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(54) **FINE FIBER LIQUID PARTICULATE FILTER MEDIA**

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**Publication Classification**

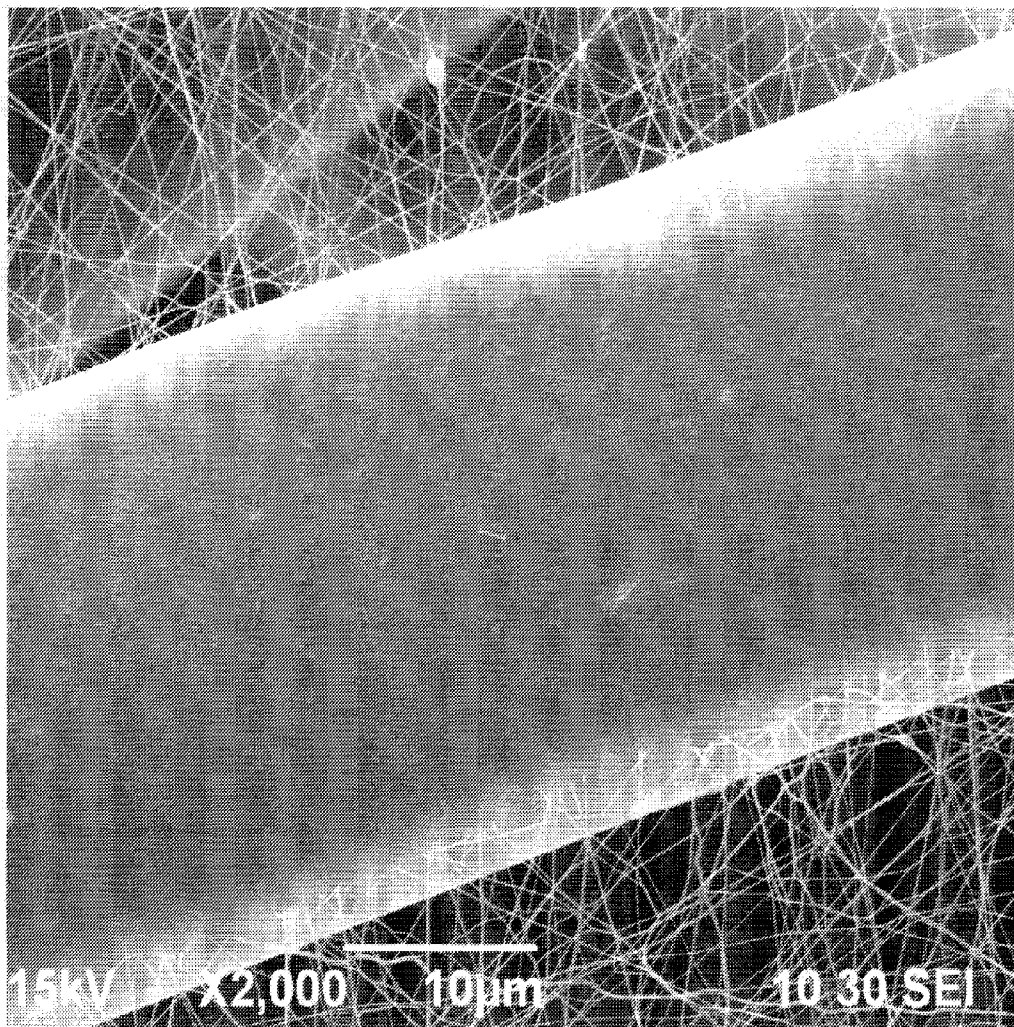
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*B01D 39/04* (2006.01)  
*B01D 37/00* (2006.01)  
*B01D 39/08* (2006.01)  
*B32B 37/00* (2006.01)  
*B29C 67/20* (2006.01)  
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(52) **U.S. Cl.** ..... **210/767**; 210/491; 156/308.2; 264/438; 156/62.8

**Related U.S. Application Data**

(60) Provisional application No. 61/383,487, filed on Sep. 16, 2010, provisional application No. 61/383,569, filed on Sep. 16, 2010, provisional application No.

**ABSTRACT**

(57) A filter media for liquid particulate filtration applications is provided. The filter media includes a substrate and fine fibers, which are compressed together.



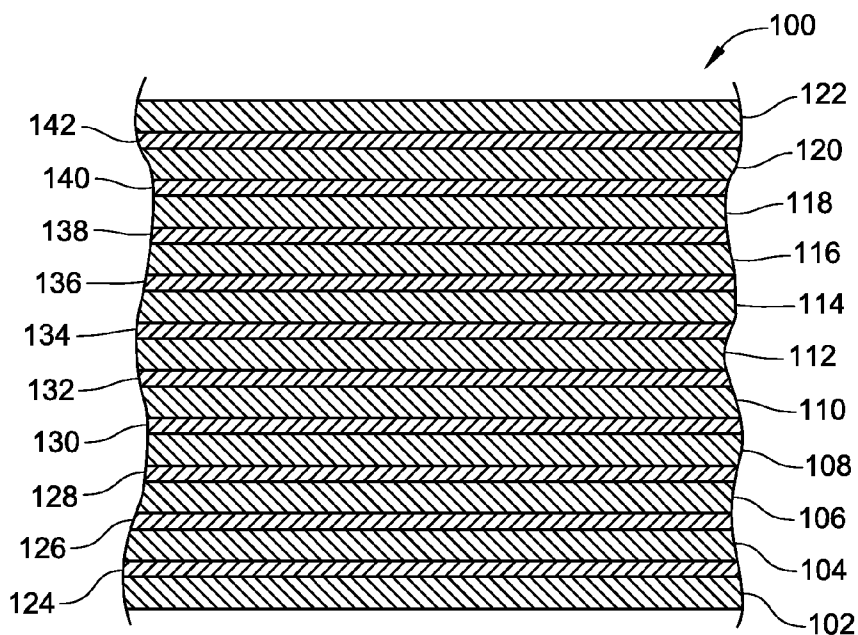


FIG. 1

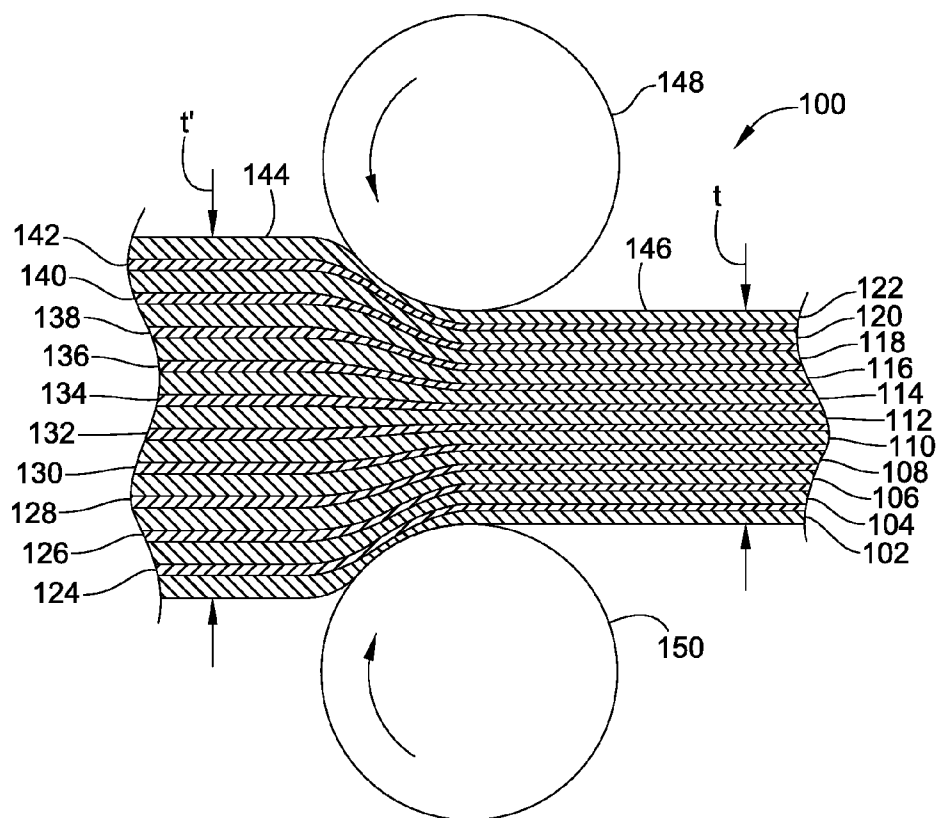


FIG. 2

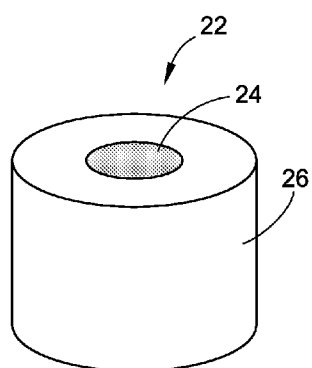


FIG. 3

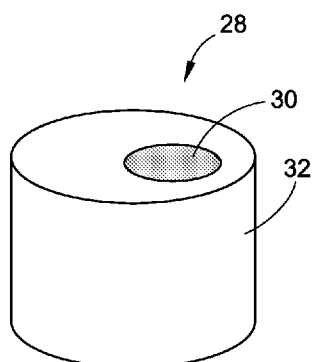


FIG. 4

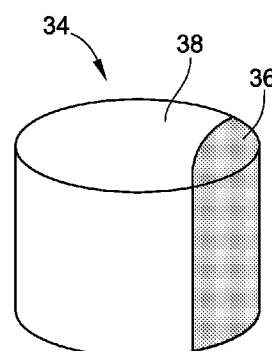


FIG. 5

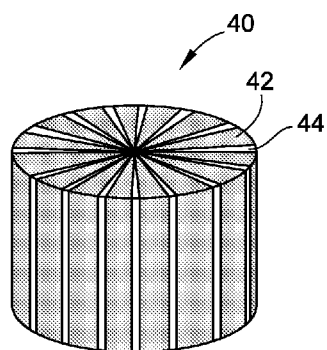


FIG. 6

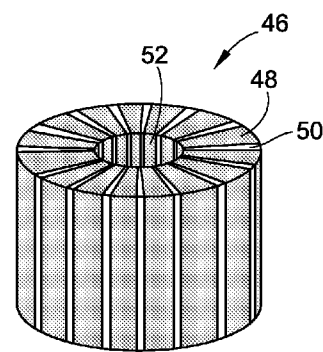


FIG. 7

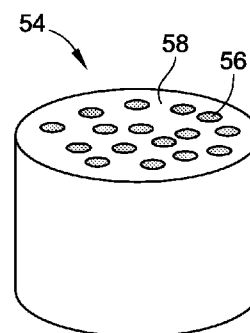


FIG. 8

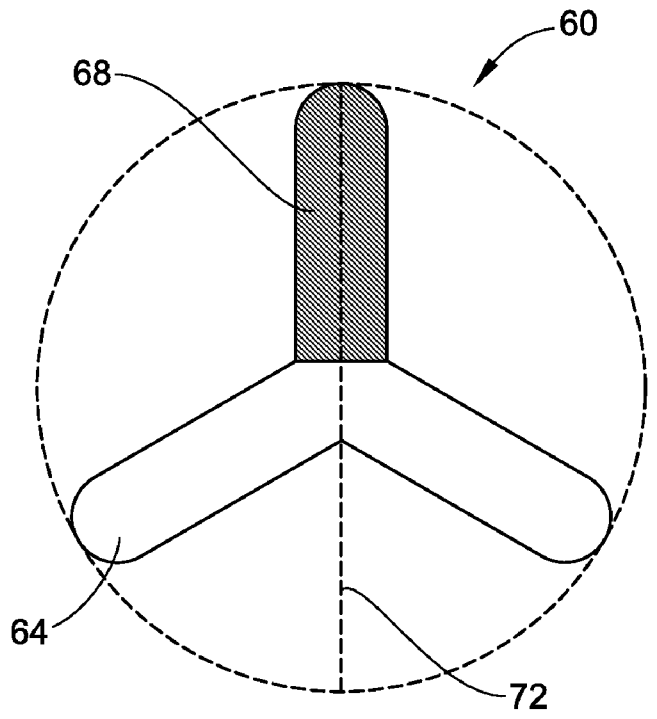
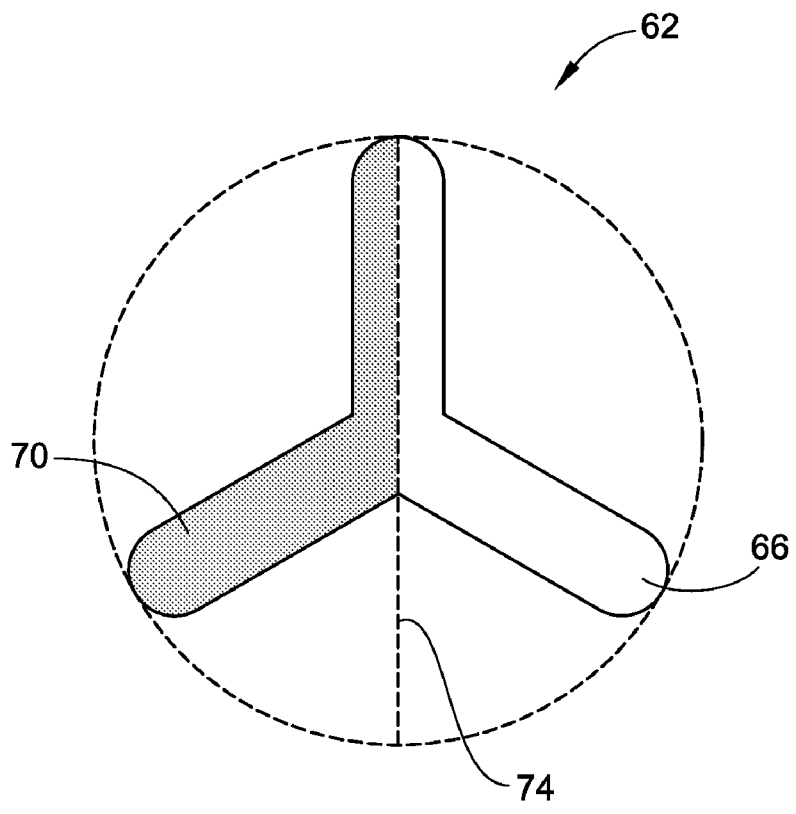


FIG. 9

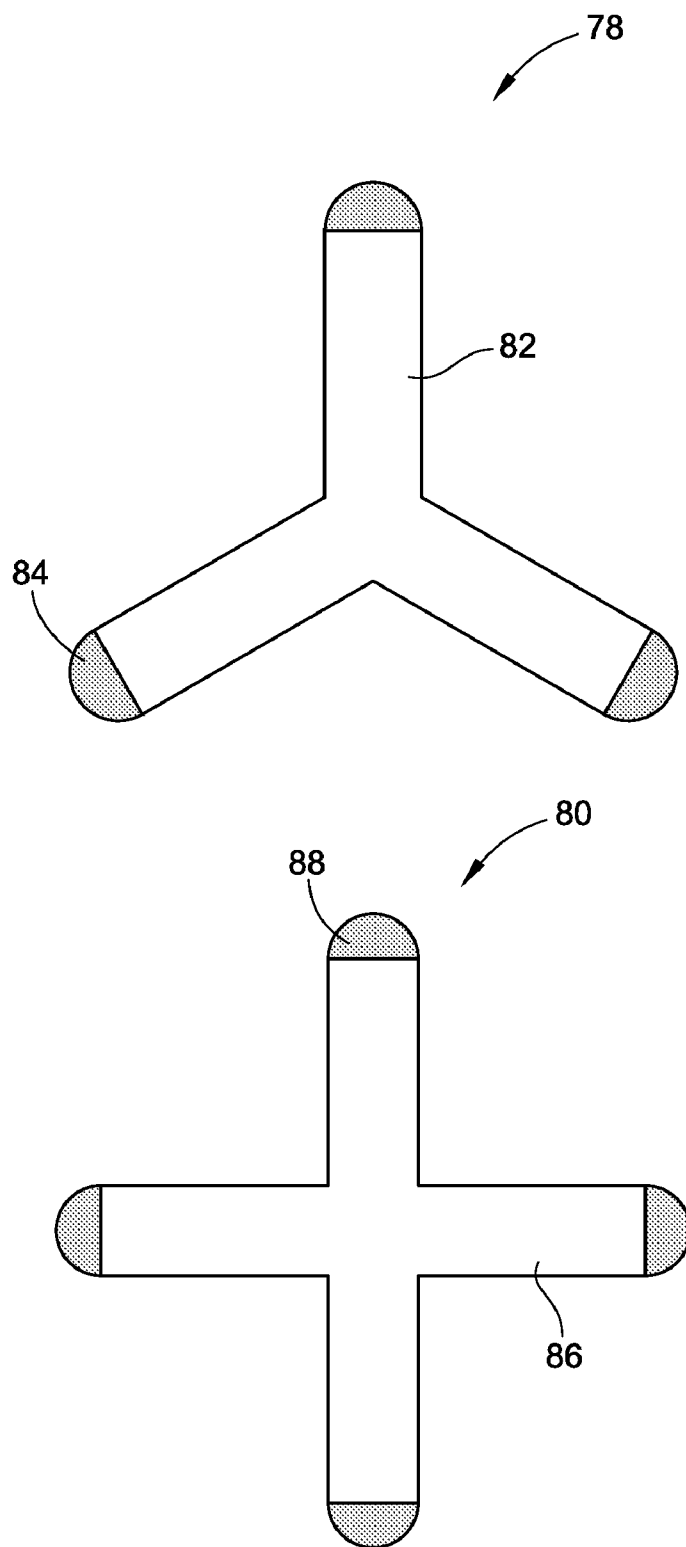
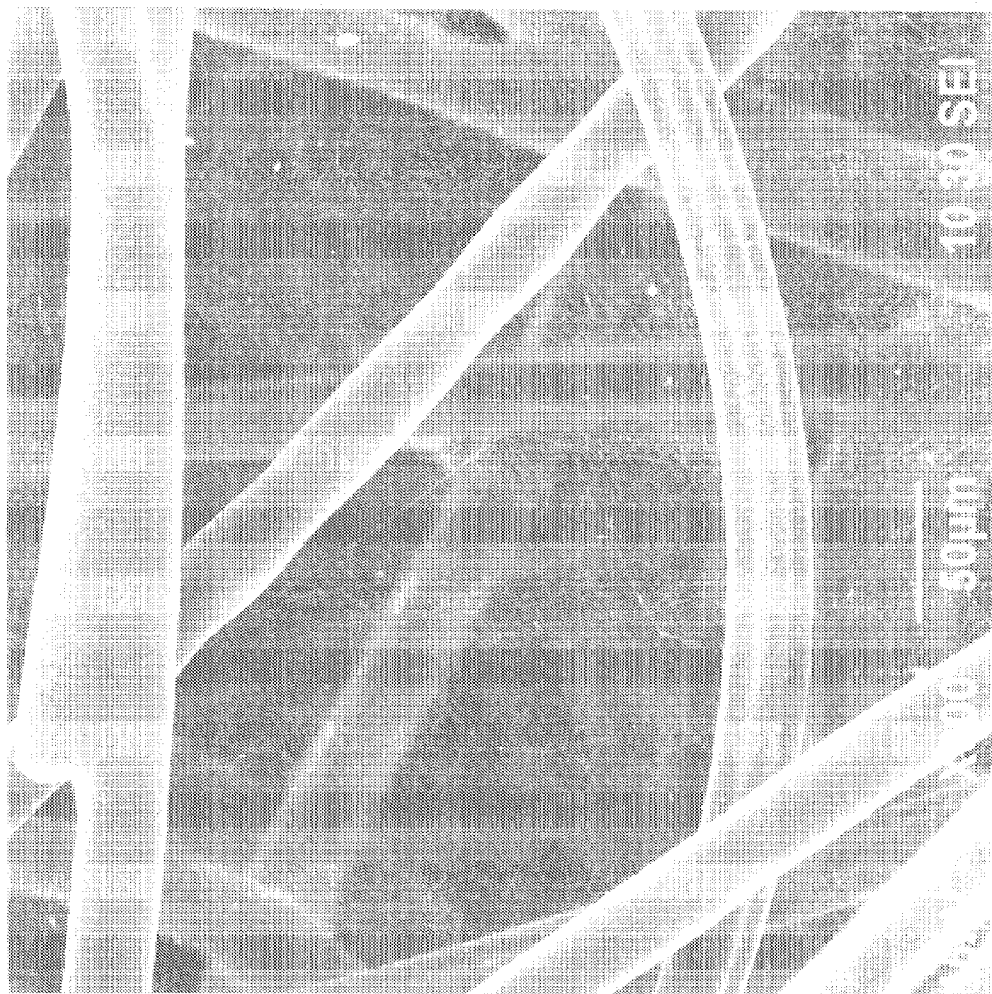


