5 μm.

4.26 MGF Gutsche GmbH & Company KG

Gutsche makes synthetic needled felt for dry filtration. The product line for Gutsche includes Advantex,[55] Microvel,[56] MPT-coated Porotex,[57] Antafin-coated Porotex,[58] and Membratex.[59] No filtration performance information was available on the company website.

4.27 Micro-One

Micro-One makes air filters for the baghouse filtration industry. In addition to the company's standard media, Micro-One laminates an ePTFE membrane on polyester, polypropylene, PPS, aramid, PTFE, and fiberglass fabric.[60] The resulting product, Microne-Tex, is marketed as having a lower pressure drop, but performance data were not provided on the company website.

4.28 Midwest Filtration Company

Midwest Filtration produces rolls of engineered nonwoven filter media for multiple applications.[61] Available products include Unipoly (spunbond polyester), Unipro (point bond polypropylene), Unilayer (spunbond polypropylene), Unifil (chemically bonded rayon/polyester), Uniblend (wet-layed polyester/cellulose blend), Unitherm (thermally bonded polyester/polyethylene), and Uniloft (spunbond polypropylene). No pressure drops or filtration efficiencies were listed on the Midwest Filtration website.

4.29 Millipore

Three Millipore products were identified. The 0.2 μm hydrophobic Aervent PTFE membrane[62] is used for the sterile filtration of gases. Aerex hydrophobic filters[63] are made from PTFE membrane and polypropylene. They are used to remove particles as small as 0.01 μm. Aervent and Aerex filters are used to retain virus aerosol, and Aervent is also used to retain liquid bacteria according to the company website. Durapore hydrophobic membrane filters are made of polyvinylidene fluoride (PVDF).[64] Pressure drop for these filters depends on model and filter size. Particle filtration efficiencies were not provided on the Millipore website.

4.30 National Nonwovens

National Nonwovens makes filters for wet and dry applications. The company's filters 29 and 30 are new high-loft needlepunch nonwoven filter mediums with low-pressure drops.[65] The PurusFelt is a scrimless filter made of polyester or Nomex.[66] The company's website does not list pressure drops or particulate filtration efficiencies.

4.31 Pall Corporation

Several products were identified in the Pall Corporation online search. The Versapor R membrane[67] is an acrylic copolymer membrane that is cast on a nonwoven nylon support, and the Versapor TR membrane[68] is a modified acrylic copolymer membrane that is cast on nonwoven polyester support. Both are available in different thicknesses of rolled media.

Available pore sizes range from 0.2 to 5 μm. The Supor R membrane is made from a modified polyethersulfone polymer on a nonwoven polyester support.[69] It is available in rolls, sheets, and disks. The company also has a line of asymmetric membranes with low-pressure drops. These have larger pores on the upstream side of the membrane that act as a prefilter before the flow reaches the smaller pores on the downstream side. The Pall Corporation Emflon PTFE membrane line is marketed with no support or with polyester or polypropylene support.[70] The Pallflex 40 medium is made of a high-strength hemp fiber base with a glass fiber matrix.[71] The Pallflex UTF media is a cast film of 100% PTFE resin.[72] Two meltblown technologies are also available from Pall Corporation.[73] NEXIS depth filter cartridges have a pore gradient structure. The POLY-FINE absolute rated depth (ARD) filter has an outer section that removes larger particles and an inner section that removes particles at the stated micron rating. Both technologies have very high-particle filtration efficiencies. The Pall Corporation website did not provide PFE data on any of the filters.

4.32 Texel

Texel manufactures nonwoven air filtration media. The company's Tribo media has an electrostatic charge and an antimicrobial coating.[74] It is available in flat, pleatable, supported, and unsupported varieties and is marketed for respiratory masks, HVAC filters, and air purifier filters. This line of filters has weights of 70 to 400 g/m^2. The company website states that the media meets NIOSH N, R, and P standards including the P100 criteria. Texel provided pressure drop and filter efficiency data versus basis weight for the NaCl and dioctylphalate (DOP) challenges. For the NaCl challenge, the pressure drop was below 2.5 mmH_2O for all basis weights. Filtration efficiency was around 100% for the same basis weight (read from a graph). For the DOP challenge, the pressure drop was below 5 mmH_2O for basis weights of 350 g/m^3 and below. Filtration efficiency was around 100% for basis weights of 350 g/m^3 and higher (read from a graph).

