CHAPTER 4

Wet-laid Fibrous Media

The media discussed in Chapters 2 and 3 mainly involved fibres – natural and synthetic – made up into bulk materials by a variety of processes, all of which operate in the dry state. This chapter features the traditional papers and paper-like materials, made by deposition from a slurry in water. These wet-laid media also involve both natural and synthetic fibres.

4.1 Introduction

A typical and conventional definition of paper – the quintessential wet-laid material – is that it is a substance made from fibrous cellulose material, such as rags, wood or bark, treated with various chemicals and formed into thin sheets for writing, printing, wrapping and a wide variety of other uses. This definition is broadly valid as the history of paper is followed over many centuries, from its earliest recorded Chinese origins in the second century BC, right up until just a few decades ago; over this immensely long time span, the cellulose material varied considerably, depending on the plants available locally (e.g. jute, flax, straw, esparto grass, cotton linters, wood pulp) but was always a vegetable fibre.

This impressive continuity has been interrupted in recent years by two separate technological developments, necessitating that the scope of this chapter is widened accordingly. One of these is the manufacture of fibres of other materials that can be formed into paper-like sheets by adapting the conventional papermaking process; the outstanding example of this is the variety of glass fibre papers, which are of major importance in filtration. The other has evolved by exploiting the characteristics of the synthetic fibres formed by the extrusion of molten polymers; adaptation of this extrusion process enables these fibres to be formed directly into the paper-like sheets of the spunbonded media discussed in Section 3.5 of Chapter 3.

Also included in this chapter are the filter sheets that are used, for example, in special forms of filter press to clarify beverages such as beer and whisky or to sterilize pharmaceutical solutions. Traditionally these sheets closely resembled thick filter paper and, in fact, were made from a mixture of cellulose and asbestos fibres; recent years have seen asbestos displaced because of its health hazards.

4.2 Cellulose Papers

If, as is often said, the filter medium is the heart of any filter, then of the many types of media this is surely true of cellulose filter paper, which lies at the heart of filtration technology itself. Apart from its popularity as a highly versatile filter medium, the process by which paper is manufactured is itself dominated by filtration. Moreover, the two basic forms of papermaking machines (the cylinders of John Dickinson and the Fourdrinier wires which evolved from the invention of Louis Robert) are clearly the progenitors of the vacuum drum and horizontal belt filters widely used in the chemical and processing industries[1].

As shown schematically in Figure 4.1, in essence the papermaking process comprises dispersing fibres to form a suspension in water, and then filtering this through a wire mesh to produce a thin mat, which can be compressed and dried. Whilst any fibrous material can potentially be processed in this way, the resultant sheet will only have sufficient strength to be usable if the fibres bond together, either because of their intrinsic properties or by impregnation of the sheet with a suitable adhesive or resin.

The preparation of the suspension is of crucial importance and typically involves a sequence of mechanical and chemical treatment stages to ensure that the original cellulose fibres are well separated from each other, and also that the structure of each fibre is partly disintegrated so that its surface is fibrillated (i.e. hairy). The possibility of achieving this state is apparent from the typical multi-layered structure of cellulose fibres; the fibres are relatively coarse, about 30 μm in diameter, but the fibrils are very much finer, their dimensions and numbers depending on the extent of the chemical and mechanical treatment.

By variation of this pretreatment process, and of the nature of the fibrous raw materials, the structure of paper made from cellulose fibres can be controlled to

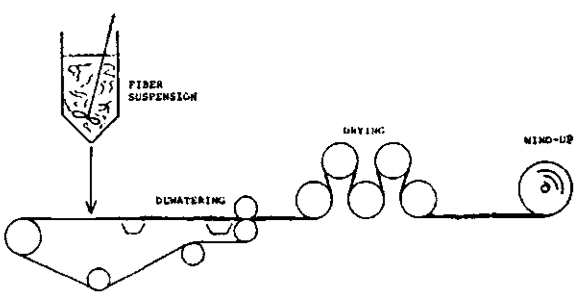

Figure 4.1. The basic wet-laid paper making process.

give a wide range of products of different permeabilities, porosities and strengths. The strength may be further enhanced by impregnating the paper with a suitable resin, especially for use under wet conditions, because absorption of water reduces the strength of untreated cellulose.

Multi-layer papers of different grades, possibly combining different materials (e.g. membranes) or including chemical reagents for specific functions, can be produced by lamination using a variety of binders and adhesives. An alternative approach pioneered by Whatman uses a single manufacturing operation to produce multi-layer graded density papers, which combine high dirt-holding capacity with low pressure drop characteristics: the practical benefits of this are illustrated by the experimental curves in Figure 4.2, showing how the life of a membrane filtering river water was maximized by a graded prefilter as compared with a conventional one of uniform density.

Although not, perhaps, in the mainstream of products covered by this Handbook, the paper used in domestic and commercial coffee filters should not be forgotten as a significant market for cellulose papers. This is marketed with bleached, and, increasingly, unbleached cellulose fibres.

4.2.1 Laboratory papers

The simple circular sheet of filter paper, familiar to chemistry students, and in analytical laboratories around the world, is an important outlet for cellulose filter papers (and also for glass fibre – see below).

It is appropriate to divide these papers into two broad categories. *Qualitative* filter papers are for use in qualitative analytical techniques aimed at identifying materials; they are accordingly also suitable for general use. *Quantitative* filter papers are for use in analytical techniques intended to quantify the composition of materials, where the purity and composition of the filter paper are of crucial importance.