FIG. 10





**FIG. 12(A)**

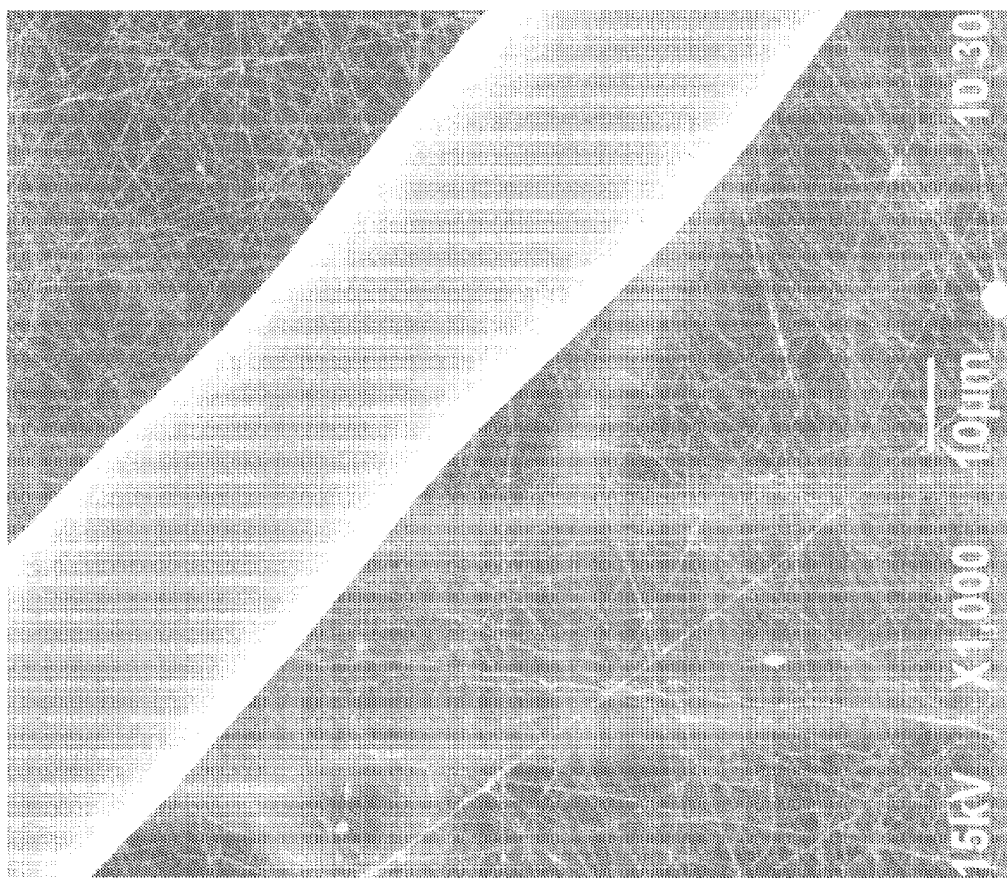


FIG. 12(B)



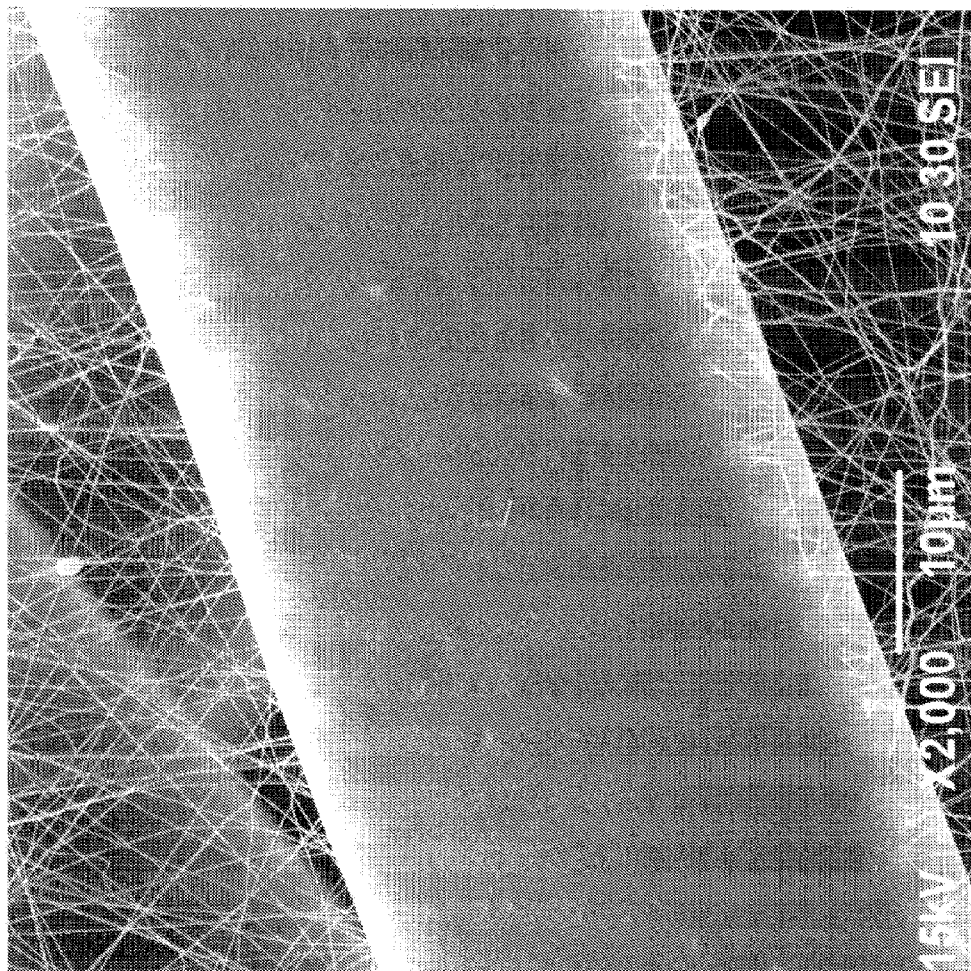


FIG. 12(C)

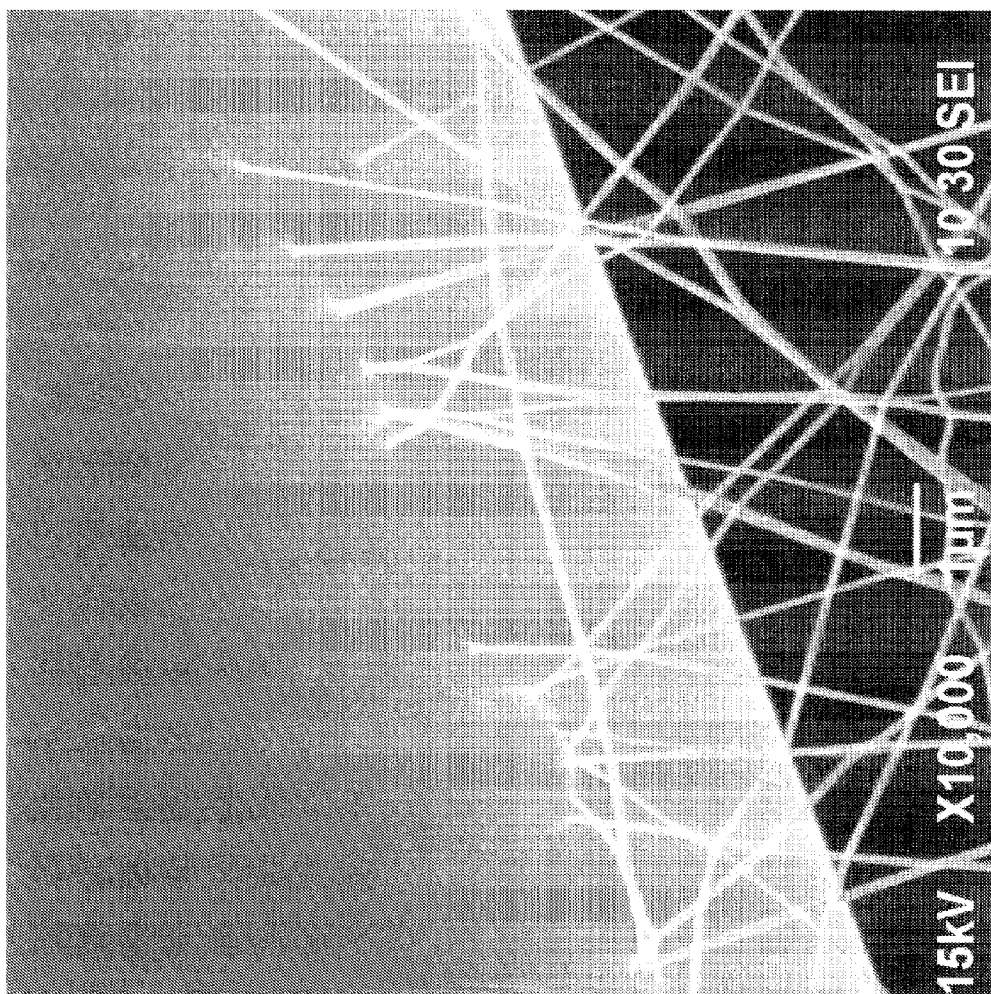


FIG. 12(D)