4.33 Toray Fine Chemicals Company, Ltd.

Several high-performance materials from Toray were identified in the search. TORAYMICRON is a nonwoven sheet of ultrafine polypropylene fibers with electret properties.[75] Toray's MB150 model meets HEPA levels, and another model, the EP100, meets ULPA levels. The MB150 is 0.93 mm thick with a particulate efficiency of 99.97% and pressure drop of 4.9 mmH_2O. The EP100 is 0.61 mm thick with a particulate efficiency of 99.999% and a pressure drop of 8.5 mmH_2O. Testing for both models was performed at 2.5 cm/s air velocity. Particles for the MB150 performance test were 0.3 μm dust particles, and 0.1 μm polystylene latex particles were used for the EP100 test. TOYOFLON media is produced by converting fluororesin into fibers.[76] The recommended uses for this product are for high-temperature filter bags and general industrial filters. No performance data were available. TEFAIRE HG[77] media is a patented blend of TEFLON fibers and glass. Performance data were not provided on the Toray website. TEFAIRE X is a blend of TEFLON fibers, glass, and Toray Torcon fibers.[77] Pressure drop for this product was reported as 30 mmH_2O, while efficiency was 99.9998% (particulate matter with diameters <2.5 μm).

4.34 TWE Dierdorf Gmbh & Company KG

TWE Dierdorf Gmbh & Company KG has several product lines including Parafil, and thermally bonded, polyester, and polypropylene nonwovens.[78] Pressure drops and filtration efficiencies for the TWE Dierdorf Gmbh & Company KG products were not listed on the company website.

4.35 Universal Air Filter Company

Universal manufactures the Quadrafoam and Quadrafoam II line of open cell polyurethane foam media with a flame- and fungus-resistant coating.[79] Both media offer low airflow resistance and high dust-holding capacity. The Quadrafoam II is intended for high-temperature and high-humidity applications. The PFE data were not provided on the company website, but the highest dust arrestance for each product line was 91%.

4.36 Vokes Air

Vokes Air has a large range of air filter media. The company manufactures Synsafe Reno,[80] which uses Nanofyne Technology as one of the filter media layers. The Synsafe is made of a prefilter layer to capture larger particles, a primary fine particle filter layer, the Nanofyne layer, and a self-cleaning layer that also provides structure and support. The composite filters are available in classes F5 to F8. The F8 filter class has PFE $\geq$ 90% for 0.4 μm particles. Pressure drop was listed as 9.7 mmH_2O at a flow rate of 94 m^3/s. The class F8 filters are used for fine dust and are efficient for particles that are $\geq$0.1 μm under European Standard EN779.

4.37 W.L. Gore & Associates, Inc.

Gore produces a range of PRISTYNE Filter Media using ePTFE laminated onto a support fabric.[81] The support fabrics are felted, woven, or spunbonded, such as Gore's woven RASTEX Fiber Fabric 7210.[82] Particulate filtration efficiency and pressure drop were not provided on the company website. The SINBRAN filter is a combination of porous polyethylene and a laminated ePTFE membrane.[83] A pressure loss of <20 mmH_2O occurs at a filter surface loading of 2 m^3/m^2 min. Again, particulate filtration efficiency was not provided. SINBRAN is intended for industrial applications only.

4.38 Whatman plc

Whatman, a part of GE Healthcare, produces membrane filters with pore sizes ranging from 0.015 to 12 μm. The company's PTFE membrane line is intended for air and gas sterilization.[84] Filtration performance data were not provided on the Whatman website.