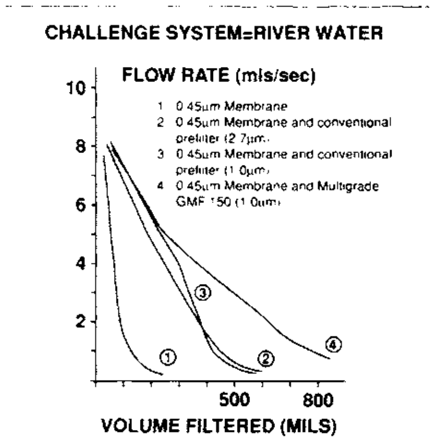

Figure 4.2. Effect of Whatman multi-layer prefilter (curve 4) on membrane life.

In respect of their 21 standard grades of this category, Whatman identified two ranges of qualitative papers (depending on whether or not they are wet strengthened) and three ranges of quantitative papers (depending on their ash content). Table 4.1 summarizes all five ranges and indicates their typical properties. Table 4.2 reproduces Whatman's notes giving guidance on their applications. Finally, Table 4.3 shows the typical trace element content both of two representative quantitative papers and, for comparison purposes, also of grade No.1 qualitative paper.

Table 4.1 Typical properties of Whatman cellulose filter papers[i]

Grade	Particle retention[a]	Air rate[b]	Ash (%)[c]	Thickness (μm)	Basis weight[e]	Wet burst[f]	Dry burst[g]	Tensile strength[h]
Qualitative								
1	11	10.5	0.06	180	88	0.3	16	39.1
2	8	21	0.06	190	103	0.7	16	44.6
3	6	26	0.06	390	187	0.5	28	72
4	20	3.7	0.06	205	96	0.7	10	28.4
5	2.5	94	0.06	200	98	0.4	21	55.6
6	3	35	0.11	180	105	0.3	15	39.1
General-purpose and wet-strengthened qualitative								
91	10	6.2	0.2	205	71	2	18	28
93	10	7	0.2	145	67	2.6	12	38
113	30	1.3	0.2	420	131	8	24	38.6
114	23	5.3	0.2	190	77	8.9	15	42.1
Ashless quantitative								
40	8	19.3	0.008	210	92	0.5	16	46.7
41	20	3.4	0.008	215	84	0.3	10	27.2
42	2.5	107	0.008	200	100	0.7	25	55.8
43	16	8.9	0.008	220	96	0.6	12	38.2
44	3	57	0.008	176	77	0.4	44	39.4
Hardened low-ash quantitative								
50	2.7	96	0.015	115	97	9.1	33	84
52	7	11.4	0.015	175	101	8.3	24	71.5
54	22	4.2	0.015	185	92	9.4	18	57.6
Hardened ashless quantitative								
540	8	13.2	0.007	160	88	9	20	63
541	22	3.8	0.007	155	82	5.3	14	43.4
542	2.7	69	0.007	150	93	9.2	28	82.6

[a] Particle retention in liquid filtration, based on challenge tests with suspensions of particles of known sizes, and is the size of particle in μm for which the filter will retain 98%.
[b] Air flow rate in s/100 ml/in^2.
[c] Ash % is determined by incineration of the cellulose filter at 900°C in air.
[d] Measured at 53 kPa.
[e] Basis weight of paper is in g/m^2.
[f] Wet burst strength in psi.
[g] Dry burst strength in psi.
[h] Tensile strength (MD) in N/15 mm.
[i] Whatman International Ltd.

Table 4.2 Whatman notes on applications of laboratory cellulose filter papers

Whatman grade	Comments
Qualitative filters	
Grade 1	Medium retention and flow rate for routine laboratory applications.
Grade 2	Slightly more retentive with a slower filtration speed than Grade 1.
Grade 3	A thick paper with good loading capacity, fine particle retention and increased strength. Particularly useful for flat Buchner funnels. The high absorbency makes it a useful sample carrier.
Grade 4	High flow rate with good retention of larger particles and gelatinous precipitates.
Grade 5	The most efficient qualitative paper for collecting small particles; slow flow rate.
Grade 6	Twice as fast as Grade 5 with almost as good particle retention. Often specified for boiler water analysis.
Wet strengthened quantitative filters	Because the strengthening resins contain nitrogen, should not be used in Kjeldahl estimations.
Grade 91	A general purpose creped filter for less critical routine analysis. Used worldwide to assay sucrose in cane sugar.
Grade 93	Similar to Grade 91 but with a smooth surface.
Grade 113	A creped filter with high loading capacity and the fastest flow rate of any qualitative grade. This is the thickest filter paper in the range and extremely strong. It is ideal for use with coarse or gelatinous precipitates.
Grade 114	A very strong paper with a smooth surface. Suitable for coarse or gelatinous precipitates.
Ashless quantitative filters	0.01% ash maximum, produced from high quality cotton linters. For routine quantitative techniques; ideal for a wide range of critical analytical filtration procedures.
Grade 40	A general purpose ashless filter paper with medium speed and particle retention. Typical applications include gravimetric analysis, the filtration of solutions prior to atomic absorption spectrophotometry and in air pollution monitoring.
Grade 41	The fastest ashless filter paper; recommended for analytical procedures involving large particles or gelatinous precipitates, e.g. hydroxides of iron or aluminium.
Grade 42	The most efficient quantitative grade for collecting small particles and fine precipitates such as barium sulphate.
Grade 43	A moderately fast filter used in the analysis of foodstuffs and in soil analysis.
Grade 44	Thinner that the other filters in this series to give the lowest ash weight for any given circle size. Slightly less efficient than Grade 42 for collecting small particles but with a higher flow rate.
Hardened low ash quantitative filters	0.025% ash maximum. The paper is treated with strong acid to produce high wet strength and chemical resistance. Particularly suited for Buchner filtrations where its tough smooth surface makes it easy to recover precipitates.
Grade 50	The thinnest of all Whatman filter papers with a slow flow rate and good particle retention characteristics. The hardened surface is virtually free from loose fibres.
Grade 52	The general purpose hardened surface filter paper with medium retention and flow rate. Ideal for use with Buchner funnels or Whatman 3-piece filter funnels.
Grade 54	Very fast filtration for use with coarse and gelatinous precipitates.