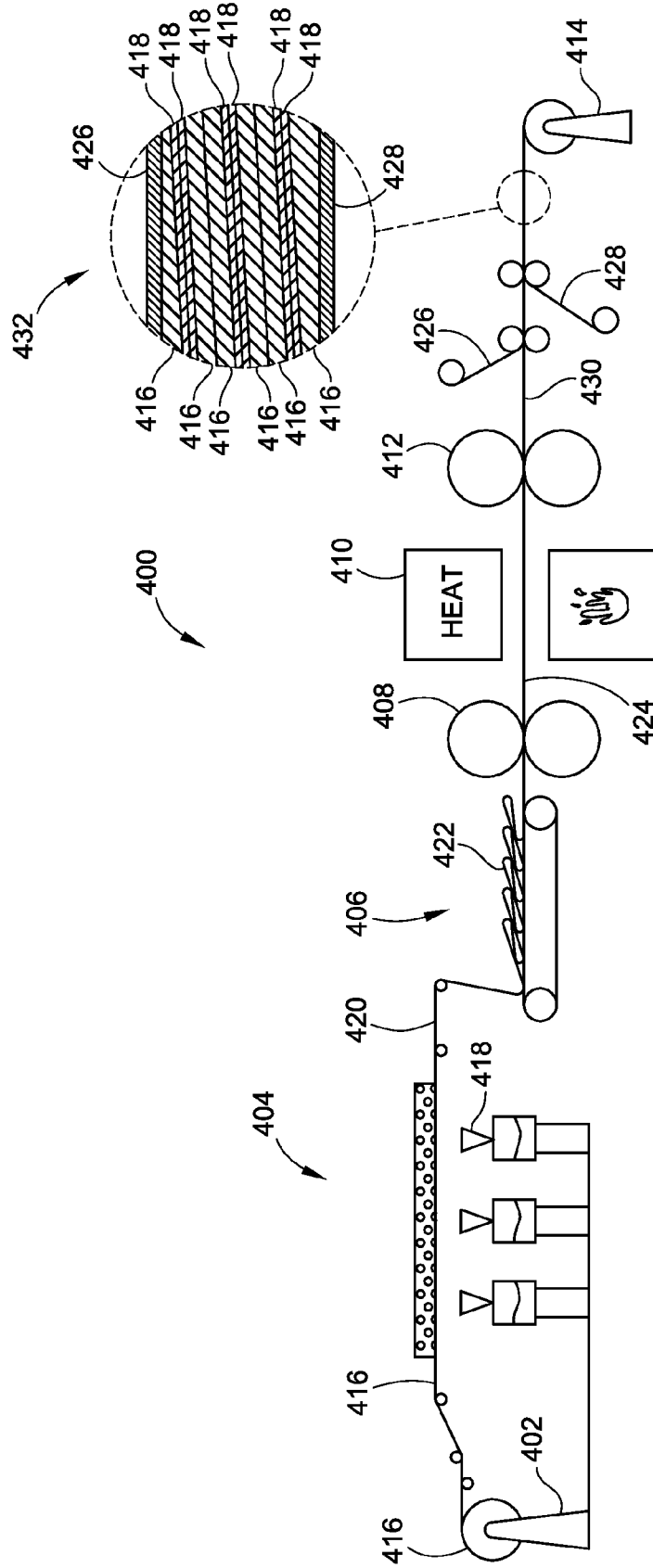


FIG. 13

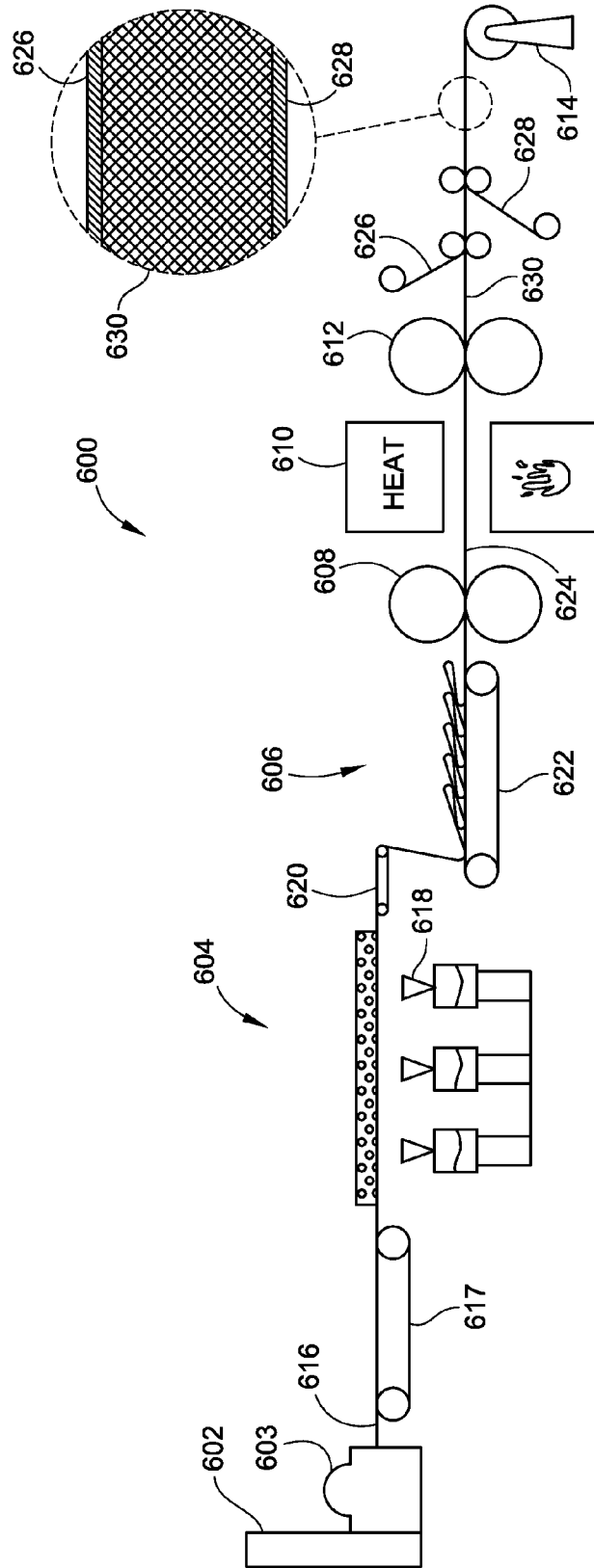


FIG. 14

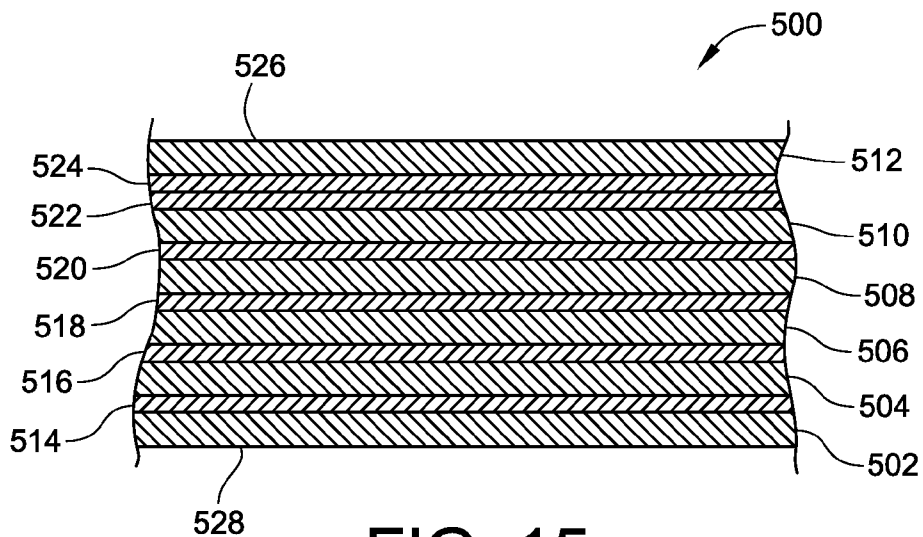


FIG. 15

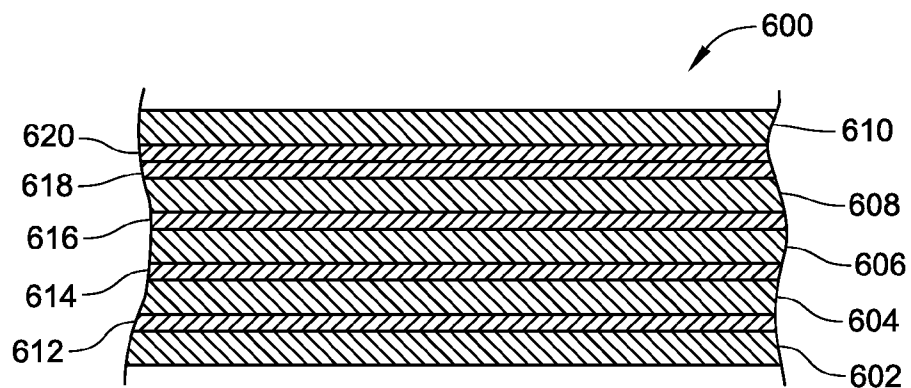


FIG. 19

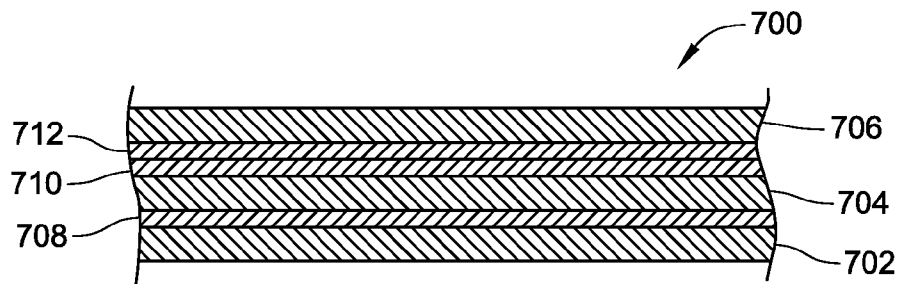


FIG. 21



ISO 16889 - FILTER ELEMENT MULTIPASS REPORT SHEET

Test File Name: 100826-00-1

TEST RESULTS II



FIG. 17

Time interval	Particle counts (per mL) and filtration ratio															
	d > 4 µm(c)	d > 5 µm(c)	d > 6 µm(c)	d > 7 µm(c)	d > 8 µm(c)	d > 10 µm(c)	d > 12 µm(c)	d > 14 µm(c)	d > 15 µm(c)	d > 17 µm(c)	d > 20 µm(c)	d > 25 µm(c)	d > 30 µm(c)	d > 35 µm(c)	d > 40 µm(c)	d > 50 µm(c)
Initial	83.2	53.1	38.1	19.0	11.0	3.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0
Up	23112.1	14039.9	8851.1	5852.0	3978.5	2031.3	1186.2	687.8	546.0	355.7	190.2	71.3	32.3	15.9	9.9	5.7
Down	1.1	0.7	0.4	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
§	21124.1	20973.5	19909.1	23380.6	25206.7	32779.3	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0
Up	28812.8	17519.0	1143.2	7363.7	5027.3	2574.0	1446.5	863.7	688.6	444.5	243.0	93.5	41.9	21.0	12.7	5.1
Down	0.4	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
§	67285.3	59589.3	59524.2	68265.7	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0
Up	29202.7	17763.9	11228.9	7444.3	5082.8	2615.1	1472.5	833.0	718.9	465.0	252.6	98.9	45.2	24.5	14.8	7.3
Down	0.9	0.3	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
§	33836.0	58109.7	54663.1	72154.3	64443.5	49662.1	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0
Up	29229.7	17738.1	11242.9	7424.1	5068.5	2585.3	1461.3	881.2	704.7	458.1	248.1	96.1	41.3	22.8	14.1	7.1
Down	7.9	4.7	3.0	1.9	1.3	0.8	0.3	0.3	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0
§	3695.2	3773.7	3804.6	3898.8	3850.7	3420.5	4529.8	2985.3	2619.9	2861.4	2321.0	100000.0	100000.0	100000.0	100000.0	100000.0
Up	29300.0	17789.5	11247.3	7437.4	5085.0	2610.5	1478.3	888.9	712.8	464.3	254.7	101.5	46.0	24.6	14.9	7.3
Down	26.4	15.9	10.2	6.9	4.6	2.1	1.2	0.6	0.4	0.2	0.1	0.0	0.0	0.0	0.0	0.0
§	1107.8	1118.8	1100.7	1074.8	1115.1	1255.4	1201.9	1427.3	1690.1	2060.8	3421.3	4298.1	100000.0	100000.0	100000.0	100000.0
Up	29369.7	17826.4	11317.7	7473.7	5096.8	2601.1	1462.7	877.3	704.2	457.5	247.7	93.9	42.2	22.5	14.5	6.4
Down	56.7	34.6	21.6	14.4	10.0	5.1	2.8	1.5	1.1	0.5	0.1	0.0	0.0	0.0	0.0	0.0
§	518.4	515.8	524.4	519.6	509.8	509.4	526.7	597.5	644.2	654.9	1859.8	100000.0	100000.0	100000.0	100000.0	100000.0
Up	29345.9	17830.8	11308.9	7483.6	5111.5	2628.2	1472.8	892.4	713.7	465.3	254.4	96.0	41.2	21.7	12.9	6.6
Down	180.5	107.9	88.2	43.3	29.1	14.2	7.5	4.3	3.2	1.6	0.7	0.2	0.1	0.0	0.0	0.0
§	162.6	165.3	165.8	172.7	175.4	185.0	197.2	209.0	221.6	293.4	349.5	508.5	510.5	100000.0	100000.0	100000.0
Up	29636.5	17968.3	11375.4	7505.7	5132.3	2638.0	1484.6	833.9	713.6	465.9	255.5	97.8	42.5	22.7	14.7	7.6
Down	697.8	417.9	263.8	175.5	119.2	59.7	31.7	18.0	13.7	7.5	3.4	0.7	0.2	0.1	0.0	0.0
§	42.5	43.0	43.1	42.8	43.0	44.2	46.8	49.6	52.0	62.0	74.4	143.9	241.6	299.7	294.6	100000.0
Up	30397.6	18464.4	11697.7	7746.0	5290.7	2704.9	1529.6	921.1	737.8	477.8	255.5	99.1	41.7	22.1	13.1	5.7
Down	1924.9	1156.6	728.3	482.6	328.1	162.4	87.8	49.6	37.6	21.7	9.1	1.3	0.3	0.0	0.0	0.0
§	15.8	16.0	16.1	16.1	16.1	16.7	17.4	18.6	19.6	22.0	28.1	74.3	141.5	810.5	479.5	100000.0
Up	32091.6	19488.4	12360.9	8173.4	5580.9	2862.6	1606.8	957.6	763.9	491.3	265.0	102.2	45.8	24.8	15.9	7.5
Down	4234.7	2539.2	1606.8	1061.5	720.9	355.1	190.5	105.4	81.6	47.5	20.1	3.5	0.7	0.2	0.1	0.0
§	7.6	7.7	7.7	7.7	7.7	8.1	8.4	9.1	9.4	10.3	13.2	28.9	64.9	109.0	212.3	100000.0
Up	28339.0	17215.4	10905.7	7211.2	4921.5	2520.8	1418.6	854.9	684.1	444.3	241.5	93.2	41.4	21.9	13.4	6.5
Down	39.1	23.5	14.8	9.6	6.5	3.2	1.7	1.0	0.7	0.4	0.1	0.0	0.0	0.0	0.0	0.0
§	724.3	733.5	735.5	753.3	761.4	792.6	841.6	899.1	956.9	1241.0	1621.8	3071.1	3592.8	100000.0	100000.0	100000.0

ISO 16889 - FILTER ELEMENT MULTIPASS REPORT SHEET

Test File Name: 100812-00-1

TEST RESULTS II



FIG. 18

Time interval	Particle counts (per mL) and filtration ratio															
	d > 4	d > 5	d > 6	d > 7	d > 8	d > 10	d > 12	d > 14	d > 15	d > 17	d > 20	d > 25	d > 30	d > 35	d > 40	d > 50
	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)
Initial	334.9	185.7	128.8	91.2	62.3	39.7	31.1	21.5	19.3	17.2	11.8	8.6	5.4	4.3	2.1	2.1
Up	22895.2	13702.3	8568.1	5573.3	3766.1	1920.8	1096.9	685.9	532.8	352.9	197.7	84.6	41.0	21.4	14.1	7.3
Down	18.2	8.6	4.4	2.9	1.8	0.4	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
β	1248.9	1589.4	1941.2	1895.8	2104.6	4686.7	6759.7	8326.4	6661.6	4413.1	10000.0	10000.0	10000.0	10000.0	10000.0	10000.0
Up	27461.3	16712.1	10566.2	6942.5	4730.0	2419.0	1381.6	844.5	672.8	445.6	244.5	98.7	45.4	25.1	13.9	7.8
Down	64.9	34.3	19.4	10.7	6.2	1.9	0.9	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
β	423.4	487.0	543.6	650.6	763.6	1284.8	1512.8	2620.7	4167.0	8493.4	10000.0	10000.0	10000.0	10000.0	10000.0	10000.0
Up	28881.6	17437.1	11035.7	7274.7	4933.2	2519.1	1435.5	872.4	704.3	464.2	253.4	104.3	47.7	27.1	17.0	9.0
Down	209.7	117.4	69.3	42.2	26.2	12.3	4.7	1.9	0.9	0.4	0.1	0.0	0.0	0.0	0.0	0.0
β	136.7	148.6	159.2	172.5	188.4	205.5	303.1	469.3	779.6	1086.6	2708.5	2214.6	10000.0	10000.0	10000.0	10000.0
Up	29015.3	17660.0	11126.4	7316.3	4977.7	2523.7	1435.6	862.9	697.1	454.5	255.4	104.8	51.3	27.9	17.6	9.7
Down	451.8	251.7	150.6	91.7	55.2	21.6	9.2	3.3	2.3	1.2	0.3	0.0	0.0	0.0	0.0	0.0
β	64.2	70.2	73.9	79.8	90.2	116.9	155.9	261.2	303.4	385.9	944.8	10000.0	10000.0	10000.0	10000.0	10000.0
Up	29105.4	17674.2	11184.0	7353.2	5018.6	2550.1	1435.6	873.9	696.8	453.4	249.2	101.5	47.6	27.5	15.2	7.7
Down	702.9	402.3	237.3	147.5	91.8	38.1	18.0	8.3	5.5	2.4	0.6	0.1	0.0	0.0	0.0	0.0
β	41.4	43.9	47.1	49.9	54.7	66.9	79.7	104.9	125.8	190.3	427.5	1879.9	10000.0	10000.0	10000.0	10000.0
Up	29390.5	17916.7	11303.9	7432.6	5046.8	2580.3	1461.3	883.0	714.5	457.8	248.5	101.3	44.6	24.1	14.9	7.1
Down	932.1	533.2	317.0	198.8	128.3	53.8	24.2	10.7	7.0	3.0	0.6	0.1	0.0	0.0	0.0	0.0
β	31.5	33.6	35.7	37.4	39.3	47.9	60.3	82.5	102.0	151.8	397.6	1024.4	10000.0	10000.0	10000.0	10000.0
Up	29503.0	17905.8	11328.0	7436.1	5049.0	2570.3	1459.1	888.6	714.8	465.8	252.2	102.8	46.9	26.4	16.1	8.2
Down	1098.2	631.1	382.6	240.5	151.0	62.0	26.9	12.8	8.8	3.7	1.2	0.1	0.0	0.0	0.0	0.0
β	26.9	28.4	29.6	30.9	33.4	41.5	54.2	69.7	81.4	125.0	218.3	1920.0	10000.0	10000.0	10000.0	10000.0
Up	29669.6	18056.0	11420.0	7509.1	5104.7	2615.8	1485.4	895.3	722.5	472.6	258.4	108.5	48.1	25.8	14.7	8.0
Down	1165.4	669.6	407.1	255.6	162.4	66.5	31.2	14.0	9.1	3.7	0.9	0.0	0.0	0.0	0.0	0.0
β	25.5	27.0	28.0	29.4	31.4	39.3	47.5	63.8	79.7	126.4	279.2	10000.0	10000.0	10000.0	10000.0	10000.0
Up	29596.0	17959.9	11322.8	7445.3	5062.8	2582.3	1450.1	888.9	694.6	444.7	240.4	97.4	44.0	24.3	14.7	7.4
Down	1181.8	683.1	408.4	255.3	158.0	66.9	30.7	14.8	10.1	5.1	1.1	0.1	0.0	0.0	0.0	0.0
β	25.0	26.3	27.7	29.2	32.0	38.6	47.2	58.9	68.9	87.6	215.2	1898.5	10000.0	10000.0	10000.0	10000.0
Up	29801.4	18088.2	11455.8	7544.0	5127.5	2624.8	1486.8	896.7	720.0	472.4	263.2	108.4	48.7	27.2	17.5	8.9
Down	1087.0	630.3	377.5	238.9	151.9	65.1	30.0	13.3	9.1	4.7	1.7	0.3	0.0	0.0	0.0	0.0
β	27.4	28.7	30.3	31.6	33.7	40.3	49.6	67.5	79.5	100.7	154.5	405.3	10000.0	10000.0	10000.0	10000.0
Up	27978.9	17001.2	10730.3	7047.0	4788.8	2440.5	1386.5	841.6	676.1	442.0	243.4	99.7	46.4	25.6	15.5	8.1
Down	496.8	282.6	168.7	104.9	65.8	27.1	12.0	5.3	3.5	1.6	0.4	0.0	0.0	0.0	0.0	0.0
β	56.3	60.2	63.6	67.2	72.8	89.9	115.2	157.7	191.1	284.9	621.8	2753.2	10000.0	10000.0	10000.0	10000.0



ISO 16889 - FILTER ELEMENT MULTIPASS REPORT SHEET

Test File Name: 100714-00-7

TEST RESULTS II



FIG. 20

Time interval	Particle counts (per mL) and filtration ratio															
	d > 4 µm(c)	d > 5 µm(c)	d > 6 µm(c)	d > 7 µm(c)	d > 8 µm(c)	d > 10 µm(c)	d > 12 µm(c)	d > 14 µm(c)	d > 15 µm(c)	d > 17 µm(c)	d > 20 µm(c)	d > 25 µm(c)	d > 30 µm(c)	d > 35 µm(c)	d > 40 µm(c)	d > 50 µm(c)
Initial	164.0	111.7	70.7	52.3	42.0	21.5	17.4	13.3	9.2	6.2	2.1	1.0	1.0	0.0	0.0	0.0
10% Down	14808.5	8968.3	5670.8	3711.4	2517.7	1253.5	720.4	418.3	331.0	215.2	111.9	36.2	15.9	5.3	4.3	2.4
β	6.5	2.6	1.7	1.2	1.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20% Down	22766.6	3385.2	3359.2	3084.0	2619.6	2616.1	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0
β	22208.2	13480.3	8477.8	5565.4	3768.3	1891.4	1046.0	636.3	503.5	325.8	171.4	66.8	27.3	13.3	8.3	3.5
Up	12.8	7.7	4.1	2.3	0.9	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
β	1729.4	1757.5	2056.5	2460.0	4241.2	4736.4	12940.1	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0
30% Down	26633.8	16186.1	10179.8	6680.2	4504.9	2289.9	1297.5	776.4	616.3	393.6	214.9	85.8	42.0	19.6	11.0	6.7
β	39.0	23.0	14.9	9.0	5.5	3.0	1.9	1.2	0.9	0.7	0.3	0.0	0.0	0.0	0.0	0.0
40% Down	683.1	702.8	683.8	736.6	815.4	763.5	693.6	642.7	696.7	546.5	693.2	100000.0	100000.0	100000.0	100000.0	100000.0
Up	28127.6	17100.8	10751.2	7048.3	4773.0	2423.2	1369.3	815.9	660.9	429.9	240.3	93.2	41.6	21.8	13.0	6.2
β	77.9	45.3	28.2	17.6	10.9	5.4	2.5	1.1	0.9	0.7	0.2	0.1	0.0	0.0	0.0	0.0
50% Down	361.2	377.8	380.8	401.1	437.2	450.3	550.0	776.3	739.2	585.0	978.8	1123.3	100000.0	100000.0	100000.0	100000.0
Up	26578.0	17324.1	10887.0	7155.4	4861.6	2501.3	1402.7	849.4	676.5	451.8	244.6	92.8	39.1	21.6	14.0	6.6
β	141.8	82.9	54.2	33.9	23.5	10.7	5.8	3.0	2.5	1.8	1.0	0.2	0.0	0.0	0.0	0.0
60% Down	2013.1	208.9	200.8	210.8	206.5	233.5	239.9	279.6	265.4	246.7	237.5	396.1	100000.0	100000.0	100000.0	100000.0
Up	28730.1	17404.0	10950.2	7198.6	4891.2	2473.6	1397.1	847.5	683.5	439.8	239.0	92.7	40.6	24.5	15.1	6.6
β	193.2	114.3	71.9	44.4	30.6	15.0	8.3	4.6	3.1	1.8	0.5	0.2	0.0	0.0	0.0	0.0
70% Down	148.7	152.3	152.4	162.2	159.9	164.4	169.2	185.0	219.2	250.8	513.4	394.9	100000.0	100000.0	100000.0	100000.0
Up	28808.2	17512.1	11063.4	7232.9	4882.9	2502.5	1401.8	852.4	676.8	438.6	240.4	87.9	39.0	19.1	11.4	5.2
β	256.1	152.4	95.7	60.9	43.0	20.2	10.9	6.5	4.7	2.7	1.4	0.2	0.0	0.0	0.0	0.0
80% Down	112.5	114.9	115.6	118.7	113.5	123.8	128.6	131.5	143.3	161.3	175.4	360.5	100000.0	100000.0	100000.0	100000.0
Up	28793.3	17402.5	10971.8	7189.2	4885.4	2454.7	1377.7	829.7	667.6	432.6	232.5	88.6	38.7	19.7	13.1	5.1
β	306.7	185.3	117.3	77.0	51.6	25.2	15.0	8.1	6.3	3.8	1.4	0.5	0.2	0.0	0.0	0.0
90% Down	93.9	93.9	93.6	93.4	94.7	97.3	91.6	101.8	105.9	113.3	171.8	186.4	243.9	100000.0	100000.0	100000.0
Up	28665.7	17366.1	10956.8	7197.1	4908.4	2507.7	1429.1	860.6	693.8	451.8	250.4	94.7	42.7	20.8	13.7	7.8
β	374.3	225.9	141.0	91.9	61.5	30.5	15.3	8.4	6.7	3.9	1.2	0.3	0.1	0.0	0.0	0.0
100% Down	76.6	76.9	77.7	78.4	79.8	82.1	83.6	102.9	102.9	116.4	204.1	368.8	495.8	100000.0	100000.0	100000.0
Up	28887.4	17534.4	11073.7	7275.9	4956.3	2507.8	1422.0	854.5	689.8	445.4	244.9	96.9	43.0	24.4	14.3	8.3
β	415.4	244.7	153.5	100.9	66.2	34.1	18.4	10.3	8.0	4.6	1.7	0.0	0.0	0.0	0.0	0.0
Average	25413.5	15425.1	9711.5	6367.4	4314.2	2190.8	1233.6	742.3	592.6	385.0	208.9	79.3	35.1	17.9	11.0	5.3
Down	103.9	61.2	38.7	24.2	16.5	7.9	4.2	2.3	1.7	1.1	0.5	0.1	0.0	0.0	0.0	0.0
β	244.6	252.1	251.1	263.2	261.6	277.7	293.3	317.6	340.9	347.3	426.0	697.7	100000.0	100000.0	100000.0	100000.0