5. DISCUSSION

While several potential candidate technologies were identified, none were significantly better than the particulate media used currently by the military. However, many of the companies did not provide enough information on their websites to fully evaluate their media. Additionally, the companies evaluated particulate filtration efficiency and pressure drops using tests with different particle challenge materials and particle sizes. Because of these challenges, the decision regarding which technologies to pursue was based on the available performance data relative to the target performance criteria as well as the user's experience and prior knowledge.

Three companies (American Air Filter, Texel, and Toray) had at least one product that met the performance requirements while six (3M, Applied Nanoscience, Inc., Donaldson, GE–Air Filtration Media, H&V, and Lydall) had prospective technologies that met some of the performance requirements but did not provide enough information on their websites to fully evaluate the product. Nineteen of the companies did not provide sufficient data on their websites to evaluate the performance characteristics of their products. The filter media from nine of the manufacturers did not meet the required performance based on the information provided on filtration and pressure drop on their websites. Two companies provided information on some products that did not meet the requirements, while information was lacking on other technologies on their websites.

Recommendations for further study of the media already researched online are summarized in Table 2. A more detailed discussion of these products follows the table.

Table 2. Products to Pursue

Manufacturer	Pursue?
3M	Yes–AEM based on previous in-house evaluations
A.R. Medicom, Inc.	No–performance not met
AIM Filtertech Pvt. Ltd.	No–performance not met; insufficient information
AllergyZone, LLC	No–performance not met
American Air Filter International	Yes–Helior
AMSOIL Inc.	No–insufficient information
Applied Nanoscience, Inc.	Yes–NEFT filter media; more information needed
Basofil Fibers, LLC and Tex Tech Industries	No–performance not met
Camfil Farr Group	No–performance not met
Cerex Advanced Fabrics, Inc.	No–insufficient information
CLARCOR Air Filtration Products, Inc.	No–performance not met
Cummins Filtration, Inc.	No–insufficient information
Donaldson Company, Inc.	Yes–Tetratex; more information needed
DuPont	No–insufficient information
Fiberweb	No–insufficient information

Table 2. Products to Pursue (continued)

Manufacturer	Pursue?
Flanders Corporation	No–insufficient information
Freudenberg Filtration Technologies, L.P.	No–performance not met
GE Energy	Yes–Preveil; more information needed
GFS	No–performance not met; insufficient information
H&V Company	Yes–NANOWEB; more information needed
Irema Ireland	No–insufficient information
Johns Manville	No–performance not met
Kimberly-Clark Filtration Products	No–insufficient information
Kolon Industries, Inc.	No–insufficient information
Lydall, Inc.	Yes–LydAir SC8501, Arioso M33, and M34; more information needed
MGF Gutsche GmbH & Co. KG	No–insufficient information
Micro-One	No–insufficient information
Midwest Filtration Company	No–insufficient information
Millipore	No–insufficient information
National Nonwovens	No–insufficient information
Pall Corporation	No–insufficient information
Texel	Yes–Tribo
Toray Fine Chemicals Company, Ltd.	Yes–TORAYMICRON MB150
TWE Dierdorf GmbH & Co. KG	No–insufficient information
Universal Air Filter Co.	No–insufficient information
Vokes-Air	No–performance not met
W. L. Gore & Associates, Inc.	No–insufficient information
Whatman plc	No–insufficient information

The 3M commercial AEM, or a custom version of this media, may be a promising candidate based on results from in-house evaluations conducted on an AEM that was chosen for a prior mask filter development effort.

The American Air Filter MEGAcel I filter with Helior media met the pressure drop and filtration efficiency requirements. The Helior media is made from ePTFE. Even though this product is intended for HVAC systems, it will be researched for potential use.

Applied NanoScience, Inc. enhances filtration of existing filter media, either by coating or impregnating the media with nanoparticles. The NanoFense Permaire face mask has a filtration efficiency of 0.03 μm particles of 99.99%. Pressure-drop information was not provided on the company website, so more information is needed from the company to determine if this product fully meets performance requirements.

Donaldson's Tetratex line consists of ePTFE membranes that can stand alone or be bonded to various substrates. A graph on the company website showed filtration efficiency >99.5% for 0.3 μm particles, which is below HEPA, but the PFE is partially

dependent on the substrate selected. It is possible that this product will meet performance requirements.