Table 4.2 (*continued*)

Whatman grade	Comments
Hardened ashless filters	0.008% ash maximum. Acid hardened to give high wet strength and chemical resistance with extremely low ash content. The tough surface makes these filters suitable for a wide range of critical filtration procedures.
Grade 540	The general purpose hardened ashless filter paper, with medium retention and flow rate. Frequently used in metal analysis.
Grade 541	High filtration speed for the retention of large particles and gelatinous precipitates in acid or alkaline solutions. The typical applications include protein determinations, cement analysis and the determination of fibre in animal foodstuffs.
Grade 542	Efficient retention of small particles in solutions that would weaken conventional filter papers. The flow rate is slow but there are many critical applications for this strong and very hard paper.

Table 4.3 Typical trace element contents (μg/g) of Whatman cellulose filter papers*

Grade	1	42	542
Aluminium	<0.05	2	1
Antimony	<0.02	<0.02	<0.02
Arsenic	<0.02	<0.02	<0.02
Barium	<1	<1	<1
Boron	1	1	2
Bromine	1	1	1
Calcium	185	13	8
Chlorine	130	80	55
Chromium	0.3	0.3	0.7
Copper	1.2	0.3	0.2
Fluorine	0.1	0.2	0.3
Iron	5	6	3
Lead	0.3	0.2	0.1
Magnesium	7	1.8	0.7
Manganese	0.06	0.05	<0.05
Mercury	<0.005	<0.005	<0.005
Nitrogen	23	12	260
Potassium	3	1.5	0.6
Silicon	20	<2	<2
Sodium	160	33	8
Sulphur	15	<5	<2
Zinc	2.4	0.6	0.3

*Whatman International Ltd

4.2.2 Industrial and general-purpose papers

Data relating to a range of cellulose filter papers produced for general industrial use, such as with filter presses, are listed in Table 4.4. Many of the grades, as indicated by the inclusion of 'w/s' in the grade designation, have their wet

Table 4.4 Typical properties of general purpose cellulose papers[a]

	Grammage[b] (g/m^2)	Filtration[c] Time (s)	Air[d] resistance (Pa)	Dry burst[e] (kPA)	Wet burst[f] (kPa)	Retention[g] size (μm)	Min[h] pore (μm)	Mean[h] pore (μm)
Creped cellulose								
H w/s	60	23	470	120	50	25	7.9	16.5
B w/s	90	72	1120	200	75	10	6.1	9.8
B140 w/s	140	28	370	180	55	13	7.8	14.2
WT w/s	180	132	880	300	150	10	5.9	10.8
BT	180	195	1700	240	–	9	4.3	8.0
Plain cellulose								
Thin white w/s	70	135	2020	250	80	6	5.5	8.1
Medium white w/s	90	161	1900	200	55	5	5.1	7.4
E w/s	140	320	2000	190	90	4	4.7	7.3
P w/s	225	749	4750	390	180	2.5	3.3	5.7
W26 w/s	225	89	710	240	50	5	7.1	12.0
TO w/s	280	459	3000	340	150	3	3.9	6.7
Plain synthetic								
V130	40	< 1	7	180	86	160		
P150	50	< 1	8	180	108	120		
P300	90	1.2	14	290	150	50		
V300	90	1.2	14	290	150	50		
R300	90	1.2	14	290	150	50		

[a] Hollingsworth and Vose Company Ltd.

[b] Grammage: The mass per unit area expressed in grams per square metre (g/m^2). For further details see BS 3432, ISO 536 and TAPPI 410.

[c] Water filtration time: Time in seconds (s) taken to collect 100 ml of water under a constant hydrostatic head. For further details see BS 6410.

[d] Air resistance: The pressure differential in pascals (Pa) measured across the paper when the linear air velocity is 10 m/min. See BS 6410.

[e] Dry burst: The maximum pressure in kilopascals (kPa) that can be sustained immediately before rupture by a circular area of dry paper. See BS 3137, ISO 2758.TAPPI 493, AFNOR 003-014.

[f] Wet pressure: Same as dry burst except that the paper is first soaked in water.

[g] Retention size: The appropriate minimum size measured in micrometers (μm) of spherical particles 90% of which will be retained on clean paper under laboratory test conditions. The actual retention achieved under operating conditions will depend on the specific application, and will be influenced by type of particle and size distribution, fluid, surface tension, flowrate, pressure drop, etc. Through tortuous path depth filtration particles much smaller than the determined pore size of a filter medium may be retained.

[h] Pore size: The minimum and mean flow pore size have been determined using a Coulter Porometer and Porofil wetting fluid, both of which are industry accepted standards for this test.

strength enhanced by impregnation with a bonding agent such as melamine formaldehyde. As shown, cellulose papers are commonly available in both smooth and creped forms; the purpose of creping is to improve the ease of handling, especially when the paper is wet. A useful visual summary of both properties and typical applications of these papers is provided by Figure 4.3.