ISO 16889 - FILTER ELEMENT MULTIPASS REPORT SHEET

Test File Name: 100624-00-1

FIG. 22

TEST RESULTS II

Time interval	d > 4	d > 5	d > 6	d > 7	d > 8	d > 10	d > 12	d > 14	d > 15	d > 17	d > 20	d > 25	d > 30	d > 35	d > 40	d > 50
Particle counts (per mL) and filtration ratio	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)	µm(c)
Initial	6566.7	3694.8	2202.2	1387.2	927.0	456.4	240.0	117.6	84.7	53.6	26.4	6.6	0.9	0.9	0.9	0.9
Up	11288.2	6863.7	4365.5	2897.0	1983.9	1028.3	590.3	361.4	290.9	194.1	111.3	49.2	24.4	13.8	9.0	4.1
Down	16.0	9.7	6.2	3.7	2.2	0.8	0.4	0.2	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0
β	704.8	704.4	707.4	779.9	895.9	1289.9	1477.9	1632.9	1405.8	1300.0	1276.2	1669.3	829.5	469.9	626.6	100000.0
Up	10660.5	6511.7	4144.6	2754.8	1894.3	985.2	570.2	351.3	286.9	189.8	108.7	46.5	22.5	12.8	8.5	4.3
Down	2.0	1.0	0.6	0.4	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
β	5396.0	6328.0	6504.5	7249.1	7378.9	10726.5	39230.4	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0
Up	10637.3	6486.4	4119.2	2736.1	1876.2	978.3	567.7	351.7	282.0	185.9	107.1	46.9	22.7	12.5	7.8	3.9
Down	1.5	0.8	0.4	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
β	7038.2	7766.2	9510.8	11277.3	17600.8	24875.3	43509.9	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0
Up	10662.6	6504.7	4138.9	2759.3	1902.0	994.6	571.2	353.0	284.7	190.4	109.2	47.2	23.8	14.0	9.0	4.7
Down	1.2	0.5	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
β	8840.9	13537.0	14079.8	15949.3	20415.0	38857.6	22315.3	27764.1	22394.5	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0
Up	10668.5	6497.6	4131.7	2748.3	1890.8	983.6	564.9	345.8	279.2	185.4	104.9	45.6	22.0	12.8	7.9	4.2
Down	1.3	0.7	0.5	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
β	8123.0	9427.1	8928.7	9812.4	8801.5	14375.9	20080.8	12294.2	9924.8	6591.9	7355.3	3198.3	1542.7	895.0	553.7	100000.0
Up	10666.3	6506.8	4134.1	2740.9	1879.6	980.9	568.6	349.8	283.4	185.6	107.4	45.9	22.6	12.9	8.1	4.6
Down	1.3	0.6	0.3	0.2	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
β	8362.5	11202.7	12378.5	13023.3	11763.5	18553.6	10755.3	13628.8	11041.6	14244.1	8243.4	3519.9	100000.0	100000.0	100000.0	100000.0
Up	10698.3	6508.0	4143.5	2753.3	1892.6	980.7	566.8	348.9	282.3	189.1	108.5	46.3	23.0	12.6	8.2	4.3
Down	3.6	1.8	1.0	0.6	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
β	2980.8	3535.2	4254.7	4554.7	4876.6	6157.5	14195.9	12862.0	10407.0	13549.8	100000.0	100000.0	100000.0	100000.0	100000.0	100000.0
Up	10660.0	6498.8	4135.9	2752.4	1896.6	992.9	572.8	352.2	284.9	190.2	109.6	47.5	24.0	13.8	9.0	4.9
Down	19.3	10.3	6.0	4.0	2.9	1.8	1.3	1.1	1.0	0.8	0.6	0.4	0.2	0.1	0.1	0.0
β	5511.6	6331.6	689.3	679.9	664.6	566.0	437.2	330.8	286.2	246.9	176.7	134.1	146.8	125.9	164.5	187.5
Up	10781.9	6577.8	4190.1	2791.3	1923.0	1011.9	580.5	359.8	290.7	194.8	110.2	48.9	24.8	13.6	8.8	4.8
Down	23.4	12.4	6.8	3.7	2.4	1.1	0.7	0.6	0.5	0.4	0.2	0.1	0.0	0.0	0.0	0.0
β	4611.6	5311.9	6161.9	7481.6	8111.1	8841.5	7901.3	6441.9	5891.2	5211.7	4581.6	4471.0	9281.8	100000.0	100000.0	100000.0
Up	10919.4	6641.0	4235.1	2826.2	1944.5	1009.5	583.8	360.2	291.9	196.2	111.1	49.0	25.7	15.3	10.2	5.3
Down	14.2	6.6	3.2	1.5	0.6	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
β	7711.4	10031.2	13111.0	19271.6	3131.2	3940.8	3336.8	3466.4	4537.3	7578.4	8412.8	100000.0	100000.0	100000.0	100000.0	100000.0
Up	10757.4	6554.1	4168.2	2770.0	1902.8	990.2	571.4	351.7	284.2	186.6	108.2	46.8	23.0	13.1	8.3	4.3
Down	3.8	2.2	1.3	0.8	0.5	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
β	2800.3	3018.3	3135.3	3459.2	3879.3	5614.7	6954.3	7816.6	6618.2	6458.3	6612.1	5773.1	3683.8	2093.1	2040.1	100000.0

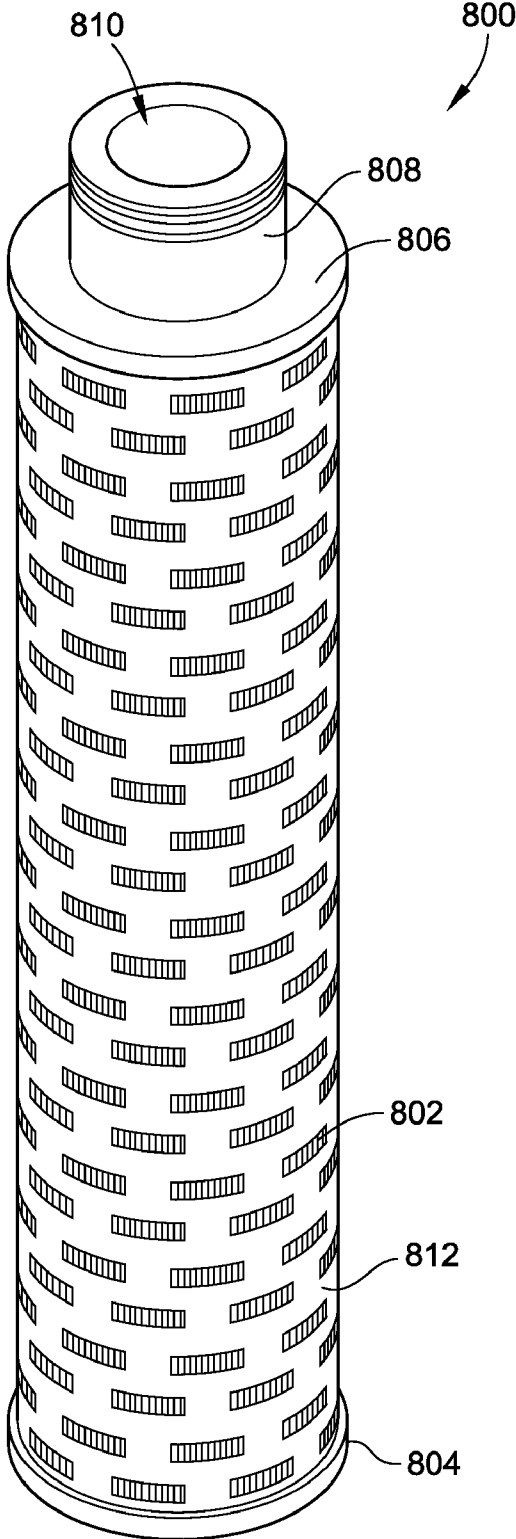


FIG. 23

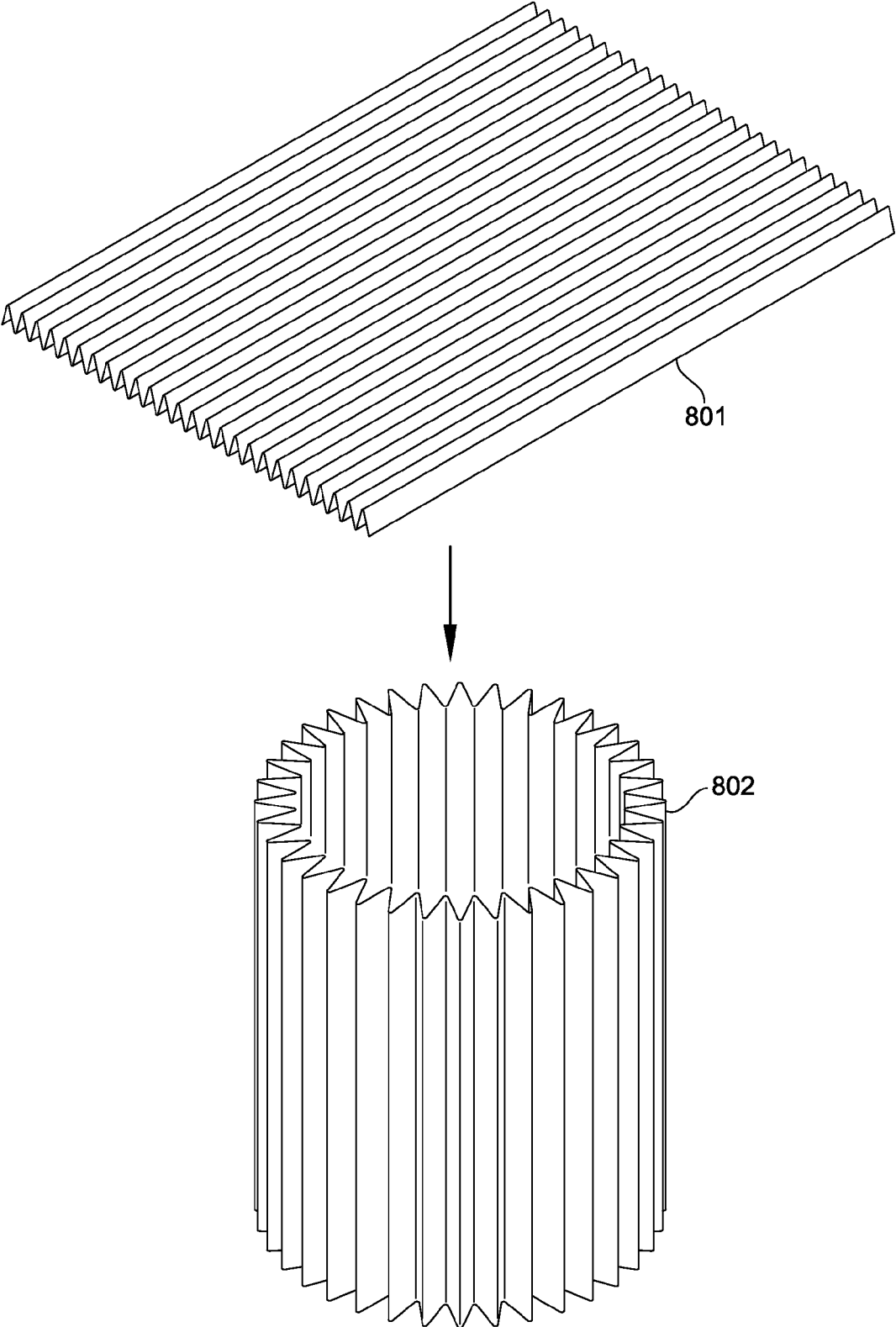


FIG. 24

## FINE FIBER LIQUID PARTICULATE FILTER MEDIA

### CROSS-REFERENCE TO RELATED PATENT APPLICATIONS

**[0001]** This patent application claims the benefit of U.S. Provisional Patent Application No. 61/383,487 filed Sep. 16, 2010; and U.S. Provisional Patent Application 61/308,488 filed Feb. 26, 2010; and U.S. Provisional Patent Application No. 61/330,462 filed May 3, 2010; and U.S. Provisional Patent Application No. 61/383,569 filed Sep. 16, 2010, the entire teachings and disclosure of which are incorporated herein by reference thereto.

### FIELD OF THE INVENTION

**[0002]** This invention generally relates to a filter media, and particularly to a composite filter media including fine fibers for liquid particulate filtration applications and methods of making the same.

### BACKGROUND OF THE INVENTION

**[0003]** Fluid streams such as liquid flows and gaseous flows (e.g. air flows) often carry particulates that are often undesirable contaminants entrained in the fluid stream. Filters are commonly employed to remove some or all of the particulates from the fluid stream.

**[0004]** Filter media including fine fibers formed using an electrostatic spinning process is also known. Such prior art includes Filter Material Construction and Method, U.S. Pat. No. 5,672,399; Cellulosic/Polyamide Composite, U.S. Patent Publication No. 2007/0163217; Filtration Medias, Fine Fibers Under 100 Nanometers, And Methods, U.S. Patent Publication No. 2009/0199717; Integrated Nanofiber Filter Media, U.S. Patent Publication No. 2009/0266759; Filter Media Having Bi-Component Nanofiber Layer, U.S. Provisional Patent Application No. 61,047,455; Expanded Composite Filter Media Including Nanofiber Matrix and Method, U.S. Provisional Patent Application No. 61/308,488; and Compressed Nanofiber Composite Media, U.S. Provisional Patent Application No. 61/330,462, the entire disclosures of which are incorporated herein by reference thereto.

**[0005]** The invention provides improved filter medias for various liquid particulate filtration applications. These and other advantages of the invention, as well as additional inventive features, will be apparent from the description of the invention provided herein.

### BRIEF SUMMARY OF THE INVENTION

**[0006]** A liquid is generally much more viscous than a gas, and thus results in a higher drag force. Therefore, liquid filtration applications pose unique challenges when compared to gas or air filtration applications, and particularly relative to fine fiber filter medias. For example, a liquid has a much greater tendency to pull particulates with it than a gas. Thus, the interception capability of a filter media for liquid filtration applications is significantly worse than gas or air filtration applications. In fact, higher the viscosity of a liquid, the lower the interception by a filter media. For example, a filtration efficiency of a filter media can drop from about 90% for an air filtration application to about 20% for a diesel fuel filtration application. Therefore, a filter media designed for air or gas filtration applications generally cannot meet filtration requirements of liquid filtration applications.

**[0007]** Filter medias including nanofibers have been known in air/gas filtration applications. However, the Applicants do not believe nanofibers have typically been used in liquid filters due to fluid characteristics of liquids. In fact, preliminary testings of fine fiber air filter medias for liquid applications for particulates/contaminants showed that nanofibers made little or no differences, as if fine fibers were non-existent. This was believed to be due to particulate momentum and viscosity posed by liquid. A composite filter media according to various embodiments of the present invention provides a filter media including nanofibers that is particularly well suited for liquid particulate filtration applications, such as particulate filtration of various hydrocarbon fuels. Various fine fiber coverage, fine fiber parameters, substrates and arrangements are discussed herein that have beneficially application to liquid filters.

**[0008]** In one aspect, the invention provides a filter media for a liquid particulate filtration application. The filter media includes a substrate and fine fibers carried on the substrate. The substrate includes coarse fibers having an average fiber diameter that is at least 4 times larger than an average fiber diameter of the fine fibers. The fine fibers have a basis weight of at least 0.03 g/m<sup>2</sup> and a linear coverage of at least about 5000 km/m<sup>2</sup>.

**[0009]** In another aspect, the invention provides a filter element for a liquid particulate filtration application. The filter element includes a filter media, a top cap and a bottom cap. The filter media includes a substrate and fine fibers carried on the substrate. The substrate includes coarse fibers having an average fiber diameter that is at least 4 times larger than an average fiber diameter of the fine fibers. The fine fibers have a basis weight of at least 0.03 g/m<sup>2</sup> and a linear coverage of at least about 5000 km/m<sup>2</sup>. Further, the top cap includes a fluid inlet. The filter media is sealingly attached to the top cap and the bottom cap.

**[0010]** In yet another aspect, the invention provides a method of forming a filter media. The method includes electrostatically spinning fine fibers having an average fiber diameter of less than 1 micron; applying the fine fibers on a substrate to provide a fine fiber basis weight of at least 0.03 g/m<sup>2</sup> and a linear coverage of the fine fibers of at least about 5000 km/m<sup>2</sup>, wherein the substrate comprising coarse fibers having an average fiber diameter of at least 4 times larger than the fine fibers; and processing the substrate with the applied fine fibers to rearrange the fine fibers on the substrate.