The GE Preveil is an ePTFE membrane that is bonded to various substrates. The membrane characteristics can be tailored to the application. Filtration performance is reported at >99.99% on the company website, but it is unclear whether this was bacterial or particulate filtration efficiency. The company website states that pressure drops are low, but does not provide any values. More information is needed to determine if Preveil could meet the pressure requirements.

H&V produces NANOWEB, a nanofiber media with a microporous structure that can be used by itself or coated on a nonwoven substrate. The media characteristics can be customized. Sample filtration efficiency and pressure drops were not provided on the company website. While the company did not provide sufficient information to fully evaluate this media, it is considered sufficiently novel to pursue research.

Lydall had three promising products. The LydAir SC 8501 is a composite media that combines mechanical filtration with an electrostatic charge. It has an NaCl penetration of <1% with a pressure drop of 7 mmH_2O. While the PFE is not specific enough, the pressure drop is close to the requirement. The Arioso M33 and M34 series exceeded the filtration efficiency requirements, but pressure-drop information was not provided on the company website. Pressure drops for the M32 series, with a lower PFE than the M33 and M34 series, are around 15 mmH_2O. Therefore, the possibility exists that the pressure drop will exceed requirements because pressure can increase with an increase in filtration performance. More information is necessary to determine if any of these three products will be useful.

Texel manufactures an electrostatic media with an antimicrobial rating. This Tribo media meets P100 requirements, so it can handle oil aerosols. Information read from graphs on the company website showed that for a DOP aerosol challenge, pressure drop was below 5 mmH_2O and particulate efficiency was close to 100%. This media will be further investigated.

Toray produces TORAYMICRON, a nonwoven sheet of ultra-fine polypropylene fibers with electret properties. Model MB150 meets HEPA efficiency with a pressure drop of 4.9 mmH_2O. The EP100 version meets ULPA efficiency but has a pressure drop of 8.5 mmH_2O. The HEPA version will be further investigated. The ULPA version may be included for comparison.

6. CONCLUSIONS AND RECOMMENDATIONS

An online market survey was performed to identify commercial manufacturers that produce novel filtration technologies. Performance requirements included a pressure drop of ≤5 mmH_2O and a particulate filtration efficiency of HEPA (99.97%) or better. Thirty-eight manufacturers had products that met the keyword search criteria. The websites of these companies were searched to determine the performance characteristics of their products. Nine

companies were identified that had at least one product or technology that was worth researching further. 3M, American Air Filter, Texel, and Toray Fine Chemicals Company, Ltd. will be contacted to obtain their products. Applied Nanoscience, Inc., Donaldson, GE–Air Filtration Media, H&V, and Lydall will be contacted to obtain more information. If any product from these companies is deemed suitable, it will be obtained. The performance of these novel aerosol filtration materials and technologies will be characterized in-house to determine if they are suitable candidates for the development of the next generation of respirator filters.

LITERATURE CITED

1. 3M. Respiratory Protection. http://solutions.3m.com/wps/portal/3M/en_US/Health/Safety/Products/Catalog/?PC_7_RJH9U5230GE3E02LES9MG812H2000000_nid=8G2B3GV59PbeF3RH7CD92Ngl (accessed 4 August 2010).

2. A.R. Medicom, Inc. Safe-Mask Premier Earloop Mask (Veterinary). http://www.medicom.com/productdetails.ch2?productid=224 (accessed 12 August 2010).

3. A.R. Medicom, Inc. Safe-Mask Premier Earloop Mask (Medical). http://www.medicom.com/productdetails.ch2?productid=123 (accessed 12 August 2010).

4. A.R. Medicom, Inc. Safe-Mask Premier Plus Earloop Mask. http://www.medicom.com/productdetails.ch2?productid=358 (accessed 12 August 2010).

5. A.R. Medicom, Inc. Safe-Mask Premier Elite Earloop Mask. http://www.medicom.com/productdetails.ch2?productid=359 (accessed 12 August 2010).