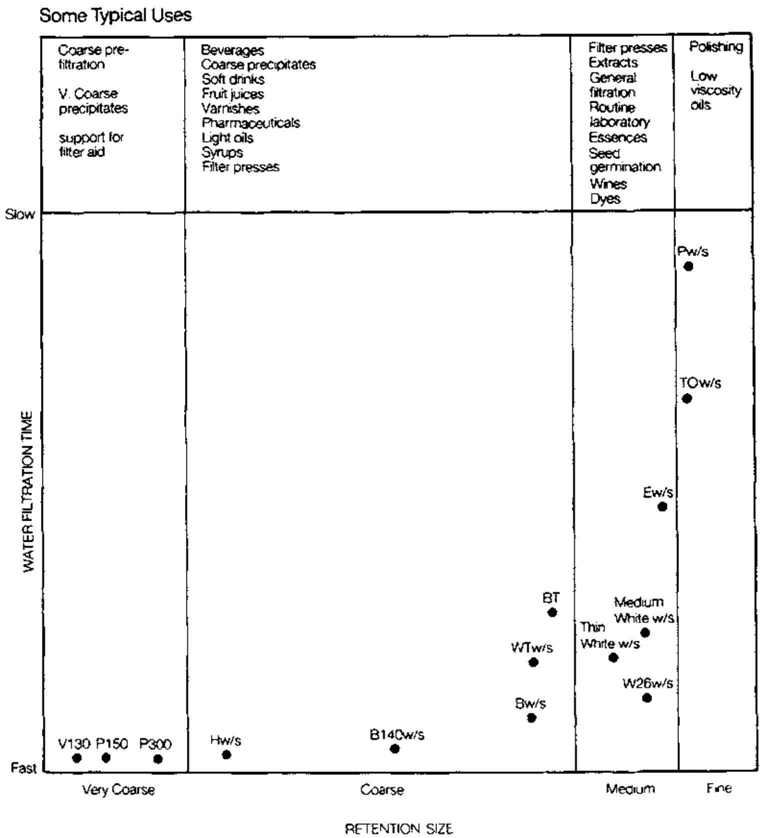

Figure 4.3. Overview of characteristics and applications of Hollingsworth and Vose Company Ltd industrial general purpose cellulose filter papers.

It is appropriate to note that the three coarsest papers included in both Table 4.4 and Figure 4.3 are not cellulose papers but spunbonded non-woven synthetic media, which are the subject of Section 3.5 of Chapter 3.

4.2.3 Automotive cellulose papers

The diverse and demanding needs of the automotive industry, embracing oil, air and fuel systems of all types and sizes, have led to the development of a substantial variety of impregnated papers tailored for specific uses.

Examples from the product range of Hollingsworth and Vose are summarized in Table 4.5. These are available slit to any width up to 1.53 m, marked with parallel lines on the 'wire side' to denote the more retentive surface. Impregnants used include standard phenolic thermosetting resins as well as flame-retardant materials. Papers may be either plain or corrugated.

Table 4.5 Typical data for automotive cellulose filter papers[a]

Grade	Impregnated[b] grammage (g/m^2)	Nominal volatile content (%)	Nominal resin content (%)	Air resistance[c] $\Delta p20$ (Pa)	Air resistance[c] $\Delta p10$ (Pa)	Pore[d] pressure (kPa)	Pore thickness (mm)	Retention[e] size (µm)	Corrugation depth (mm)	Typical application
EA31/131	130	9	23	70	–	0.88	0.50	46	0.22	Air/lube oil
G54D/202	158	7	26	88	–	0.97	0.60	38	0.30	Air/lube oil
FF00/254	174	10	30	92	–	0.98	0.66	37	0.17	Hydraulic oil
F54E/185	139	6	26	106	–	1.05	0.66	33	–	Flame ret. air
F54E/122	127	8	18	100	–	1.05	0.63	33	–	Air/lube oil
G53E/131	144	9	22	108	–	1.02	0.52	35	0.24	Spark erosion
FF1/185	168	6	26	120	–	1.06	0.76	32	–	Flame ret. air
FF1/131	165	9	22	124	–	1.07	0.62	32	0.20	Air/lube oil
H52C/129	155	8	28	120	–	1.06	0.70	32	–	Flame ret. air
EA44/245	141	7	21	140	–	1.12	0.49	29	0.30	Fuel oil
EA146/122	138	9	18	200	–	1.18	0.60	25	–	Heavy duty air
FF3/128	157	8	17	205	–	1.23	0.56	24	0.21	Spark erosion
FF3/254	187	10	30	210	–	1.23	0.60	24	0.18	Hydraulic oil
M49F/256	200	7	22	–	150	1.31	0.60	23	0.32	High temp. oil
EA138/226	122	7	20	–	158	1.66	0.40	11	0.25	Heavy duty air
2009/255	138	7	18	–	162	1.72	0.45	10	0.33	Heavy duty air
FF6/143	186	9	15	–	256	1.60	0.58	14	0.20	Hydraulic/fuel
EA152/139	134	9	15	–	310	2.05	0.51	8	–	Hydraulic/fuel
FF8/143	188	9	15	–	510	2.52	0.57	6	0.18	Hydraulic/fuel
M43/208	224	11	30	–	580	2.60	0.70	5	–	Coalescer/ stripper

[a] Hollingsworth and Vose Company Ltd.
[b] Impregnated grammage = typical weight as received.
[c] $\Delta p10$ = air pressure@ 10 m/min $\Delta p20$ = air pressure @ 30 m/min.
[d] Pore pressure = bubble point pressure.
[e] Retention = appropriate minimum size spherical particles, 90% of which will be retained on clean paper under particular test conditions.

4.3 Glass Papers

The process for manufacturing glass paper is essentially the traditional wet-laid papermaking process shown in Figure 4.1, but with pretreatment adapted to suit the distinctive properties of glass microfibres. Some, but not all, of the significant physical differences between glass fibres and those of cellulose can be seen in Figure 4.4.

By comparison with cellulose, the glass fibres used are smaller in diameter and much longer, as well as being of a far simpler structure, which does not fibrillate but, because of the brittleness of glass, would disintegrate if subjected to the vigorous pretreatment methods needed for cellulose fibres. Fortunately, glass microfibres are commercially available in a range of controlled diameters, which can be roughly divided into four categories comprising superfine (<0.5 μm), fine (0.5–2.0 μm), coarse (2–4 μm) and reinforcing (>4 μm).