**[0011]** In another aspect, the invention provides a method of filtering a liquid. The method includes a step of providing the filter media according to any of the embodiments described herein, and a step of flowing a liquid stream through a filter media to capture particulates in the liquid stream.

**[0012]** Other aspects, objectives and advantages of the invention will become more apparent from the following detailed description when taken in conjunction with the accompanying drawings.

### BRIEF DESCRIPTION OF THE DRAWINGS

**[0013]** The accompanying drawings incorporated in and forming a part of the specification illustrate several aspects of the present invention and, together with the description, serve to explain the principles of the invention. In the drawings:

**[0014]** FIG. 1 is a schematic cross-sectional view (e.g. relative illustrated thickness not to scale) of a filter media including tightly compacted multiple scrim layers carrying fine fibers according to an embodiment of the present invention;

[0015] FIG. 2 is a schematic cross-sectional view of the filter media of FIG. 1 in a pre-compressed state being compressed to a compressed state by a set of rollers;

[0016] FIG. 3 is a schematic illustration of a concentric sheath/core type bi-component fiber of a substrate according to an embodiment of the present invention;

[0017] FIG. 4 is a schematic illustration of an eccentric sheath/core type bi-component fiber of a substrate according to an embodiment of the present invention;

[0018] FIG. 5 is a schematic illustration of a side-by-side type bi-component fiber of a substrate according to an embodiment of the present invention;

[0019] FIG. 6 is a schematic illustration of a pie wedge type bi-component fiber of a substrate according to an embodiment of the present invention;

[0020] FIG. 7 is a schematic illustration of a hollow pie wedge type bi-component fiber of a substrate according to an embodiment of the present invention;

[0021] FIG. 8 is a schematic illustration of an islands/sea type bi-component fiber of a substrate according to an embodiment of the present invention;

[0022] FIG. 9 is a schematic illustration of a trilobal type bi-component fiber of a substrate according to an embodiment of the present invention;

[0023] FIG. 10 is a schematic illustration of tipped typed bi-component fiber of a substrate according to an embodiment of the present invention;

[0024] FIG. 11 is a schematic illustration of a system for making a filter media according to an embodiment of the present invention;

[0025] FIG. 12(A) is a Scanning Electron Microscopic image showing bi-component fibers and the fine fibers of a composite media produced using the system of FIG. 11 taken at a magnification level  $\times 300$ ;

[0026] FIG. 12(B) is a Scanning Electron Microscopic image showing bi-component fibers and the fine fibers of a composite media produced using the system of FIG. 11 taken at a magnification level  $\times 1,000$ ;

[0027] FIG. 12(C) is a Scanning Electron Microscopic image showing bonding between bi-component fibers and the fine fibers of a composite media produced using the system of FIG. 11 taken at a magnification level  $\times 2,000$ ;

[0028] FIG. 12(D) is a Scanning Electron Microscopic image showing bonding between bi-component fibers and the fine fibers of a composite media produced using the system of FIG. 11 at a magnification level  $\times 10,000$ ;

[0029] FIG. 13 is a schematic illustration of a system for making a filter media according to a different embodiment of the present invention;

[0030] FIG. 14 is a schematic illustration of a system for making a filter media according to yet another embodiment of the present invention;

[0031] FIG. 15 is a schematic cross-sectional view of a filter media including tightly compressed multiple scrim layers and fine fibers according to an embodiment of the present invention;

[0032] FIG. 16 is efficiency test results of first test samples;

[0033] FIG. 17 is efficiency test results of second test samples;

[0034] FIG. 18 is efficiency test results of third test samples;

[0035] FIG. 19 is a schematic cross-sectional view of a filter media according to a different embodiment of the present invention;

[0036] FIG. 20 is efficiency test results of fourth test samples;

[0037] FIG. 21 is a schematic cross sectional view of a filter media according to yet another embodiment of the present invention;

[0038] FIG. 22 is efficiency test results of fifth test samples;

[0039] FIG. 23 is a perspective view of a filter element for a liquid particulate filtration application including a pleated filter media according to an embodiment of the present invention; and

[0040] FIG. 24 is a perspective view of the pleated filter media in the filter element of FIG. 23.

[0041] While the invention will be described in connection with certain preferred embodiments, there is no intent to limit it to those embodiments. On the contrary, the intent is to cover all alternatives, modifications and equivalents as included within the spirit and scope of the invention as defined by the appended claims.

#### DETAILED DESCRIPTION OF THE INVENTION

[0042] Prior to turning to the details, some lexicography will be developed to assist in understanding the present invention. As used herein, the term "substrate" is meant to be broad in nature and meant to include any structure upon which fine fibers are carried or deposited. "Substrate" may include conventional formed filter medias such as scrims and the like that may be unwound from media rolls. Such filter medias have a fiber entanglement that typically bonded or secured together mechanically, chemically, adhesively and/or otherwise and thereby have strength such that they cannot be easily torn manually (e.g. a 1 square foot sheet typically holds up to application of tension of 5 lbs force) and have filtrations properties. "Substrate" may also include looser fiber entanglements that may not be bonded together or secured together (e.g. a 1 square foot sheet may fall apart upon application of tension of 5 lbs force). A "scrim" used as herein refers to woven or non-woven fiber entanglement, wherein the fibers are bonded and compressed into a planar formed media.

[0043] There are a few ways that nanofiber coverage can be characterized. A first way to characterize nanofiber coverage is basis weight. However, basis weight is dependent in part upon the specific gravity of the material of the nanofiber, as well as the selected size (e.g. also interchangeably referred to as fiber diameter and/or thickness) of the nanofiber. Another useful measure for characterizing nanofiber coverage is calculated lineal distance of nanofiber coverage that can be expressed in terms of kilometer per square meter ( $\text{km}/\text{m}^2$ ), which is useful as this measure of coverage eliminate variability due to diameter of the fine fiber and variability due to specific gravity differences among different materials that may be employed.

[0044] In many exemplary embodiments discussed herein, fine fibers having an average fiber diameter of 0.08 micron (80 nanometer) were employed. However, it will be appreciated that a double sized fiber (e.g. a 160 nanometer sized fine fiber) based on a simple area calculation ( $\Pi \cdot R^2$ ) will have 4 times the weight; and a quadruple sized fiber will thus have 16 times the weight. An overapplication of fine fibers can lead to a plastic film that is not very pervious or porous, thus not suitable for a filter media. Using smaller fine fibers is desirable as a higher linear coverage level can be obtained. Considering that larger diameters of fine fibers will have a tendency to occupy greater void space, generally or as a rule of

thumb, it is desirable that the application rate of fine fibers on a kilometer basis be lower as the fine fiber diameter increases. However, coverage on a basis weight may nevertheless increase as fine fiber diameter increases, due to the quadrupling of mass for doubling of diameter. As a rule of thumb, basis weight may increase 2-2.5 times for a doubling in fiber diameter (about 4-6 times for a quadrupling of fiber diameter); and for purposes of ease a doubling will be employed. Thus, if a  $0.15 \text{ g/m}^2$  is employed for an 80 nm average diameter, then for a 160 nm fiber, a coverage of  $0.30 \text{ g/m}^2$  would be used, and a 320 nm fiber, a coverage of  $0.6 \text{ g/m}^2$ . Embodiments herein are useable for a range of fine fibers less than 1 micron, typically less than 500 nm, and more preferably smaller fibers under 150 nm. However, coverage adjustments can be made according to principles above to embodiments herein.

[0045] Herein, the terms “first”, “second” or third” in reference to a filter media composite or layers is not meant to refer to a specific location. “First layer” is not intended to mean the very first layer, nor meant to be indicative of upstream or downstream location relative to another layer (“upstream” or “downstream”) can be used for that purpose. Instead, such terms as “first” and “second” are used for antecedent basis purposes.

[0046] Multilayer Composite Filter Media

[0047] FIG. 1 is a schematic cross-sectional view of a filter media 100 according to an embodiment of the present invention. It is schematic in the sense that in reality the fine fiber layer has virtually no thickness, but for illustration and understanding, thickness is illustrated in FIG. 1 and other schematic illustrations. The filter media 100 is configured to capture solids in a liquid stream, such as hydrocarbon fuels, water and lube. In preferred embodiments, the filter media 100 includes at least two different fibers, for example, electrospun nanofibers and a substrate of coarser fibers carrying the nanofibers. As such, the filter media 100 is also referred to as a composite filter media, a composite media, or other like terms in this application. Although, the filter media 100 is particularly well suited for liquid particulate filtration applications with examples/embodiments having a significant particulate filtration impact now to liquid applications, the filter media 100 may be used in other fluid filtration applications.

[0048] In the embodiment shown in FIG. 1, the filter media 100 comprises 10 layers of substrate 102, 104, 106, 108, 110, 112, 114, 116, 118, 120, each of which carrying fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142, and a media 122 on top of the fine fibers 142. The substrate, 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 and the media 122 are formed of fibers having an average fiber diameter typically larger than that of the fine fibers. The substrate layers 102, 104, 106, 108, 110, 112, 114, 116, 118, 120, the fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142, and the media 122 are laminated and tightly compressed together to increase fiber surface area per volume and to provide a sufficient rigidity/structural integrity to filter particulates from a stream of liquid such as diesel fuel. Although this embodiment is shown with the media layer 122, this media layer is optional, and thus, the filter media 100 according to other embodiments may not include this media layer 122.

[0049] The filter media of FIG. 1 may be formed using the process shown in FIG. 2. FIG. 2 illustrates the filter media 100 in a pre-compressed state 144 and a compressed state 146. As shown, the filter media 100 in the pre-compressed state 144 has an initial thickness  $t'$  (also referred herein as an original

thickness.) The filter media 100 in the pre-compressed state 144 is compressed into the compressed state 146 using a set of rollers 148, 150, wherein the initial thickness  $t'$  is reduced to a final thickness  $t$ .

[0050] In some embodiments, the filter media 100 in the pre-compressed state 144 is heated before compressing. In certain preferred embodiments, fibers of the substrate relax and reorient to increase an average distance between the fibers during heating (such as a scrim that has been at least partially compressed during the scrim production process.) As such, the substrate layers expand and loft, wherein the thickness of each of the substrate layer increases. Further, as the fibers proximate the surface of the substrate relax and reorient, the fine fibers which are carried by these fibers move and reorient with the fibers. Thus, fine fibers are extended, pushed and pulled with the larger fibers. It is believed this may create a 3-dimensional matrix for fine fibers as opposed to being merely flat or planar (such 3-dimensional matrix of fine fibers can still be considered to be and may be referred herein as a “layer” even if integrated into surface of substrate.)

[0051] In such embodiments, the initial thickness  $t'$  of the pre-compressed state 144 can increase by at least 1.5 times, 2 times, 3 times or even more via heating. In such embodiments, the final thickness  $t$  of the filter media 100 after subsequent compression of the lofted filter media 100 can be either less than, or equal to, or greater than the initial thickness  $t'$ , depending on the amount of expansion during heating and the amount of reduction during compression. In other embodiments, the filter media 100 in the pre-compressed state 144 can be heated and compressed simultaneously via a set of heated calendering rollers. In such embodiments, there may not be any expansion or a very slight increase in the initial thickness  $t'$  prior to the thickness reduction to the final thickness  $t$ . In yet different embodiments, the compressed filter media 100 having the final thickness  $t$  can be heated post compression, wherein the thickness  $t$  may be increased. In some embodiments, the filter media 100 can be heated more than once. For example, the filter media 100 can be compressed by a set of rollers arranged in an oven, such that the filter media 100 is heated immediately before being compressed, while being compressed, and immediately after being compressed. In any event, it has been realized that processing of the media after deposition of the fine fibers to rearrange fine fibers into more of a 3-dimensional matrix is advantageous. Expansion and/or compression are examples of such processing. Such processing can afford a greater porosity and may be used for better flow and/or to facilitate heavier coverage of fine fiber deposition.

[0052] In one embodiment, the final thickness  $t$  can be between about 50% and 300% of the initial thickness  $t'$ , preferably between about 70% and 200% of the initial thickness  $t'$ , and more preferably between 80% and 150% of the initial thickness  $t'$ . As the filter media 100 in the pre-compressed state 144 is pressed down to the final compressed state 146, the fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142 become more integrated with the coarse fibers of the adjacent substrate layers 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 and form 3 dimensional fine fiber matrix within the filter media 100. Although, the filter media 100 in this embodiment includes 10 layers of substrate carrying fine fibers, other embodiments can include more or less substrate layers carrying fine fibers. For example, a filter media can include a single substrate layer carrying a sufficiently heavy coverage of fine fibers (e.g. at least about  $0.3 \text{ g/m}^2$ .)

[0053] The substrate layers **102, 104, 106, 108, 110, 112, 114, 116, 118, 120** can be formed of any suitable porous material. Each of the substrate layer can be formed of a same type of porous material or different types of porous material. In one embodiment, each layer of the substrate **102, 104, 106, 108, 110, 112, 114, 116, 118, 120** comprises a formed filter media. The formed filter media comprises fibers that are bonded together. For example, the fibers of the formed filter media may be bonded together by solvent bonding, thermal bonding, and/or pressure bonding. The formed filter media can carry fine fibers and provide a structural support. The formed filter media is also referred to as a substrate filter media, a filter media substrate, a substrate, a filter media, or other like terms in the present application.

[0054] Alternatively, the substrate may comprise one or more webs of fibers which are loosely tangled together in a highly fluffed thick state and may not be bonded together as in the case of a formed filter media. Thus, the web of coarse fibers can easily be pulled apart with very little manual effort and has little structural integrity such that it is not considered a formed filter media in the conventional sense. The fibers of the web of fibers typically have a larger average fiber diameter than an average fiber diameter of the fine fibers. As such, the web of fibers is also referred to as a web of coarse fibers or other like terms in this application. A composite filter media including fine fibers integrated with such web of coarse fibers is described in Integrated Nanofiber Filter Media, US Patent Application Publication No. 2009/0266759, which is assigned to the assignee of the present application, the entire disclosures of which are incorporated herein by reference thereto.

[0055] Preferably, the substrate is formed of a multi-component filter media. As used herein, the term “multi-component filter media”, “multi-component media”, “multi-component fiber media” and other similar terms can be used interchangeably to refer to filter medias including at least two different materials. For example, a multi-component filter media can comprise fibers formed of a first material and fibers formed of a second material, wherein the first material and the second material are different materials. Alternatively, a multi-component filter media can be formed of fibers including at least two different materials, such as fibers including a core formed of the first material and a sheath formed of the second material, as described in detail below. A multi-component filter media including two different materials is referred to herein as “bi-component filter media”, “bi-component media”, and like terms.

[0056] In one preferred embodiment, each of the substrate layers **102, 104, 106, 108, 110, 112, 114, 116, 118, 120** comprises a scrim formed of bi-component fibers including two different materials having different melting points. A composite filter media comprising fine fibers and a substrate formed of such multi-component fibers are described in Multi-Component Filter Media with Nanofiber Attachment, PCT Patent Application No. PCT/US09/50392, which is assigned to the assignee of the present application, the entire disclosure of which are incorporated herein by reference thereto.

[0057] In this embodiment, one component of the bi-component fibers of the scrim has a lower melting point than the other component. The low melt component can be any suitable polymer such as polypropylene, polyethylene, or polyester. The other component may be a polymer having a higher melting point than the low melt component, or other suitable

fiber materials such as glass and/or cellulose. The bi-component fibers are bonded together and/or compressed together to form a scrim or a substrate filter media having a certain thickness.

[0058] The bi-component fibers of the scrim used as the substrate **102, 104, 106, 108, 110, 112, 114, 116, 118, 120** can include a high melt polymer component and a low melt polymer component. For example the bi-component may comprise a high-melt polyester and a low-melt polyester, in which one has a higher melting temperature than the other. FIG. 3 schematically illustrates a bi-component fiber **22** according to one embodiment. As shown, the bi-component **22** is a concentric sheath/core type, wherein a core **24** is formed of a high melt polymeric component and a sheath **26** is formed of a low melt polymeric component.

[0059] The high melt polymer component is formed of a polymer having a higher melting temperature than the low melt polymer component. Suitable high melt polymers include, but are not limited to, polyester and polyamide. Suitable low melt polymers include polypropylene, polyethylene, co-polyester, or any other suitable polymers having a lower melting temperature than the selected high melt polymer. For example, bi-component fibers may be formed of a polyester core and a polypropylene sheath. In this embodiment, the bi-component fibers are formed of two different types of polyesters, one having a higher melting point than the other.

[0060] Other types of bi-component fibers may be used to form the substrate in other embodiments. Some examples of different types of bi-component fibers are schematically illustrated in FIGS. 4-10. An eccentric sheath/core type bi-component fiber **28** comprising a core **30** and a sheath **32** is shown in FIG. 4. This fiber is similar to the concentric sheath core fiber **22**, but with the core **30** shifted off-center. The different shrinkage rates of the two polymer components can cause the fiber to curl into a helix when heated. This allows an otherwise flat fiber to develop crimp and bulk, and can result in different fiber reorientation, expansion and/or undulation of surface under heat.

[0061] FIG. 5 schematically illustrates a side-by-side type bi-component fiber **34** including a first polymer component **36** and a second polymer component **38**. Depending on an application, the first polymer component may be a higher or lower melt polymer than the second polymer component. This is a further extension of the eccentric sheath/core fiber, in which both polymers occupy a part of the fiber surface. With proper polymer selection, this fiber can develop higher levels of latent crimp than the eccentric sheath/core fiber **28**.

[0062] A pie wedge type bi-component fiber **40** is schematically illustrated in FIG. 6. The pie wedge fiber **40** comprises a plurality of adjacent wedges formed of a first polymer component **42** and a second polymer component **44**. Each of the first polymer component **42** has a second polymer component **44** on either side. The first polymer component **42** may be a higher or lower melt polymer than the second polymer component **44**. These fibers are designed to be split into the component wedges by mechanical agitation (typically hydroentangling), yielding microfibers of 0.1 to 0.2 denier in the filter media.

[0063] FIG. 7 is a schematic illustration of a hollow pie wedge type bi-component fiber **46** comprising first polymer wedges **48** and second polymer wedges **50**. Again, depending on an application, the first polymer wedges **48** may be formed of a higher or lower melt polymer than the second polymer wedges **50**. The hollow pie wedge fiber **46** is similar to the pie



wedge fiber **40** but with a hollow center **52** core that prevents the inner tips of the wedges from joining, thus making splitting easier.