6. A.R. Medicom, Inc. Safe-Mask Sof Skin Earloop Mask (Dental). http://www.medicom.com/productdetails.ch2?productid=350 (accessed 12 August 2010).

7. A.R. Medicom, Inc. Safe-Mask Sof Skin Earloop Mask (Medical). http://www.medicom.com/productdetails.ch2?productid=351 (accessed 12 August 2010).

8. A.R. Medicom, Inc. Safe-Mask Sof Skin Earloop Mask (Industrial). http://www.medicom.com/productdetails.ch2?productid=348 (accessed 12 August 2010).

9. A.R. Medicom, Inc. Safe-Mask Sof Skin Earloop Mask (Veterinary). http://www.medicom.com/productdetails.ch2?productid=216 (accessed 12 August 2010).

10. AIM Filtertech Pvt. Ltd. Performance Engineered Nonwovens: Products. http://www.aimfiltration.com/products_syn_air.asp (accessed 12 August 2010).

11. AllergyZone, LLC. AllergyZone Furnace Filters. http://www.allergyzone.com/ (accessed 5 August 2010).

12. American Air Filter International. MEGAcel 1. Retrieved http://www.aafintl.com/Products/HEPA%20Filtration/Filters/MEGAcel%20I.aspx (accessed 9 August 2010).

13. AMSOIL Inc. AMSOIL Ea Air Filters. http://www.amsoil.com/storefront/eaa.aspx (accessed 5 August 2010).

14. Applied Nanoscience, Inc. Applied Nanoscience Announces Successful Coating of Filter Media for NanoFense Protective Face Mask. http://www.appliednanoscience.com/page1.html (accessed 5 August 2010).

15. Basofil Fibers, LLC and Tex Tech Industries. Basotex Filter Media. http://www.textech.us/BASOTEX.pdf (accessed 5 August 2010).

16. Camfil Farr. HemiPleat Filters. http://www.farrapc.com/products/hemipleat/nano (accessed 12 August 2010).

17. Camfil Farr. EPTFE Absolute Filters. http://www.filterair.info/literature/Files/EPTFE%20Product%20Sheet.pdf (accessed 12 August 2010).

18. Camfil Farr. Megalam HEPA/ULPA Panel Filters. http://www.filterair.info/literature/Files/MEGALAM%20PANELS%20PRODUCT%20SHEET.PDF (accessed 12 August 2010).

19. Camfil Farr. Ultra-Pac Close-Pleat Technology High-Efficiency Air Filter. http://www.filterair.info/literature/Files/ULTRAPAC%20PRODUCT%20SHEET.PDF (accessed 12 August 2010).

20. Cerex Advanced Fabrics, Inc. Typical Physical Properties of SpectraMax Fabrics. http://www.cerex.com/Zones/Org1/uploads/spectramax_pp.pdf (accessed 5 August 2010).

21. CLARCOR Air Filtration Products, Inc. Purolator Permalast Air Filter Media. http://www.purolatorair.com/brochures/P-PERMA.pdf (accessed 5 August 2010).

22. Cummins Filtration, Inc. StrataPore Filtration Media. http://www.fleetguard.com/html/en/innovation/technology/stratapore.html (accessed 5 August 2010).

23. Donaldson Company, Inc. Tetratex. http://www.donaldson.com/en/filtermedia/support/datalibrary/059984.pdf (accessed 12 August 2010).

24. Donaldson Company, Inc. Ultra-Web Nanofiber Technology. http://www.donaldson.com/en/engine/support/datalibrary/063312.pdf (accessed 12 August 2010).

25. Donaldson Company, Inc. Donaldson Filtration Solutions. http://www.emea.donaldson.com/en/gasturbine/support/datalibrary/033652.pdf (accessed 12 August 2010).

26. Donaldson Company, Inc. Filter Media Technology. http://www.donaldson.com/en/gasturbine/support/datalibrary/000934.pdf (accessed 12 August 2010).