4.3.1 Manufacture of glass fibre

The production of glass paper begins with the selection of a blend of fibre sizes, together with appropriate bonding resins or sizings, which are then gently dispersed in water to form the required stock suspension, at a concentration usually of less than 1%.

The diameter of glass fibres varies according to the process by which they are manufactured, and is of crucial importance in determining the filtration efficiency of the glass papers, with the highest performance demanding the finest fibres. The modern processes have been characterized respectively as drawing, blowing, centrifugal and combined[(2)]; however the production of microfine glass fibres is only possible by two combined processes, centrifugal-blowing (the rotary process) and drawing-blowing (the flame attenuation process).

A leading manufacturer of glass microfibres, Johns Manville (having taken over Schuller, the original makers) spins them from molten glass by versions of the two combined processes. The Micro-Aire media are produced from a saucer-shaped spinner rotating at high speed; molten glass is ejected through fine holes in its perimeter wall, to meet a blast of cold air that solidifies the glass into relatively coarse and short fibres. These media are the basis of medium efficiency bag type air filters and are discussed further in Section 5.2 of Chapter 5.

Johns Manville's Micro-Strand Micro-Fibers comprise long fibres, which have some of the finest diameters of any filtration material, and are an ideal basis for glass paper. They are made by the 'pot and marble' process, whereby glass marbles are melted in a pot with a perforated base. As the emerging streams of molten glass solidify, they are kept soft by very hot gas, whilst they are stretched to finer diameters (0.25–3 μm). They are available in three formulations, the chemical compositions of which are summarized in Table 4.6.

The two main formulations are tailored to meet specific end-use requirements; these are the 100 Series and 200 Series products, which are supplied in bulk form, with no binders or sizings. The 100 Series, with nominal fibre diameters of

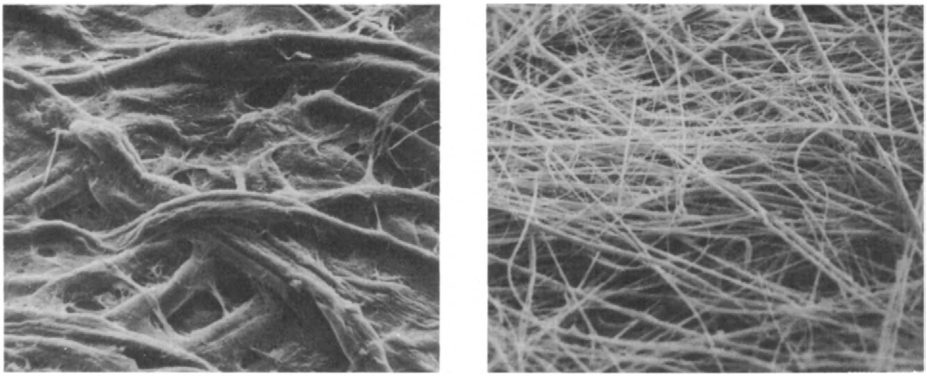

Figure 4.4. (a) Cellulose fibres in Whatman 42 filter paper at ×500 magnification; (b) glass microfibres in Whatman GF/D filter paper at ×500 magnification.

Table 4.6 Chemical composition of Johns Manville *Micro-Strand Micro-Fibers*[a]

Oxide	Nominal weight (%)		
	100 Series Type 475 fibre	200 Series Type 253 fibre	Q-Fiber
SiO_2	58.3	65.5	99.9
Al_2O_3	5.8	3.1	<0.05
B_2O_3	11.3	5.3	<0.01
Na_2O	10.1	16.0	<0.05
K_2O	2.9	0.7	–
CaO	1.8	5.9	<0.02
MgO	0.3	3.0	<0.01
BaO	5.0	0.01 (max)	–
ZnO	4.0	–	–
Fe_2O_3	–	–	<0.01

[a] Johns Manville Inc.

Table 4.7 Range of fibre diameters of Johns Manville 100 *Series Micro-Strand Micro-Fibers*[a]

Product code	Fibre diameter range (μm)		
	Minimum	Nominal	Maximum
90	0.21	0.26	0.31
100	0.22	0.32	0.47
102	0.24	0.40	0.58
104	0.40	0.50	0.60
106	0.50	0.65	0.87
108A	0.72	1.00	1.33
108B	1.26	1.80	2.34
110X	2.00	2.70	3.40
112X	3.00	4.00	5.00
CX	4.30	5.50	6.70

[a] Johns Manville Inc.

0.26–5.5 μm, is designed for demanding air filtration applications; the ranges of fibre diameters for 10 standard grades are given in Table 4.7. The 200 Series, with nominal fibre diameters of 0.76–5.5 μm, is a special higher silica formulation, combining exceptional chemical resistance with fine filtration for applications such as battery separators; the ranges of fibre diameters of four standard grades are given in Table 4.8.

Q-Fiber is an exceptionally pure fibrous silica material for specialized applications. As Table 4.6 shows, the nominal silica content of this is 99.9%. Q-Fiber is available with nominal diameters of 0.5–4.0 μm; it is both low density and non-crystalline.

Table 4.8 Range of fibre diameters of Johns Manville 200 Series *Micro-Strand Micro-Fibers*[a]

Product code	Fibre diameter range (μm)		
	Minimum	Nominal	Maximum
206	0.60	0.76	0.96
210X	2.55	3.00	3.45
212X	3.20	4.10	5.20
CX	4.30	5.50	6.70

[a] Johns Manville Inc.