**[0064]** FIG. **8** is a schematic illustration of a islands/sea type bi-component fiber **54**. This fiber is also known as the "pepperoni pizza" configuration where a first polymer component **56** is the pepperoni and a second polymer component **58** is the cheese. In some embodiments, the first polymer component **56** is formed of a higher melt polymer than the second polymer component **58**, or the second polymer component **58** is formed of a soluble polymer. In such embodiments, this fiber allows the placement of many fine strands of high melt polymer **56** within a matrix of low melt or soluble polymer **58** that is subsequently melted or dissolved away. This allows the production of a media made of fine microfiber because the fibers are easier to process in the "pizza" form rather than as individual "pepperonis." Staple fibers can be made of **37** pepperonis on each pizza, producing fibers about 0.04 denier (about 2 microns diameter), or even finer.

**[0065]** The bi-component fibers may be formed into different shapes. For example, some bi-component fibers may not have a cylindrical shape with a circular cross section as the bi-component fibers described above. FIGS. **9** and **10** illustrate some examples of bi-component fibers with irregular shapes. Although, these fibers do not have a circular cross section, each has a diameter in context of the present invention. The diameter of the fibers having a non-circular cross section is measured from the outer perimeter of the fiber. FIG. **9** is a schematic illustration of a trilobal type bi-component fibers **60, 62**. Each of the trilobal fibers **60, 62** comprises a first polymer component **64, 66** and a second polymer component **68, 70**. Each of the trilobal fibers **60, 62** are measured by its diameter **72, 74**. In some embodiments, the first polymer component **64, 66** is formed of a higher melt or lower melt polymer than the second polymer component **68, 70**.

**[0066]** FIG. **10** is a schematic illustration of a tipped type bi-component fibers **78, 80**. The fiber **78** is a tipped trilobal bi-component fiber with a first polymer center **82** and second polymer tips **84**. The fiber **80** is a tipped cross bi-component fiber with a first polymer center **86** and second polymer tips **88**. Preferably, the first polymer center **82, 86** is formed of a higher melt polymer than the second polymer tips **84, 88**.

**[0067]** Now referring back to FIG. **1**, the fibers of the substrates are formed to have a larger average fiber diameter than that of the fine fibers. In one embodiment, the fibers of the substrates have an average fiber diameter that is at least 4 times as that of the fine fibers. In another embodiment, the fibers of the substrates can have an average fiber diameter of greater than about 0.6 micron, preferably greater than about 3 micron, and more preferably, greater than 5 micron. In one embodiment, an average diameter of the bi-component fibers of the substrate are between about 1 micron and about 40 micron, and more typically between about 10-40 microns.

**[0068]** The coarse fibers are compressed and/or heated, for example via a set of calendaring rollers and/or an oven, to form the substrate **102, 104, 106, 108, 110, 112, 114, 116, 118, 120**, wherein any of the substrate layers has a thickness between about 0.05 and 1.0 mm, preferably between about 0.1 and 0.5 mm. Such substrate can provide a structural support necessary for the fine fibers. Bi-component scrim of various thicknesses suitable for use as any of the substrate layers are commercially available through various suppliers, such as HDK Industries, Inc. of Rogersville, Tenn., or other

filter media suppliers. Thus, the substrate can be selected from such off the shelf bi-component medias.

**[0069]** In one embodiment, each layer of the substrate **102, 104, 106, 108, 110, 112, 114, 116, 118, 120** and the media **122** comprise a scrim formed of bi-component staple fibers having a high melt polyester core and a low melt polyester sheath. The bi-component staple fibers are compressed together to form the scrim, wherein the bi-component staple fibers are bonded together chemically, mechanically and/or thermally. For example, the bi-component staple fibers are heated to or near the melting temperature of the low melt polyester and compressed together, wherein the sheath formed of the low melt polyester melts or softens and acts as a bonding agent to bond fibers together.

**[0070]** The fine fibers **124, 126, 128, 130, 132, 134, 136, 138, 140, 142** can be deposited directly on the corresponding substrate **102, 104, 106, 108, 110, 112, 114, 116, 118, 120** as they are formed. Alternatively, the fine fibers may be separately prepared as a web of fine fibers, then laminated with the substrate. Although, the fine fibers may comprise fibers having various fiber diameters, preferably, the fine are nanofibers having very fine fiber diameter. Such fine fibers can be formed by electrospinning or other suitable processes. In one embodiment, the fine fibers are electrospun nanofibers having an average fiber diameter less than about 1 micron, preferably less than 0.5 micron, and more preferably between 0.01 and 0.3 microns. Examples herein have employed a smaller average diameter of 0.08 micron (80 nm). Such small diameter fine fibers can afford the ability to pack more fibers together in a given volume to provide an increased fiber surface area, which can increase filtration efficiency while decreasing pressure drop of a filter media.

**[0071]** The fine fibers may be formed by various suitable polymeric materials. To avoid destruction of the fine fibers during heating and/or compressing of the filter media **100**, the fine fibers are typically formed of a material having a higher melt temperature than at least the low-melt component of the bi-component fibers of the substrate. In preferred embodiments, the fine fibers are formed of a polyamide. Other suitable polymers include, but not limited to, polyvinyl chloride (PVC), polyolefin, polyacetal, polyester, cellulose ether, polyalkylene sulfide, polyarylene oxide, polysulfone, modified polysulfone polymers and polyvinyl alcohol, polyamide, polystyrene, polyacrylonitrile, polyvinylidene chloride, polymethyl methacrylate, polyvinylidene fluoride. Solvents for making polymeric solution for electrostatic spinning may include acetic acid, formic acid, m-cresol, tri-fluoro ethanol, hexafluoro isopropanol chlorinated solvents, alcohols, water, ethanol, isopropanol, acetone, and N-methyl pyrrolidone, and methanol.

**[0072]** In one embodiment, the fine fibers are formed of nylon-6 (polyamide-6, also referred to as "PA-6" herein) via electrospinning, wherein the electrospun fine fibers are deposited directly on the substrate. In this embodiment, the fine fibers **124** are generated electrostatically from a solution containing nylon-6 and deposited on a surface of the substrate **102**. The fine fibers **126** can be similarly generated and deposited on the substrate layer **104**, and so on. The substrate layers **102, 104, 106, 108, 110, 112, 114, 116, 118, 120** coated with the electrospun nanofibers **124, 126, 128, 130, 132, 134, 136, 138, 140, 142** are then laminated together with the media **122**, such that each layer of the fine fibers is sandwiched between the adjacent substrate and/or the media **122** to create the filter media **100** in the pre-compressed state **144** as shown in FIG.

2. As discussed above, the filter media **100** in the pre-compressed state **144** is then compressed to form the filter media **100** in its final compressed state **146** as shown in FIGS. **1** and **2**. In preferred embodiments, the filter media **100** is heated before, during, and/or after the compression. For example, the filter media **100** in the pre-compressed state **144** is heated prior to passing through the set of rollers **148, 150**. Further, the set of rollers **148, 150** can be heated to further heat the filter media **100** during the compression.

**[0073]** The bonding between the fine fibers and adjacent coarser fibers of the substrates and/or media **122** may involve solvent bonding, pressure bonding, and/or thermal bonding. For example, as the fine fibers are electrostatically generated from a polymer solution containing a solvent, the solvent remaining on the surface of the fine fibers can effectuate a solvent bonding as the fiber fibers come in contact with the coarse fibers of the substrate. Further, the low melt component of the bi-component fibers of the substrate can be used to enhance bonding between the fine fibers and the adjacent coarse fibers of the substrate. In such embodiment, the filter media **100** is heated to or near the melting point of the low melt component and compressed, wherein the low melt component of the bi-component coarse fibers melts or softens, which allows the adjacent fine fibers to embed into the low melt component as they are compressed together, thereby enhancing the bonding between the coarse fibers and the fine fibers (via pressure bonding and thermal bonding.) In a preferred embodiment, the adhesion between the fine fibers and the substrate on which the fine fibers were deposited are greater than that of between the fine fibers and the other adjacent substrate. For example, the adhesion between the fine fibers **124** and the substrate **102** is greater than the adhesion between the fine fibers **124** and the substrate **104**. As such, when a delamination is forced, the fine fibers **124** will delaminate from the substrate **104** and remain on the substrate **102**. Thus, when forced, the filter media **100** of such embodiment can be separated into ten layers of substrates carrying fine fibers (**102/124, 104/126, 106/128, 108/130, 110/132, 112/134, 114/136, 116/138, 118/140, 120/142**) and the media **122**.

**[0074]** In one embodiment, each of the substrate layers is formed of a bi-component fiber scrim having an average fiber diameter between about 1 and 40 microns and a basis weight between about 0.5 and 15 oz/yd<sup>2</sup>. The bi-component fibers comprise a high-melt polyester core and a low melt polyester sheath. The fine are electrospun nanofibers formed of nylon-6. The fine fibers have an average fiber diameter between about 0.01 and 0.5 microns, wherein each layer of the fine fibers **124, 126, 128, 130, 132, 134, 136, 138, 140, 142** has a basis weight between about 0.03 g/m<sup>2</sup> and 0.5 g/m<sup>2</sup>, providing total fine fiber basis coverage between 0.3 g/m<sup>2</sup> and 5 g/m<sup>2</sup>. The fine fiber coverage of the filter media **100** for liquid particulate filtration applications is significantly greater than the fine fiber coverage of gas or air filtration medias. A target basis weight of fine fibers on each substrate layer is selected according to an average diameter of the fine fibers and a desired efficiency and capacity of the filter media. A desired efficiency and capacity of the filter media **100** can be obtained by adjusting fine fiber diameter, fine fiber coverage on each substrate, number of fine fiber layers, amount of lofting and compression.

**[0075]** Although, the fine fiber coverage can be characterized in terms of a basis weight, the basis weight depends upon a specific weight of a polymer(s) and a diameter of the fine fibers. Thus, it is most useful to characterize the fine fiber coverage in terms of linear coverage per area (km/m<sup>2</sup>) as this takes out the variability associated with the specific weight and fine diameter. Thus, the linear coverage truly measures how much fiber is laid down as the quantity of fiber. In this regard, preferred fine fiber linear coverage ranges are greater than 5,000 km/m<sup>2</sup> for the heaviest coverage fine fibers, more preferably greater than 10,000 km/m<sup>2</sup>, and most preferably between 20,000 km/m<sup>2</sup> and 60,000 km/m<sup>2</sup>. The fine fiber coverages in various terms including the basis weight and linear coverage for fine fibers having an average fiber diameter of about 0.08 micron (80 nm) according to embodiments of the present invention are shown below in Table 1. The fine fibers of these embodiments are formed of PA-6 having a density of 1.084 g/cm<sup>3</sup> via a electrospinning process. As shown, Table 1 includes fine fiber mass coverage from 0.03-0.225 g/m<sup>2</sup>.

TABLE 1

ID	Nanofiber Coverage						
	1	2	3	4	5	6	7
NF coverage g/m <sup>2</sup>	0.225	0.15	0.09	0.075	0.05	0.0375	0.03
cm <sup>3</sup> PA6/m <sup>2</sup>	0.208	0.138	0.083	0.069	0.046	0.035	0.028
Linear cm of NF/m <sup>2</sup>	4.129E+09	2.753E+09	1.652E+09	1.376E+09	9.176E+08	6.882E+08	5.506E+08
Linear Meters of NF/m <sup>2</sup>	4.129E+07	2.753E+07	1.652E+07	1.376E+07	9.176E+06	6.882E+06	5.506E+06
Linear Miles of NF/m <sup>2</sup>	25658.691	17105.794	10263.476	8552.897	5701.931	4276.448	3421.159
2d area of NF cm <sup>2</sup>	33034.928	22023.285	13213.971	11011.643	7341.095	5505.821	4404.657
2d area of NF m <sup>2</sup>	3.303	2.202	1.321	1.101	0.734	0.551	0.440

TABLE 1-continued

Nanofiber Coverage							
ID	1	2	3	4	5	6	7
surface area of NF m <sup>2</sup>	10.378	6.919	4.151	3.459	2.306	1.730	1.384

[0076] Table 2 shows filter medias including multilayer substrates coated with fine fibers according to various embodiments of the present invention. The fine fibers were applied on a substrate layer at one of the line speeds according to embodiments shown in Table 1.

[0080] The upstream system **201** includes an unwinding station **202**, an electrospinning station **204**, an optional oven **206**, an optional set of rollers **207** and a rewinding station **208**. In this embodiment, a roll of scrim **210**, which is used here as a substrate layer, is unwound from the unwinding station **202**.

TABLE 2

Filter Medias			
ID of fine fiber application on each substrate layer	Total Basis Weight (g/m <sup>2</sup> )	Linear Coverage (km/m <sup>2</sup> )	Efficiency Beta Ratio (% efficiency = 1 - (1/β))
5-2-1-1-1-1	1.1	201,866	
5-5-4-3-2-1	0.64	117,452	β33-522 (H2O pleated element)
5-5-4-3-2-1	0.64	117,452	β300-10000 (Hydraulic pleated element 15 min)
5-5-4-3-2-1	0.64	117,452	β40-10000 (Hydraulic pleated element full test)
5-4-3-2-1	0.59	108,276	
5-5-4-3-2	0.415	76,162	β39-22 (H2O pleated element)
5-5-4-3-2	0.415	76,162	β55-10000 (Hydraulic pleated element full test)
5-5-4-3-2	0.415	76,162	β100-10000 (Hydraulic pleated element 15 min)
5-4-3-2	0.365	66,986	β40-15 (H2O pleated element)
4-4-2-1-1	0.75	137,630	
5 × (4) + 5 × (3) + 5 × (2)	1.575	289,050	β10,000+ (Hydraulic Flat)

[0077] While fine fiber coverage may vary based on fiber diameter, based on examples using 80 nm fibers and other calculations, typically embodiments that employ fine fibers having less than 500 nm average diameter will have similar coverage ranges for purpose of broad characterization and claiming purposes.

[0078] Method of Making Multilayer composite Filter Media

[0079] FIG. 11 schematically illustrates a representative process of making a filter media according to a processing embodiment of the present invention. Although this embodiment includes process steps for making the filter media **100** of FIG. 1, the process can produce filter medias according to other embodiments of the present invention with minor modifications. A system **200** shown in FIG. 11 includes an upstream system **201** for making a composite media including a substrate and fine fibers deposited thereon, and a downstream system **203** for laminating, lofting and compressing multiple layers of composite media to make a multilayer composite filter media for liquid particulate filtration applications.

The scrim **212** unwound from the roll of scrim **210** travels in a machine direction **214** toward the electrospinning station **204**. In the electrospinning station **204**, fine fibers **216** are formed and deposited on one surface of the scrim **212** to form a composite media **218** comprising the scrim carrying the fine fibers **216**. The composite media **218** may be heated and compressed in the optional oven **206** and the optional set of rollers **207** before being wound into a roll of composite media **230** on the rewind station **208** for improved adhesion between the fine fibers and the substrate.

[0081] The scrim may be formed in an upstream process of the system **200** (either part of a continuous line process or interrupted line process) or may be purchased in a roll form from a supplier such as HDK or other suitable media supplier such as H&V or Ahlstrom or the like. The scrim can be formed of various suitable materials, such as bi-component fibers of FIGS. 3-10 as discussed above. For example, the scrim can be formed of high melt polyester core/low melt polyester sheath bi-component staple fibers, which are compressed and/or heated to form the roll of scrim **210** having a

desired thickness and solidity. Alternatively, the substrate layer may be other single component media that may be compressed and held in place via a solvent bond, heat bond or the like.

**[0082]** In the case of bi-component fibers, for example, the concentric sheath/core type bi-component fibers may be coextruded using a high melt polyester as the core and a low melt polyester as the sheath. Such bi-component fibers can then be used to form a scrim or a filter media. In one embodiment, the bi-component fibers are used as staple fibers to form a multi-component filter media or a scrim via conventional dry laying or air laying process. The staple fibers used in this process are relatively short and discontinuous but long enough to be handled by conventional equipment. Bales of the bi-component fibers can be fed through a chute feed and separated into individual fibers in a carding device, which are then air laid into a web of fibers (which itself for purposes of the present disclosure may be used as a substrate.) The web of fibers is then compressed using a set of calendaring rollers to form the roll of scrim **210** (which can also be used as a substrate.) The web of the fibers may optionally be heated before entering the set of calendaring rollers. Since the scrim **210** of this embodiment comprises bi-component fibers, including a high melt component and a low melt component, it is also referred to as a bi-component filter media. In some embodiments, the web of fibers are folded before being calendared to form a thicker bi-component filter media.

**[0083]** In a different embodiment, a web comprising high melt polymer fibers such as polyester fibers and a web comprising low melt polymer fibers such as polypropylene fibers can be formed, separated and laminated together to form the roll of bi-component filter media or scrim. In such embodiment, the fine fibers **216** are deposited on the low melt side of the scrim **212**. In this embodiment, the low melt web is substantially thinner than the high melt web, such that the low melt component does not clog the surface of the high melt web when heated and melted.

**[0084]** In another embodiment, the bi-component fiber scrim can be formed via a melt blowing process. For example, molten polyester and molten polypropylene can be extruded and drawn with heated, high velocity air to form coarse fibers. The fibers can be collected as a web on a moving screen to form a bi-component scrim **210**.

**[0085]** The multi-component fiber filter media or scrim may also be spun-bounded using at least two different polymeric materials. In a typical spun-bounding process, a molten polymeric material passes through a plurality of extrusion orifices to form a multifilamentary spinline. The multifilamentary spinline is drawn in order to increase its tenacity and passed through a quench zone wherein solidification occurs which is collected on a support such as a moving screen. The spun-bounding process is similar to the melt blowing process, but melt blown fibers are usually finer than spun-bounded fibers.

**[0086]** In yet another embodiment, the multi-component filter media is wet-laid. In a wet laying process, high melt fibers and low melt fibers are dispersed on a conveying belt, and the fibers are spread in a uniform web while still wet. Wet-laid operations typically use  $\frac{1}{4}$ " to  $\frac{3}{4}$ " long fibers, but sometimes longer if the fiber is stiff or thick. The above discussed fibers, according to various embodiments, are compressed to form a scrim **210** or a filter media having a desired thickness.

**[0087]** Referring back to FIG. 11, the scrim **212** enters the electrospinning station **204**, wherein the fine fibers **216** are formed and deposited on one surface of the scrim **212**. In the electrospinning station **204**, the fine fibers **216** are electrospun from electrospinning cells **222** and deposited on the web of scrim **212**. The electrospinning process of the system **200** can be substantially similar to the electrospinning process disclosed in Fine Fibers Under 100 Nanometers, And Methods, U.S. Patent Application Publication No. U.S. 2009/0199717, assigned to the assignee of the present application, the entire disclosure of which has been incorporated herein by reference thereto. Alternatively, nozzle banks or other electrospinning equipment can be utilized to form the fine fibers. Such alternative electrospinning devices or rerouting of chain electrodes of the cells **222** can permit the fibers to be deposited in any orientation desired (e.g. upwardly is shown although fibers can also be spun downwardly, horizontally or diagonally onto a conveyor carrying coarser fibers).