27. Donaldson Company, Inc. Fibra-Web Cartridge. http://www2.donaldson.com/torit/en-us/documents/productdatasheets/fibra-web.pdf (accessed 12 August 2010).

28. Donaldson Company, Inc. The New Filter Media: Synteq XP. http://www.donaldson.com/en/compressor/support/datalibrary/065003.pdf (accessed 12 August 2010).

29. DuPont. New DuPont Nomex KD. http://www2.dupont.com/Nomex/en_US/assets/downloads/DP_Nomex%20KD_v15.pdf (accessed 12 August 2010).

30. Fiberweb. Typar/Tekton Spunbond Polypropylene Filtration Media. http://www.reemay.com/Typar_Tekton.cfm (accessed 5 August 2010).

31. Fiberweb. Synergex Composite Polyester Filtration Media. http://www.reemay.com/Synergex.cfm (accessed 5 August 2010).

32. Fiberweb. Reemay Spunbond Polyester Filtration Media. http://www.reemay.com/Reemay.cfm (accessed 5 August 2010).

33. Fiberweb. MasterFlo Product Properties. http://www.reemay.com/media-properties-MasterFlo.cfm (accessed 5 August 2010).

34. Flanders Corporation. Permaire. http://www.florencefilter.com/FFC%20Products/Bulk%20Rolls/P210%20Permaire.pdf (accessed 5 August 2010).

35. Freudenberg Filtration Technologies, L.P. Viledon Nonwovens for Respirators. http://www.freudenberg-filter.com/us/products/human-protection-air-filtration/filter-media-for-respiratory-masks (accessed 16 March 2011).

36. General Electric Energy. Aspire Filtration Media and Membrane Solutions. http://www.gepower.com/prod_serv/products/membrane_technologies/en/micro_filtration.htm (accessed 5 August 2010).

37. General Electric Energy. Preveil ePTFE Membrane. http://www.gepower.com/prod_serv/products/particulate_matter/en/ffp/bha_tex_membrane/index.htm (accessed 5 August 2010).

38. General Electric Energy. Tri-Loft and Reverse Air Tri-Loft fiberglass. http://www.gepower.com/prod_serv/products/particulate_matter/en/fbc/fs.htm (accessed 5 August 2010).

39. Global Finishing Solutions. GFS WAVE Filter Media. http://globalfinishing.com/parts_and_fIlters/parts_products/pf_filters.html (accessed 5 August 2010).

40. Hollingsworth & Vose Company. PerForm Next-Generation HEPA/ULPA Filter Media. http://hollingsworth-vose.com/pdf/HEPA-ULPA%20Insert.pdf (accessed 5 August 2010).

41. Hollingsworth & Vose Company. NANOWEB: H & V's Advanced Nanofiber Technology. http://hollingsworth-vose.com/pdf/Nanoweb-Brochure.pdf (accessed 5 August 2010).

42. Hollingsworth & Vose Company. NanoWave Synthetic Filter Media. http://hollingsworth-vose.com/pdf/NanowaveInsert.pdf (accessed 5 August 2010).

43. Hollingsworth & Vose Company. Technostat Filter Media. http://www.hollingsworth-vose.com/pdf/resp-technostat.pdf (accessed 5 August 2010).

44. Hollingsworth & Vose Company. Industrial Meltblown Filtration Media. http://www.hollingsworth-vose.com/pdf/industrial-meltblown.pdf (accessed 5 August 2010).

45. Hollingsworth & Vose Company. Capaceon Heavy Duty Filter Media. http://hollingsworth-vose.com/pdf/Capaceon-HD-Insert.pdf (accessed 5 August 2010).

46. Irema Ireland. Meltblown nonwovens. http://www.irema.com/products/meltblown-filter-media/ (accessed 21 March 2011).

47. Johns Manville. Assurance With SSP Air Filtration Media. http://www.jm.com/engineered_products/filtration/5370.htm (accessed 5 August 2010).

48. Kimberly-Clark Professional Filtration Products. Intrepid Filtration Media Technical Data. http://www.kcfiltration.com/assets/intrepid/itech.htm (accessed 12 August 2010).