Table 4.9 Properties of Whatman glass microfibre laboratory filter papers[i]

Grade	Particle retention[a]	Air rate[b]	Thickness (μm)[c]	Basis weight[d]	Wet burst[e]	Tensile strength[f]
GF/A	1.6	4.3	260	53	0.3	5.5
GF/B	1.0	12	675	143	0.5	6.4
GF/C	1.2	6.7	260	53	0.3	6.6
GF/D	2.7	2.2	675	121	0.3	6.4
GF/F	0.7	19	420	75	0.3	8.9
934-AH	1.5	3.7	435[g]	64	0.5	4.1
QM-A	2.2	6.4	475	87	1.5	7.3
GMF 150	1.2	3.1	730	139	1.4	4.2
EPM2000	2.0	4.7	450	85	1.8	6.3
Grade 72	N/A[h]	5	800	211	0.6	5.5

[a] Particle retention in liquid filtration, based on challenge tests with suspensions of particles of known sizes, and is the size of particle in μm for which the filter will retain 98%.
[b] Air flow rate in s/100 ml/in^2.
[c] Measured at 53 kPa.
[d] Basis weight of paper in g/m^2.
[e] Wet burst strength in psi.
[f] Tensile strength (MD) in N/15 mm.
[g] Measured at 3.5 kPa.
[h] Not applicable as medium is for adsorption from vapour phase.
[i] Whatman International Ltd.

Table 4.10 Whatman notes on applications of laboratory glass filter papers

Whatman grade	Comments
GF/A	For high efficiency general purpose filtration; widely specified for air pollution monitoring.
GF/B	Thicker than GF/A with higher wet strength and increased loading capacity. Recommended for filtering concentrated suspensions of small particles and for sampling techniques that require absorption of relatively large volume of liquid.
GF/C	The standard filter for many countries for the determination of suspended solids in water. Widely used in biochemistry for cell harvesting, liquid scintillation counting and binding assays. Provided in two formats, FilterCard and Filter Slide, for automated laboratory filtration procedures. FilterCard is a circle of GF/C with a lightweight polyester surround. Filter Slide surround is a more rigid polycarbonate and is bar coded for automatic monitoring. Both can be dried at 105°C.
GF/D	A general purpose membrane prefilter in sizes for most holders.
GF/F	Retains smaller particles than other glass microfibre filters. Selected for critical applications, e.g. clarifying protein solutions and for filtering samples and solvents prior to HPLC.
943-AH	Smooth surface, high retention borosilicate glass microfibre filter that is binder free and will withstand temperatures over 500°C.
QM-A	Very pure quartz (SiO_2) microfibre for monitoring trace levels of pollutants in air. Heat-treated after manufacture to remove organic traces which may interfere with analyses. Recommended for ambient and high temperature (maximum 500°C) sampling of stacks, flue outlets and aerosols, including acidic gases and airborne lead and inorganic compounds of lead.
GMF 150	Graded density combining coarse and fine layers. Exceptionally good loading capacity with fast flow rates and fine particle retention; ideal where extended life is required, e.g. as membrane prefilter. Two types available, rated at 1 and 2 μm, to fit standard membrane holders.
EPM 2000	Specially produced for high volume air samplers. Combines high chemical purity with rapid air flow and 99.999% retention efficiency for NaCl particles of mass median 0.6 μm. Heat-treated after manufacture to remove organic traces which may interfere with analyses.
Grade 72	Cellulose and glass microfibre filter loaded with activated charcoal for iodine adsorption.

4.3.2 Laboratory glass papers

The standard Whatman glass microfibre papers are made from long fibres of 100% borosilicate glass without any added binders. Their mechanical strength arises partly from the very high surface area of the submicrometre fibres, and partly from entanglement of the very long fibres.

Table 4.9 summarizes of the properties of the standard range of Whatman glass microfibre laboratory papers, while Table 4.10 reproduces Whatman's notes giving guidance on their applications.

These papers can be used at temperatures up to 500°C, and at low temperatures, without embrittlement or a significant change in performance. They are extremely white, with a brightness of 96% compared with 86% for cellulose (and 100% for magnesium oxide). Immersion in a liquid of similar refractive index, such as ethyl benzoate, renders them completely transparent.

By comparison with Table 4.1, it can be seen that the glass microfibre papers are thicker than the cellulose papers, with correspondingly lower retention sizes, but are generally less strong. They are used for air filtration (sampling and testing) as well as in liquid filtration situations.

4.3.3 Industrial and general-purpose glass papers

In addition to being strengthened by the inclusion of a binder such as latex, acrylic polymers or polyvinyl alcohol, these papers are usually made more robust by being laminated to a scrim of spunbonded material such as Reemay on one or both sides, thereby enhancing not only the strength but also the durability and pleatability. Typically this is done using a roto gravure laminator, which applies a hot melt adhesive in a dot matrix pattern to provide a strong bonding without significantly affecting the filtration characteristics.

Representatives of these are Lydall's Lypore media, of which the properties of the standard grades are summarized in Table 4.11. These are reported as being used primarily in high-efficiency/high-capacity hydraulic and lubrication oil elements for off-road vehicles, trucks and heavy machinery, as well as for industrial fluids and chemicals.

Table 4.11 Typical properties of Lypore liquid filtration media[a]

Grade number	9470	9215	9221	9220	9400	9224B	9229B	9381	9232
Mean flow pore size[b]	3.1	3.8	6.1	7.4	8.8	13.0	16.4	23.0	30.0
Basis weight (g/m^2)	78	78	78	75	75	81	81	73	70
Thickness (mm)	0.40	0.38	0.40	0.38	0.38	0.40	0.40	0.38	0.36
Liquid filtration									
Particle size (μm @ beta ratio = 75) (i.e. 98.67% removal efficiency)	0.5	1	2	3	6	12	20	25	30+
Dirt holding capacity[c] (mg/cm^2)	–	–	5.4	–	7.4	9.3	11.6	13.2	9232
Air filtration									
DOP penetration (0.3 μm particles @ 5.3 cm/s, %)	0.0005	0.015	4.0	7.0	14	35	55	75	85
Flow resistance (@ 5.3 cm/s, mm WG	44	36	15	12	9	5	3.5	1.5	0.8

[a] Lydall Inc.