**[0088]** The electrospinning process produces synthetic fibers of small diameter, which are also known as nanofibers. The basic process of electrostatic spinning involves the introduction or electrostatic charge to a stream of polymer melt or solution in the presence of a strong electric field, such as a high voltage gradient. Introduction of electrostatic charge to polymeric fluid in the electrospinning cells **222** results in formation of a jet of charged fluid. The charged jet accelerates and thins in the electrostatic field, attracted toward a ground collector. In such process, viscoelastic forces of polymeric fluids stabilize the jet, forming small diameter filaments. An average diameter of fibers may be controlled by the design of electrospinning cells **222** and formulation of polymeric solutions.

**[0089]** The polymeric solutions used to form the fine fibers can comprise various polymeric materials and solvents. Examples of polymeric materials include polyvinyl chloride (PVC), polyolefin, polyacetal, polyester, cellulous ether, polyalkylene sulfide, polyarylene oxide, polysulfone, modified polysulfone polymers and polyvinyl alcohol, polyamide, polystyrene, polyacrylonitrile, polyvinylidene chloride, polymethyl methacrylate, polyvinylidene fluoride. Solvents for making polymeric solution for electrostatic spinning may include acetic acid, formic acid, m-cresol, tri-fluoro ethanol, hexafluoro isopropanol chlorinated solvents, alcohols, water, ethanol, isopropanol, acetone, and N-methyl pyrrolidone, and methanol. The solvent and the polymer can be matched for appropriated use based on sufficient solubility of the polymer in a given solvent and/or solvent mixture (both of which may be referred to as "solvent".) For example, formic acid may be chosen for nylon-6. Reference can be had to the aforementioned patents for further details on electrospinning of fine fibers.

**[0090]** In the electrospinning station **204**, an electrostatic field is generated between electrodes in the electrospinning cells **222** and a vacuum collector conveyor **224**, provided by a high voltage supply generating a high voltage differential. As shown in FIG. 11, there may be multiple electrospinning cells **222**, wherein fine fibers **216** are formed. The fine fibers **216** formed at the electrodes of the electrospinning cells **222** are drawn toward the vacuum collector conveyor **224** by the force provided by the electrostatic field. The vacuum collector conveyor **224** also holds and transfers the scrim **212** in the machine direction **214**. As configured, the scrim **212** is positioned between the electrospinning cells **222** and the vacuum collector conveyor **224**, such that the fine fibers **216** are

deposited on the scrim **212**. In embodiments, wherein the scrim **212** is a multi-component filter media including a low melt component on one surface and a high melt component on the other surface, the multi-component scrim **212** is positioned between the electrospinning cells **222** and the vacuum collector conveyor **224**, such that the low melt component surface of the multi-component scrim faces the electrospinning cells **222**.

**[0091]** In one preferred embodiment, the electrospinning cells **222** contain a polymeric solution comprising polyamide-6 (PA-6) and a suitable solvent consisting of  $\frac{2}{3}$  acetic acid and  $\frac{1}{3}$  formic acid. In such a solvent, both acetic acid and formic acid act as a dissolving agent to dissolve PA-6, and acetic acid controls conductivity and surface tension of the polymeric solution. The electrospinning cells **222** generate fine fibers formed of PA-6, which are deposited onto a surface of the scrim **212**. As the fine fibers **216** are deposited on the surface of the scrim **212**, some fine fibers **216** entangle with coarse fibers of the scrim proximate the surface facing the electrospinning cells **222**. When some fine fibers **216** entangle with some coarse fibers, solvent remaining in the fine fibers **216** from the electrospinning process can effectuate a solvent bonding between the fine fibers **216** and the coarse fibers of the scrim **212**.

**[0092]** In other embodiments, the fine fibers can be formed by other suitable processes such as a melt blowing process. For example, the fine fibers having an average fiber diameter of about 0.6-0.7 micron can be formed via a melt blowing under an influence electrical fields. In such embodiments, the coarse fibers for a substrate are prepared to have an average fiber diameter at least 4 times larger than the fine fibers. For purposes of differentiation, melt blown fibers and electrospun nanofibers are thus meant to be more specific terms than fine fibers, which is intended to be generic.

**[0093]** The bonding between bi-component fibers of the scrim **212** and the fine fibers **216** may be enhanced via thermal bonding and pressure bonding by the optional oven **206** and the optional set of calendaring rollers **207**. As the composite media **218** is heated in the oven **206**, the low melt polymer component of the bi-component fibers softens or melts and allowing the fine fibers **216** to embed into the low melt polymer component. Thus, during the heat treatment, the composite filter media **218** is heated to at least above the glass transition temperature of the low melt component, and more preferably to or near the melting temperature of the low melt component. For example, the composite media **218** is heated to or near the melt point of low melt polyester, such that the outer low melt polyester layer of the bi-component fibers melts and bonds with the fine fibers **216** formed of PA-6. In such embodiments, PA-6 fine fibers **216** and the high melt polyester core of the bi-component fibers do not melt, since PA-6 and the high melt polyester have a significantly higher melting temperature than that of the low melt polyester. The low melt polyester, which has the lowest melting temperature, melts or softens, and adjacent PA-6 fine fibers **216** are embedded in the softened or melted low melt polyester, thereby bonding the fine fibers **216** and the scrim **212** together. Thus, the low melt polyester acts as a bonding agent between the bi-component fiber scrim **212** and the fine fibers **216**. The bonding between the fine fibers **216** and the scrim **212** can further be enhanced through pressure bonding via the set of rollers **207**. As the composite media passes through the rollers **207**, the fine fibers **216** and the scrim **212** are compressed together, wherein the fine fibers are further embedded into the

fibers of the scrim **212**. Further, the compression reduces voids in the composite media to form a composite media **220** with an increased solidity.

**[0094]** FIGS. **12(A)**-**12(D)** are Scanning Electron Microscopic (SEM) images of the bi-component fibers of the scrim **212** and the fine fibers **216** proximate the surface of the scrim **212** taken at various magnification levels. As shown in the SEM images taken at magnification levels  $\times 300$  and  $\times 1000$  of FIGS. **12(A)** and **12(B)**, the fine fibers **216** deposited on the web of scrim **212** form a spider web like fiber structure between the coarser bi-component fibers that are located proximate the surface of the scrim **212**. The SEM images taken at higher magnifications (FIG. **12(C)** at  $\times 2,000$  and FIG. **12(D)** at  $\times 10,000$ ) show the bonding between the fine fibers **216** and the bi-component fibers. As shown clearly in FIG. **12(D)**, the fine fibers **216** are embedded on the low melt polyester surface of the bi-component fibers.

**[0095]** The roll of composite media **230** including the bi-component scrim **212** and the fine fibers **216** is laminated with other composite medias **232**, **234**, **236**, **238**, **240**, **242**, **244**, **246**, **248**, and a media **250** in the downstream system **203**. Each of the composite media rolls **230**, **232**, **234**, **236**, **238**, **240**, **242**, **244**, **246**, **248**, and a roll of the media **250** are unwound from unwind stations **252**, **254**, **256**, **258**, **260**, **262**, **264**, **266**, **268**, **270**, **272**, and laminated together by a set of rollers **274**. The set of rollers may be a calendaring rollers to apply a significant pressure to laminate and significantly reduce a thickness of the layers of composite medias. Alternatively, the set of rollers **274** may apply a small pressure to laminate and reduce the thickness of the laminated layers just enough to fit through an oven **276**. In such embodiment, the laminated layers **280** is heated in the oven **276** and compressed via a set of calendaring rollers **282**, wherein the laminated layers **280** is compressed together into a compressed state having a desired thickness and solidity.

**[0096]** In this embodiment, each roll of the composite media **232**, **234**, **236**, **238**, **240**, **242**, **244**, **246**, **248** is prepared similarly as the roll of the composite media **230**. Therefore, each of the roll of the composite media **232**, **234**, **236**, **238**, **240**, **242**, **244**, **246**, **248** includes a substrate formed of a bi-component fiber scrim **284**, **286**, **288**, **290**, **292**, **294**, **296**, **298**, **300**, and electrospun nanofibers **302**, **304**, **306**, **308**, **310**, **312**, **314**, **316**, **318**, carried by the bi-component fiber scrim **284**, **286**, **288**, **290**, **292**, **294**, **296**, **298**, **300**.

**[0097]** In one embodiment, each of the substrates **212**, **284**, **286**, **288**, **290**, **292**, **294**, **296**, **298**, **300** and the media **250** are formed of a same bi-component fiber scrim having a thickness between about 0.05 mm and 1.0 mm. Each layer of the fine fibers **216**, **302**, **304**, **306**, **308**, **310**, **312**, **314**, **316**, **318**, is formed by electrospinning PA-6 polymer solution to produce a fine fiber coverage between about 0.03 g/m<sup>2</sup> and 0.5 g/m<sup>2</sup>. In other embodiments, the substrates may be formed of different types of filter media or scrim, and each of the fine fibers layer may have different fine fiber coverage.

**[0098]** The composite media **280** is heated in the oven **276** to or near a melting temperature of the low melt polyester component of the bi-component fiber scrim. During heating the substrates can relax and expand in thicknesses. Thus, the lofted composite media **281** can have a thickness that is at least 1.5 times, 2 times, 3 times or even greater than the thickness of the composite media **280** before being heated in the oven **276**. The lofted composite media **281** is then compressed via the set of calendaring rollers **282** into the compressed state **320**. The composite media is compressed, such

that the thickness of the composite media **280** is reduced between about 50% and 300%, preferably between about 70% and 200%, and more preferably between about 80% and 150% of the original thickness of the composite media **280** prior to heating ((total thickness of 10 scrim layers carrying 10 fine fiber layers+thickness of media–thickness of the composite media in the compressed state **320**)/(total thickness of 10 scrim layers carrying 10 fine fiber layers+thickness of media).) The thickness reduction can depend on the amount of lofting during heating. Thus, when the lofting from heating is large, the final thickness of the composite media after compression may be greater than the initial thickness of the composite media before heating. The composite media in the compressed state **320** is then wound into a roll of filter media **324**.

[0099] In this embodiment, the rolls of the composite media **230**, **232**, **234**, **236**, **238**, **240**, **242**, **244**, **246**, **248**. and the media **250** are laminated together, such that each of the fine fiber layers **216**, **302**, **304**, **306**, **308**, **310**, **312**, **314**, **316**, **318** is sandwiched between adjacent substrate layer and/or media. However, in other embodiments, the composite media layers may be laminated such that some of the fine fiber layers face each other to form fine fiber to fine fiber or substrate to substrate bonding within the final composite media **320**. For example, the system **200** can be used to make the filter media **500** of FIG. **15**. In this embodiment, each of the first five unwind stations **252**, **254**, **256**, **258**, **260** unwinds a roll of composite media such that the nanofibers are facing upward as shown in FIG. **11**. However, the unwind station **262** unwinds a composite media such that the nanofibers are facing downward. As such, the fine fibers on the first four substrate layers **514**, **516**, **518**, **520** are sandwiched between the substrates **502**, **504**, **506**, **508**, **510** as shown in FIG. **15**. However, the fine fibers **522** on the substrate **510** and the fine fibers **524** of the substrate **512** face each other forming the fine fiber-fiber fiber.

[0100] FIG. **13** schematically illustrates a system and a process of making a filter media according to a different embodiment of the present invention. A system **400** generally includes an unwinding station **402**, an electrospinning station **404**, a folding station **406**, a set of rollers **408**, an oven **410**, and a set of calendering rollers **412** and a rewinding station **414**.

[0101] In this embodiment a roll of substrate **416** is unwound from the unwinding station **402** and transferred to the electrospinning station **404**, wherein fine fibers are formed and deposited on a surface of the substrate **416**. The electrospinning station **404** and the process are similar to the electrospinning station **204** and the process described above. In this embodiment, the substrate **416** is a scrim formed of bi-component fibers including a high melt polyester core and a low melt polyester sheath. The fine fibers **418** are formed of PA-6.

[0102] The composite media **420** comprising the substrate **416** and fine fibers **418** is folded in the folding station **406**. The composite media **420** can be folded to 2-20 folds thick depending on desired characteristics of the final media. As shown, the folding creates fine fiber to fine fiber laminated surfaces and substrate to substrate laminated surfaces. The folding station **406** in this embodiment is shown as folding the composite media **420** in a line direction, such that the folds are pointing toward the set of the rollers **408**. However, in other embodiments, the composite media **402** may be folded such that the folds are pointing toward the electrospinning

station **404**, or folded in cross-line directions. The folded composite media **422** is then compressed to a thickness appropriate to pass through an oven **410**. As the composite media **424** is heated, the low melt polyester sheath melts or softens to effectuate thermal bonding between layers. After exiting the oven **410**, the composite media **424** passes through the set of calendering rollers **412**. The calendering rollers **412** are spaced apart from each other according to a desired final thickness of the media. The composite media **424** is pressed down into a compressed state having a desired thickness as it passes through the set of calendering rollers **412**.

[0103] Further, media layers **426**, **428** are laminated on each surface of the media **430** and wound into a roll in the rewinding station **414**. An expanded cross sectional view of a filter media **432** including the media **430**, the media layers **426**, **428** is shown in FIG. **13**. As shown, the media **430** includes multiple layers of substrate **416** and multiple layers of fine fibers **418** in a slanted orientation from the folding process. The media layers **426**, **428** can be formed of any suitable media, but in this embodiment, the media layers **426**, **428** are formed of the same bi-component fiber scrim used for the substrate **416**.

[0104] FIG. **14** shows yet a different embodiment of a system and a process of making a media. A system **600** is similar to the system **400** but the fine fibers in this embodiment are not deposited on a substrate. Rather, the fine fibers are formed and deposited onto a web of loosely entangled coarse fibers. The system **600** generally includes a chute **602**, a carding device **603**, an electrospinning station **604**, a folding station **606**, a set of rollers **608**, an oven **610**, and a set of calendering rollers **612** and a rewinding station **614**.

[0105] In the system **600**, the web of coarse fibers **616** is formed from staple fibers using a dry laying or air laying process. The staple fibers of this embodiment are bi-component fibers comprising a high melt polyester core and a low-melt polyester sheath. The bi-component staple fibers are relatively short and discontinuous, but long enough to be handled by conventional equipment. Bales of staple fibers are fed through the chute feed **602**. In the carding device **603**, the bi-component staple fibers are separated into individual fibers and air laid to form the web of coarse fiber **616**. At this point, the web of coarse fiber **616** can be loosely tangled together in a highly fluffed thick state and may not be bonded together. The web of coarse fiber **616** can be easily pulled apart with very little manual effort and has little structural integrity at this point such that it is not considered a filter media or substrate in the conventional sense.

[0106] The web of coarse fiber **616** is transferred via a conveyor belt **617** toward the electrospinning station **604**, wherein the fine fibers **618** are formed and deposited on a surface of the web of coarse fiber **616**. As the fine fibers **618** are deposited on the web of coarse fiber **616**, the fibers **618** are integrated with the coarse fibers of the web of coarse fiber **616** much more than in the previous embodiment with the substrate **416**, as the web of coarse fiber **616** are much more porous and less dense to allow deeper integration of the fine fibers **616**.

[0107] The web of coarse fiber **616** integrated with the fine fibers **618** are then folded into 10-30 folds in the folding station **606** and compressed via the set of rollers **608**, which is heated in the oven **610** and compressed again via the set of calendering rollers **612** as it was with the system **400**. The media **630** is then laminated with a media layer **626** and a porous layer **628** to form a filter media **632**. The coarse

bi-component fibers and the fine fibers of the media **630** of this embodiment are much more integrated. Thus, a cross sectional view of the media **630** does not show multiple layers, but rather appears more like a single integrated media **630**. The media **630** has a sufficient fine fiber coverage and structural integrity to capture particulate matters from a liquid stream, such as a hydrocarbon fuel stream.

[0108] The media according to various embodiments of the present invention can be configured into various shapes and sizes for various applications. For example, the media can be used in spin-on filter applications, large fuel filtration vessels, aviation filter systems, hydraulic filter elements, bio-fuel systems, diesel fuel filters, lube filters, and water filtration systems. The media can be pleated or gathered into a fluted filter, a pleated filter, or other such typical filter element arrangements.

#### EXAMPLES AND TEST RESULTS

[0109] FIG. **15** is a schematic cross-sectional view of a filter media **500** according to a different embodiment of the present invention. The filter media **500** is similarly constructed as the filter media **100**, but includes six layers of substrate **502, 504, 506, 508, 510, 512**, each of which carrying fine fibers **514, 516, 518, 520, 522, 524**, instead of ten layers of substrate carrying fine fibers. Further, the most upstream composite media layer comprising the substrate layer **512** and fine fibers **524** is reversed such that the fine fibers **524** face the fine fibers **522** forming a fine fiber-fine fiber interface. As shown, the substrate **512** provides an upstream surface **526** of the filter media **500**, thus fine fibers are not exposed and protected.

[0110] The test samples of the filter media **500** were prepared in a laboratory. Test samples of all embodiments described herein are prepared to have a sample area of 0.1 ft<sup>2</sup>. A bi-component fiber scrim comprising a high melt polyester core and a low melt polyester sheath having a basis weight of 35.0 GSY was used for each of the substrate layers **502, 504, 506, 508, 510, 512**. The fine fibers were formed via an electrospinning process from a polymeric solution comprising PA-6 and deposited on each of the substrate layers. On the substrate **512**, about 0.05 g/m<sup>2</sup> of the PA-6 nanofibers **524** having an average fiber diameter of 0.08 micron were formed and deposited. This level of fine fiber basis weight provides a linear fine fiber coverage of about 9176 km/m<sup>2</sup> (5,702 miles/m<sup>2</sup>). On the substrate **510**, about 0.15 g/m<sup>2</sup> of the PA-6 nanofibers **522** having an average fiber diameter of 0.08 micron were formed and deposited. This level of fine fiber basis weight provides a linear fine fiber coverage of about 27,530 km/m<sup>2</sup> (17,106 miles/m<sup>2</sup>). On each of the substrate layers **502, 504, 506, 508**, about 0.225 g/m<sup>2</sup> of the PA-6 nanofibers **514, 516, 518, 520** having an average fiber diameter of 0.08 micron were formed and deposited. This level of fine fiber basis weight provides a linear fine fiber coverage of about 41,290 km/m<sup>2</sup> (25,659 miles/m<sup>2</sup>) on each substrate. Thus, the filter media **500** includes a total fine fiber basis weight of about 1.1 g/m<sup>2</sup>, which provides about 201,866 km/m<sup>2</sup> (125,444 miles/m<sup>2</sup>) of linear fiber coverage.