49. Kolon Industries, Inc. Aramid. http://www.kolonindustries.com/Eng/Product/product02_06.asp (accessed 22 February 2012).

50. Lydall, Inc. Lydall Filtration/Separation LydAir MG. http://www.lydallfiltration.com/products/air/mg.shtml (accessed 10 August 2010).

51. Lydall, Inc. Lydall Filtration/Separation LydAir MB. http://www.lydallfiltration.com/products/air/mb.shtml (accessed 10 August 2010).

52. Lydall, Inc. Lydall Filtration/Separation LydAir SC. http://www.lydallfiltration.com/products/air/sc.shtml (accessed 10 August 2010).

53. Lydall, Inc. Lydall Filtration/Separation Arioso High Performance Air Filtration Composite Media. http://www.lydallfiltration.com/products/air/Arioso.shtml (accessed 10 August 2010).

54. Lydall, Inc. Lydall Filtration/Separation ActiPure. http://www.lydallfiltration.com/products/liquid/actipure.shtml (accessed 10 August 2010).

55. MGF Gutsche GmbH & Co. KG. Gutsche Advantex: The trend to economy. http://www.gutsche-mgf.com/english/advantex.html (accessed 21 March 2011).

56. MGF Gutsche GmbH & Co. KG. Gutsche Microvel: The trend to zero emissions. http://www.gutsche-mgf.com/english/microvel.html (accessed 21 March 2011).

57. MGF Gutsche GmbH & Co. KG. Gutsche MPT: High efficiency surface filtration. http://www.gutsche-mgf.com/english/mpt.html (accessed 21 March 2011).

58. MGF Gutsche GmbH & Co. KG. Gutsche Antafin: Release those sticky dusts. http://www.gutsche-mgf.com/english/antafin.html (accessed 21 March 2011).

59. MGF Gutsche GmbH & Co. KG. Gutsche Membratex: PTFE foam for intelligent surface filtration.
http://www.gutsche-mgf.com/english/membratex.html (accessed 21 March 2011).

60. Micro-One. Microne-Tex expanded PTFE Membrane Filter Media.
http://www.micro-one.kr/english/products/products_01_02.html (accessed 10 August 2010).

61. Midwest Filtration Company. Engineered Media.
http://www.midwestfiltration.com/engineered-media.php#top (accessed 5 August 2010).

62. Millipore. Sterilizing-Grade Aervent Cartridge Filters.
http://www.millipore.com/CATALOGUE/MODULE/C588 (accessed 5 August 2010).

63. Millipore. Aerex Hydrophobic Cartridge Filters.
http://www.millipore.com/CATALOGUE/MODULE/C6010 (accessed 5 August 2010).

64. Millipore. Durapore 0.22 μm Hydrophobic Cartridge Filters.
http://www.millipore.com/CATALOGUE/MODULE/C534 (accessed 5 August 2010).

65. National Nonwovens. Filter 29 and 30: Low-Density – high loft with no latex binder.
http://www.nationalnonwovens.com/f_media.htm#LowDensity (accessed 5 August 2010).

66. National Nonwovens. PurusFelt – "scrimless" filter designs.
http://www.nationalnonwovens.com/f_media.htm#PureFelt® (accessed 5 August 2010).

67. Pall Corporation. Versapor R Membrane.
http://www.pall.com/main/OEM-Media-Membranes-and-Materials/Product.page?id=43420 (accessed 12 August 2010).

68. Pall Corporation. Versapor TR Membrane. Retrieved
http://www.pall.com/main/OEM-Media-Membranes-and-Materials/Product.page?id=41265 (accessed 12 August 2010).

69. Pall Corporation. Supor R Membrane.
http://www.pall.com/main/OEM-Media-Membranes-and-Materials/Product.page?id=41260 (accessed 12 August 2010).

70. Pall Corporation. Emflon PTFE Membrane.
http://www.pall.com/main/OEM-Media-Membranes-and-Materials/Product.page?id=41242 (accessed 12 August 2010).