[b] Determined by Coulter Porometer 1.

[c] Multipass testing of flat sheet and element with hydraulic oil Mil 5606 containing 10 mg/l of AC fine test dust, at a flow rate of 176 l/m^2 min to a terminal pressure of 2 bar.

Table 4.12 Lypore laminated grade identification system[a]

Letter code	Scrim
A	18 g/m^2 Reemay
B	97 g/m^2 woven glass cloth
C	16 g/m^2 Hollitex (calendered Reemay)
D	28 g/m^2 Cerex
E	32 g/m^2 Reemay
F	32 g/m^2 Cerex
G	Tea bag non-woven
H	9232/1232
I	9381/1381
J	44 g/m^2 Reemay with FDA Adhesive no. 4165
K	10 g/m^2 Cerex
O	No scrim

[a] Lydall Inc.

As indicated in Table 4.11, Lydall utilize the Beta (β) factor notation to indicate the efficiency of their liquid filtration media, where β is the ratio of the number of particles N_u greater than a defined size upstream of a filter to the number downstream N_d; therefore $\beta = N_u/N_d$ (this is also known as the Beta ratio). Each filter medium can be characterized by identifying the size of particle for which β has a particular value, such as $\beta = 75$ as in Table 4.11. Efficiency may also be expressed as the percentage of particles removed by a filter medium: $E\,(\%) = 100(\beta - 1)/\beta$.

Most Lypore media comprise a single uniform layer, but some are of two-layer graded construction. The latter are thicker, with the upper (felt) side serving as a prefilter for larger particles and the finer lower (wire) side determining the final efficiency rating of the medium; in some cases, their dirt-holding capacities can be enhanced by 50–100%.

More complex laminated grades are identified by combining standard grade code numbers with the letter codes for the scrims listed in Table 4.12, a letter for the wire side scrim before a slash (/) and then a second letter to designate the scrim on the felt side. Thus 9220-A/O identifies a 9220 standard grade with an 18 g/m^2 Reemay scrim on the wire side and no scrim on the felt side.

4.3.4 Battery separators

Battery separators constitute an important and very sophisticated market for a wide variety of specialist porous papers that are closely allied to filter papers (and do perform a kind of filtration function). A substantial proportion of these are based on glass microfibres, notably for lead acid batteries, but many other fibres are also used. For example, alumina competes with borosilicate glass in primary lithium cells, while in primary alkali cells the separators are manufactured from high-purity cellulose that has been treated with sodium hydroxide.

To withstand the associated stringent environment and demanding operating conditions, the chemical and physical properties of battery separator material have to be specially tailored. For example, the thicknesses required range from

100 μm or less up to some 3 mm. Tensile strength is of crucial importance, both for battery manufacture processability and to ensure integrity of separators in use, while fineness of pore size benefits both strength and absorbency. As indicated above, Johns Manville's 200 Series Micro-Strand Micro-Fibers products are manufactured for this application (see Table 4.8).

This is an application for which membranes are being increasingly used, partly because of the ease with which membrane material can be tailored to match the electrolytic needs of the battery (or fuel cell).

4.3.5 Glass paper media for air filtration

Glass microfibre media are of crucial importance in filters for air, notably for those of high efficiency, variously known as HEPA (High Efficiency Particulate Air), ULPA (Ultra Low Penetration Air) and absolute; these correspond to the top end of the Eurovent scale, with ratings from EU 10 (85% efficient) to EU 17 (99.999995% efficient).

To achieve these increasingly high efficiencies, correspondingly fine fibres are required. For example, for this market, Johns Manville produce their 100 Series Micro-Strand Micro-Fibers, comprising 10 standard grades with nominal diameters from 5.5 μm down to 0.26 μm (see Table 4.7).

Papers made from microfibres such as these are strengthened either by use of a bonding resin or by laminating to a backing scrim. Fuller information is given in Chapter 5, which is devoted to air filter media.

4.4 Papers from Other Fibres

Here, as elsewhere in this Handbook, it is difficult to draw hard and fast lines between one type of filter medium and another. Thus it is now perfectly possible to use the wet-laying, or papermaking process to produce sheet materials from synthetic fibres, which look and feel like papers – but which could as easily have been classed in the chapter on non-woven media, since that is what they are. Fibre makers are looking to expand their markets into papermaking – and papermakers are looking for better materials for special needs within the paper industry.

Synthetic fibres have the advantage over cellulose that they can be made as long as the end-use requires, with uniform thickness – longer fibres are needed to make stronger papers. Synthetic fibres can be a great deal more resistant to some chemical solutions, especially to acids, and so can extend the range of filter paper applications to such solutions. Cellulose fibre gains or loses absorbed moisture according to the ambient conditions; it thus changes its dimensions and the paper may curl – whereas synthetic fibre paper will be dimensionally stable.

On the other hand, this very hygroscopicity enables cellulose fibres to bond together as they dry, so that cellulose fibre papers do not need the additional bonding process (adhesive or thermal) that will be necessary for synthetic fibres.

The main disadvantage of synthetics, however, lies in their cost. Even reconstituted cellulose costs 3–5 times as much as raw cellulose, while the standard synthetics, such as amides, polyesters or acrylics, can cost 10 or 20 times as much. Synthetic fibre papers are thus reserved for special duties – amongst which is filtration.

4.4.1 Plastic fibres

The Japanese speciality papermaking company Tomoegawa Paper[3] was among the first to adapt the conventional wet-laid papermaking process so as to produce filter papers comprising 100% fibres of synthetic polymers (and also of metals). The fibre webs formed by filtration are bonded and strengthened by sintering. Representative of the resultant papers is the group of standard PTFE products summarized in Table 4.13.