[0111] The six substrate layers carrying the fine fibers were arranged as shown in FIG. **15** such that the substrate layer **512** forms the upstream surface **526** and the substrate layer **502** forms the downstream surface **528**. The six composite media layers were heated and compressed via a calendering roller as described in the previous embodiments to form the composite filter media **500**.

[0112] Test samples of the filter media **500** were prepared and tested for efficiency and dust holding capacity according to the ISO 16889 international standard for multi-pass method for evaluating filtration performance. All tests were performed using a hydraulic fluid Mil-H-5606 having a viscosity at the test temperature of 15 mm<sup>2</sup>/s loaded with ISOMTD test dust.

[0113] In the first test, the test fluid having a base upstream contaminant concentration of 5.00 mg/L was used at a flow rate of 0.26 GPM. FIG. **16** shows particle counts per mL and filtration ratio at 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100% time intervals during the 6-hour test period. When the test results were converted to a fluid cleanliness rating according to ISO 4406:99 cleanliness code (R4/R6/R14), the cleanliness rating at 10% time interval is 7/5/0, at 100% is 13/11/7, and average is 6/4/0.

[0114] In the second test, the test fluid having a base upstream contaminant concentration of 15.00 mg/L was used at a flow rate of 0.26 GPM. FIG. **17** shows particle counts per mL and filtration ratio test results. The cleanliness rating at 10% time interval is 7/6/0, at 100% is 19/18/14, and average is 12/11/7.

[0115] Test samples of the filter media **500** for the third test were prepared in a laboratory similarly as the test samples for the first test and the second test. However, the fine fiber basis weight of each substrate layer was changed. On each of the substrates **510** and **512**, about 0.05 g/m<sup>2</sup> of the PA-6 nanofibers **522, 524** having an average fiber diameter of 0.08 micron were formed and deposited. This level of fine fiber basis weight provides a linear fine fiber coverage of about 9176 km/m<sup>2</sup> (5,702 miles/m<sup>2</sup>) on the each substrate. On the substrate **508**, about 0.075 g/m<sup>2</sup> of the PA-6 nanofibers **520** having an average fiber diameter of 0.08 micron were formed and deposited. This level of fine fiber basis weight provides a linear fine fiber coverage of about 13,760 km/m<sup>2</sup> (8,553 miles/m<sup>2</sup>). On the substrate **506**, about 0.09 g/m<sup>2</sup> of the PA-6 nanofibers **518** having an average fiber diameter of 0.08 micron were formed and deposited. This level of fine fiber basis weight provides a linear fine fiber coverage of about 16,520 km/m<sup>2</sup> (10,263 miles/m<sup>2</sup>). On the substrate **504**, about 0.15 g/m<sup>2</sup> of the PA-6 nanofibers **516** having an average fiber diameter of 0.08 micron were formed and deposited. This level of fine fiber basis weight provides a linear fine fiber coverage of about 27,530 km/m<sup>2</sup> (17,106 miles/m<sup>2</sup>). On the substrate **502**, about 0.225 g/m<sup>2</sup> of the PA-6 nanofibers **514** having an average fiber diameter of 0.08 micron were formed and deposited. This level of fine fiber basis weight provides a linear fine fiber coverage of about 41,290 km/m<sup>2</sup> (25,659 miles/m<sup>2</sup>). Thus, the filter media **500** includes a total fine fiber basis weight of about 0.64 g/m<sup>2</sup>, which provides about 117,452 km/m<sup>2</sup> (72,985 miles/m<sup>2</sup>) of linear fiber coverage.

[0116] In the third test, the test fluid having a base upstream contaminant concentration of 15.00 mg/L was used at a flow rate of 0.26 GPM. FIG. **18** shows particle counts per mL and filtration ratio test results. The cleanliness rating at 10% time interval is 11/9/4, at 100% is 17/16/11, and average is 16/15/10.

[0117] FIG. **19** is a schematic cross-sectional view of a filter media **600** according to a different embodiment of the present invention. The filter media **600** is similarly constructed as the filter media **500** of FIG. **15**, however the filter media **600** include five substrate layers **602, 604, 606, 608, 610** and five fine fiber layers **612, 614, 616, 618, 620**. Test samples of the filter media **600** for the fourth test were prepared

pared in a laboratory similarly as the previous test samples. For these test samples, about 0.15 g/m<sup>2</sup> of the PA-6 nanofibers **612**, **614**, **616**, **618**, **620** having an average fiber diameter of 0.08 micron were formed and deposited on each of the substrate layers **602**, **604**, **606**, **608**, **610**. This level of fine fiber basis weight provides a linear fine fiber coverage of about 27,530 km/m<sup>2</sup> (17,106 miles/m<sup>2</sup>) on each substrate. Thus, the filter media **600** includes a total fine fiber basis weight of about 0.75 g/m<sup>2</sup>, which provides about 137,650 km/m<sup>2</sup> (85,530 miles/m<sup>2</sup>) of linear fiber coverage.

[0118] In the fourth test, the test fluid having a base upstream contaminant concentration of 15.00 mg/L was used at a flow rate of 0.26 GPM. FIG. 20 shows particle counts per mL and filtration ratio test results. The cleanliness rating at 10% time interval is 10/8/0, at 100% is 16/13/11, and average is 14/12/8.

[0119] FIG. 21 is a schematic cross-sectional view of a filter media **700** according to yet another embodiment of the present invention. The filter media **700** is similarly constructed as the filter media **500** of FIG. 15, however the filter media **700** include three substrate layers **702**, **704**, **706** and three fine fiber layers **708**, **710**, **712**. Test samples of the filter media **700** for the fifth test were prepared in a laboratory similarly as the previous test samples. For these test samples, about 0.075 g/m<sup>2</sup> of the PA-6 nanofibers **712** having an average fiber diameter of 0.08 micron were formed and deposited on the substrate **706**. This level of fine fiber basis weight provides a linear fine fiber coverage of about 13,760 km/m<sup>2</sup> (8,553 miles/m<sup>2</sup>). On the substrate **704**, about 0.09 g/m<sup>2</sup> of the PA-6 nanofibers **710** having an average fiber diameter of 0.08 micron were formed and deposited. This level of fine fiber basis weight provides a linear fine fiber coverage of about 16,520 km/m<sup>2</sup> (10,263 miles/m<sup>2</sup>). On the substrate **702**, about 0.15 g/m<sup>2</sup> of the PA-6 nanofibers **708** having an average fiber diameter of 0.08 micron were formed and deposited. This level of fine fiber basis weight provides a linear fine fiber coverage of about 27,530 km/m<sup>2</sup> (17,106 miles/m<sup>2</sup>). Thus, the filter media **700** includes a total fine fiber basis weight of about 0.315 g/m<sup>2</sup>, which provides about 57,810 km/m<sup>2</sup> (35,922 miles/m<sup>2</sup>) of linear fiber coverage.

[0120] In the fifth test, the test fluid having a base upstream contaminant concentration of 5.00 mg/L was used at a flow rate of 0.26 GPM. FIG. 22 shows particle counts per mL and filtration ratio test results. The cleanliness rating at 10% time interval is 11/10/5, at 100% is 11/9/4, and average is 9/8/0.

[0121] Filter Element

[0122] The filter media according various embodiment of the present invention can be pleated, gathered, or formed into different shapes according to various liquid filtration applications. FIG. 22 shows a filter element **800** for a locomotive diesel fuel system according to an embodiment of the present invention. The filter element **800** includes a pleated filter media **802**, a bottom cap **804**, a top cap **806**, and an outer protective layer **812**. The pleated filter media **802** can be formed of a filter media of various embodiments of the present invention, such as the filter media **500** of FIG. 15. FIG. 23 shows a pleated filter media **801** formed of the filter media **500**. The pleated filter media **801** can be pleated to have various pleat depths. The pleated filter media **801** formed of the compressed filter media **500** including six layers of substrate and six layers of fine fibers has a greater rigidity and structural integrity compared to pleated filter medias formed of other multilayer or single layer medias. Thus, the pleated filter media **801** is well suited to filter particulates in viscous

liquid streams such as the diesel fuel. The pleated filter media **801** is then rolled into the pleated filter media **802** having a cylindrical shape.

[0123] The bottom end cap **804** and the top end cap **806** are then placed on each end of the cylindrical pleated filter media **802**. The pleated filter media **802** is then thermally welded to the bottom end cap **804** and the top end cap **806** to prevent a liquid stream from flowing between ends of the pleated filter media **802** and the top and bottom end caps **804**, **806**. The top and bottom end caps **804**, **806** can be formed of various suitable polymeric materials. In this embodiment, the top and bottom end caps **804**, **806** were formed of a polyester. The bottom end cap **804** forms a closed end without a fluid path. The top cap **808** includes a hollow cylindrical piece **808** extending from its top surface, which provides a fluid flow path **810**. The outer protective layer **812** includes large openings and forms an outer periphery of the filter element **800** to protect the pleated filter media **802**.

[0124] All references, including publications, patent applications, and patents cited herein are hereby incorporated by reference to the same extent as if each reference were individually and specifically indicated to be incorporated by reference and were set forth in its entirety herein.

[0125] The use of the terms “a” and “an” and “the” and similar referents in the context of describing the invention (especially in the context of the following claims) is to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms “comprising,” “having,” “including,” and “containing” are to be construed as open-ended terms (i.e., meaning “including, but not limited to,”) unless otherwise noted. Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., “such as”) provided herein, is intended merely to better illuminate the invention and does not pose a limitation on the scope of the invention unless otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the invention.

[0126] Preferred embodiments of this invention are described herein, including the best mode known to the inventors for carrying out the invention. Variations of those preferred embodiments may become apparent to those of ordinary skill in the art upon reading the foregoing description. The inventors expect skilled artisans to employ such variations as appropriate, and the inventors intend for the invention to be practiced otherwise than as specifically described herein. Accordingly, this invention includes all modifications and equivalents of the subject matter recited in the claims appended hereto as permitted by applicable law. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the invention unless otherwise indicated herein or otherwise clearly contradicted by context.



What is claimed is:

1. A filter media for a liquid particulate filtration application, comprising:

a substrate including coarse fibers;

fine fibers carried on the substrate, wherein the fine fibers have an average fiber diameter that is at least 4 times as small as the coarse fibers; and

wherein a basis weight of the fine fibers is at least  $0.03 \text{ g/m}^2$  and a linear coverage of the fine fibers is at least about  $5000 \text{ km/m}^2$ .

2. The filter media of claim 1, wherein the filter media comprises at least two substrate layers, each substrate layer carrying the fine fibers; wherein the basis weight of the fine fibers on at least one of the substrate layer is at least  $0.03 \text{ g/m}^2$  and the linear coverage of the fine fibers is at least about  $5000 \text{ km/m}^2$ , and other substrate layers have a same or a different fine fiber basis weight and linear coverage than the at least one of the substrate layer.

3. The filter media of claim 1, wherein the fine fibers are electrospun fine fibers formed by an electrospinning process, the fine fibers having an average fiber diameter of less than 0.1 micron.

4. The filter media of claim 3, wherein the electrospun fine fibers are deposited on the substrate, wherein the fine fibers are rearranged and partially integrated with the coarse fibers by lofting and compression.

5. The filter media of claim 1, wherein the fine fibers are at least partially integrated with the coarse fibers of the substrate; wherein the at least some fine fibers are attached to adjacent coarse fibers.

6. The filter media of claim 1, wherein the substrate is a scrim comprising bi-component fibers, the bi-component fibers having a high melt component and a low melt component.

7. The filter media of claim 6, wherein the bi-component fibers comprise a high melt polyester core and a low melt polyester sheath, wherein the at least one substrate and the fine fibers are heated and compressed together to form a filter media, wherein the low melt polyester sheath melts or softens to bond the coarse fibers and the fine fibers.

8. The filter media of claim 7, wherein the fine fibers are formed of a polyamide.

9. The filter media of claim 1, wherein the filter media comprises at least three substrate layers, each substrate layer formed of a scrim formed of bi-component coarse fibers; wherein each substrate layer carries the fine fibers; wherein each substrate layer carries the fine fibers at a basis weight of between about  $0.05 \text{ g/m}^2$  and about  $0.225 \text{ g/m}^2$  and a linear coverage of between about  $9,000 \text{ km/m}^2$  and about  $41,300 \text{ km/m}^2$ ; wherein the filter media has a total basis weight of between  $0.3 \text{ g/m}^2$  and about  $4.8 \text{ g/m}^2$  and a total linear coverage of between about  $60,000 \text{ km/m}^2$  and about  $300,000 \text{ km/m}^2$ ; wherein the substrate layers and the fine fibers are lofted by heating and compressed to form a compacted filter media configured for a liquid filtration.

10. The filter media of claim 9, wherein the fine fibers carried on each of the substrate layers is sandwiched between two substrate layers.

11. The filter media of claim 9, wherein the compacted filter media includes a fine fibers to fine fibers interface.

12. The filter media of claim 9, wherein the filter media has a ISO 4406:09 cleanliness code at 10% time interval of a filtra-

tion efficiency test according to ISO 16889 international standard for multi-pass method of between about 11/10/5 and 7/5/0.

13. A filter element for a liquid particulate filtration application, comprising:

a filter media, comprising:

a substrate including coarse fibers;

fine fibers carried on the substrate, wherein the fine fibers have an average fiber diameter that is at least 4 times as small as the coarse fibers; and

wherein a basis weight of the fine fibers is at least  $0.03 \text{ g/m}^2$  and a linear coverage of the fine fibers is at least about  $5000 \text{ km/m}^2$ ;

a top cap including a fluid inlet; and

a bottom cap; wherein the filter media is sealingly attached to the top cap and the bottom cap.

14. The filter element of claim 13, wherein the filter media comprises at least three substrate layers, each substrate layer formed of a scrim formed of bi-component coarse fibers; wherein each substrate layer carries the fine fibers; wherein each substrate layer carries the fine fibers at a basis weight of between about  $0.05 \text{ g/m}^2$  and about  $0.225 \text{ g/m}^2$  and a linear coverage of between about  $9,000 \text{ km/m}^2$  and about  $41,300 \text{ km/m}^2$ ;

wherein the filter media has a total basis weight of between  $0.3 \text{ g/m}^2$  and about  $4.8 \text{ g/m}^2$  and a total linear coverage of between about  $60,000 \text{ km/m}^2$  and about  $300,000 \text{ km/m}^2$ ; wherein the substrate layers and the fine fibers are lofted by heating and compressed to form a compacted filter media configured for a liquid filtration.

15. The filter element of claim 14, wherein the fine fibers are formed of a polyamide and have an average fiber diameter of less than 0.1 micron; wherein the bi-component coarse fibers include a high melt polyester core and a low melt polyester sheath; wherein the compacted filter media includes at least some fine fibers embedded in the low melt polyester sheath.

16. The filter element of claim 13, wherein the filter media is pleated, and the pleated filter media is sealingly attached to the top cap and the bottom cap by thermal plastic welding.

17. The filter element of claim 16, wherein the thermal plastic welding attachment of the pleated filter media to the top and bottom caps prevents a liquid stream from bypassing the pleated filter media.

18. A method of forming a filter media, comprising:

electrostatically spinning fine fibers having an average fiber diameter of less than 1 micron;

applying the fine fibers on a substrate to provide a fine fiber basis weight of at least  $0.03 \text{ g/m}^2$  and a linear coverage of the fine fibers of at least about  $5000 \text{ km/m}^2$ , wherein the substrate comprising coarse fibers having an average fiber diameter that is at least 4 times larger than the fine fibers; and

processing the substrate with the applied fine fibers to rearrange the fine fibers on the substrate.

19. The method of claim 18, wherein rearrangement of the fine fibers on the substrate includes lofting the substrate and the fine fibers by heating, and compacting the substrate and the fine fibers via a set of rollers.

20. The method of claim 18, further comprising:

providing at least two substrate layers, wherein each substrate layer is formed of a scrim comprising bi-component coarse fibers;

applying the fine fibers on a first substrate layer to provide a fine fiber basis weight of between about 0.05 g/m<sup>2</sup> and about 0.225 g/m<sup>2</sup> and a linear coverage of between about 9,000 km/m<sup>2</sup> and about 41,300 km/m<sup>2</sup>;

applying the fine fibers on a second substrate layer to provide a fine fiber basis weight of between about 0.05 g/m<sup>2</sup> and about 0.225 g/m<sup>2</sup> and a linear coverage of between about 9,000 km/m<sup>2</sup> and about 41,300 km/m<sup>2</sup>;

laminating the first substrate layer carrying the fine fibers and the second substrate layer carrying the fine fibers; and

compressing the first and second substrate layers and the fine fibers to form a compressed filter media configured for a liquid filtration.

**21.** The method of claim **20** further including lofting the first and second substrate layers and the fine fibers prior to compressing to rearrange the fine fibers and to at least partially integrate the fine fibers with the coarse fibers of the substrate.

**22.** The method of claim **20**, wherein applying the fine fibers such that the basis weight and the linear coverage of the fine fibers on the first substrate is greater than that of the second substrate layer.

**23.** The method of claim **20**, wherein applying the fine fibers such that the basis weight and the linear coverage of the fine fibers on the first substrate layer is equal to that of the second substrate layer.

**24.** The method of claim **18**, wherein electrostatically spinning fine fibers include forming the fine fibers from a solution including a polyamide.

**25.** The method of claim **18**, further including pleating the filter media.

**26.** A method of filtering a liquid, comprising: providing the filter media of claim **1**; and flowing a liquid stream through a filter media to capture particulates in the liquid stream.

**27.** A filter media for a liquid particulate filtration application, comprising:

a substrate including bi-component coarse fibers having an average fiber diameter of greater than 0.6 micron;

fine fibers carried on the substrate, the fine fibers having an average fiber diameter of less than 0.6 micron, wherein the average diameter of the coarse fibers is at least 4 times larger than the average fiber diameter of the fine fibers; and

wherein a basis weight of the fine fibers is at least 0.03 g/m<sup>2</sup> and a linear coverage of the fine fibers is at least about 5000 km/m<sup>2</sup>.

**28.** A filter media for a liquid particulate filtration application, comprising:

at least two layers of substrate, each of the substrate layers formed of coarse fibers;

fine fibers carried on each of the substrate layers, wherein an average fiber diameter of the coarse fibers is at least 4 times larger than an average fiber diameter of the fine fibers; and

wherein a basis weight of the fine fibers on at least one substrate layer is at least 0.03 g/m<sup>2</sup> which provides a linear fiber coverage of at least about 5000 km/m<sup>2</sup>.

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