71. Pall Corporation. Pallflex 40 Medium. http://www.pall.com/main/OEM-Materials-and-Devices/Product.page?id=3907 (accessed 12 August 2010).

72. Pall Corporation. Pallflex UTF Series Cast PTFE. http://www.pall.com/main/OEM-Materials-and-Devices/Product.page?id=3958 (accessed 12 August 2010).

73. Pall Corporation. Melt Blown Material Capabilities. http://www.pall.com/main/OEM-Materials-and-Devices/Product.page?id=25013 (NEXIS and ARD) (accessed 12 August 2010).

74. Texel. Tribo Air Filtration Application. http://texel.ca/imports/pdf/en/DepTribo-En.pdf (accessed 10 August 2010).

75. Toray Fine Chemicals Company, Ltd. (2007). High Performance Materials: TORAYMICRON. Retrieved August 5, 2010 from: http://www.torayfinechemicals.com/english/products/kino/kin_001a.html.

76. Toray Fine Chemicals Company, Ltd. High Performance Materials: Fluorocarbon Fibers TOYOFLON. http://www.torayfinechemicals.com/english/products/kino/kin_004.html (accessed 12 August 2010).

77. Toray Fine Chemicals Company, Ltd. TFA Teflon High Temperature Filtration Products. http://www.torayfluorofibers.com/Default.aspx?tabid=71 (HG and X) (accessed 5 August 2010)

78. TWE Dierdorf GmbH & Co. KG. ParaFil: Nonwovens from endless filaments for filtration. http://www.vliesstoffe-dierdorf.de/engl/produktlinien/parafil/index.htm (accessed 5 August 2010).

79. Universal Air Filter, Co. Quadrafoam Air Filters. http://www.uaf.com/quadrafoam-air-filters-nebs-certified.htm (accessed 5 August 2010).

80. Vokes Air. Synsafe Revo. http://www.vokesair.com/products/bag-filters-0/synsafe-revo (accessed 5 August 2010).

81. W.L. Gore & Associates, Inc. PRISTYNE Filter Media. http://www.gore.com/en_xx/products/filtration/pristyne/index.html?RDCT=pristyne.com (accessed 5 August 2010).

82. W.L. Gore & Associates, Inc. Woven RASTEX Fiber Fabric 7210. http://www.gore.com/en_xx/products/filtration/pristyne/rastex/1223620918112.html (accessed 5 August 2010).

83. W.L. Gore & Associates, Inc. Simple filtering: Product and Material of GORE SINBRAN Filters. http://www.gore.com/en_xx/products/filtration/baghouse/sinbran/sinbran_product_material.html (accessed 5 August 2010).

84. Whatman plc. PTFE Membranes. http://www.whatman.com/PRODPTFEMembranes.aspx (accessed 24 March 2011).

ABBREVIATIONS AND ACRONYMS

AEM	advanced electret media
AAF	American Air Filter International
ARD	absolute rated depth
BFE	biological filtration efficiency
CBRN	chemical, biological, radiological, and nuclear
DOP	dioctylphalate
ECBC	U.S. Army Edgewood Chemical Biological Center
EN	Europeen de Normalisation
ePTFE	expanded polytetrafluoroethylene
FFP	filtering face piece
GE	General Electric
GFS	Global Finishing Solutions
HAF	high airflow
HEPA	high-efficiency particulate air
H&V	Hollingsworth & Vose
HVAC	heating, ventilation, and air conditioning
JSGPM	Joint Service General Purpose Mask
MERV	minimum efficiency reporting value
MPPS	most penetrating particle size
NaCl	sodium chloride
NEFT	Nanoparticle-Enhanced-Filtration-Technology
NIOSH	National Institute of Occupational Safety and Health
PAO	polyalpha olefin
PAPR	powered air purifying respirator
PBT	poly butylene tephthalate
PET	polyethylene terephthalate
PFE	particulate filtration efficiency
PTFE	polytetrafluoroethylene
PVDF	polyvinylidene fluoride

UHMWPE	ultra-high molecular weight polyethylene
ULPA	ultra-low penetration air


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