Important properties of these papers are their moulding and laminating characteristics. Sheets can be moulded into different shapes and forms, such as

Table 4.13 Examples of papers made from 100% PTFE fibres[a]

Product	P-60	Q-75	R-125	R-250	R-350	R-500
Fibre diameter (μm)	15	25	35	35	35	35
Sheet thickness (μm)	59	70	125	250	350	500
Weight (g/m^2)	41	40	82	190	280	360
Density (g/cm^3)	0.69	0.57	0.66	0.76	0.82	0.80
Tensile strength						
2MD[b] (kg/15 mm)	0.3	0.2	0.4	0.6	1.2	1.6
2CD[c] (kg/15 mm)	0.2	0.1	0.3	0.4	0.8	1.2
Bubble point						
Min. pressure (kPa)			0.24	0.36	0.54	
Max. pore dia. (μm)			190	125	102	
Ave. pore dia. (μm)			43.5	41.8	35.2	

[a] Tomoegawa Paper Company Ltd.
[b] MD = machine direction.
[c] CD = cross machine direction.

Table 4.14 Wet-laid polyester media for liquid filtration[a]

Grade	Weight (g/m^2)	Thickness (mm)	Air permeability ($l/m^2/s$)[b]	Water permeability[c]	Tensile strength[d]	Bubble point (μm)	Mean flow pore (μm)
FFK2662	25	0.28	2500	714	70	270	50
FFK2663	37	0.30	1550	443	105	250	40
FFK2664	50	0.37	1200	343	150	180	30
FFK2666	60	0.50	1180	337	205	120	25

[a] Freudenberg Vliesstoffe KG, Filter Division.
[b] At 50 Pa.
[c] l/m^2 @ 200 mmWG.
[d] N/5 cm in machine direction.

cylinders. In addition, sheets of different pore size can be laminated to form a graded pore structure.

In 1992 the German papermaker Papierfabrik Schoeller & Hoesch introduced a range of special papers based on Lenzing's high-temperature P84 polyimide fibre. Four grades were offered, but production was short-lived.

A typical set of data for wet-laid polyester media, for liquid filtration, are shown in Table 4.14. These are intended for simple pressure filters used in industrial operations such as machine tool coolant separation.

Spunbonded media such as Reemay, mostly made from polyester or polypropylene, are frequently used in place of conventional cellulose paper for many applications, including filtration. Detailed information on this material is provided in Section 3.5 of Chapter 3.

4.4.2 Inorganic fibres

As mentioned above, Tomoegawa Paper[3] has made filter papers comprising 100% metal fibres by means of the conventional wet-laid papermaking process. As with polymer fibres, the webs of metal fibres formed by filtration are bonded and strengthened by sintering. Data for some typical sheets based on stainless steel fibres of 1.2 and 8 μm in diameter are summarized in Table 4.15.

For many years prior to the recognition of its health hazards, asbestos was widely used in industry in a variety of forms and for many purposes, ranging from thermal insulation to filtration. Thick papers made from asbestos fibres incorporated cellulose as a bonding agent, thus forming the original versions of

Table 4.15 Examples of stainless steel fibre papers[a]

	Fibre diameter							
	1 μm		2 μm			8 μm		
Product	SS1-250L	SS1-250H	SS2-100L	SS2-200L	SS2-300H	SS8-250L	SS8-200H	SS8-300H
Weight (g/m^2)	250	250	100	200	300	250	200	300
Thickness (μm)	576	48	182	351	65	370	43	58
Density (g/cm^2)	0.4	5.0	0.6	0.6	4.6	0.7	4.7	4.5
Tensile strength								
MD[b] kg/15 mm	1.1	9.5	1.3	2.8	12.8	2.1	3.3	4.9
CD[c] kg/15 mm	0.9	7.4	1.0	2.6	8.1	1.6	2.6	3.0
Elongation								
MD (%)	0.9	2.0	1.0	0.6	2.0	3.1	3.0	4.6
CD (%)	0.9	2.1	2.1	1.5	2.3	6.1	2.7	3.1
Porosity (%)	95	38	93	93	42	88	41	44

[a] Tomoegawa Paper Company Ltd.

[b] MD = machine direction.

[c] CD = cross machine direction.

the filter sheets that, for many years, were used to clarify beverages such as beer etc.; these are discussed in Section 4.5.

Other mineral fibres are usable safely for filtration media. Alumina fibre papers are available for high-temperature applications. These papers, with thicknesses of 0.5, 1, 2 and 3 mm and densities of 140–200 kg/m^3, are made from ICI's Saffil fibre and a combination of organic and inorganic binders. Saffil is a high-purity crystalline alumina, now marketed by J & J Dyson, stabilized by a small amount of silica; it is characterized by uniform fibre diameters (2–4 μm) and the virtual absence of any non-fiberized material. After burn-out of the 5% of organic content, the composition of the papers comprises 94% alumina and 6% silica.

4.5 Filter Sheets

Filter sheets are superficially very similar to thick filter paper (in the range 2–6 mm). They are in fact made by the same wet-laid process and contain a substantial proportion of cellulose fibres, together with large quantities of other particulate or fibrous material, which confer a rougher texture, greater hardness and higher rigidity.

They function primarily by depth filtration, and are able to remove low concentrations of fine inert or biological particles from liquids, so as to clarify, polish or sterilize them, notably in the beverage and pharmaceutical industries. They are mostly used in rectangular form in special types of filter press (Figure 4.5), or in circular form in enclosed pressure filters (Figure 4.6), but are now increasingly popular as lenticular cartridges (Figure 4.7).

One face of a filter sheet is more dense and harder than the other, this being the face in contact with the wire belt on which the sheet is formed by drainage. This

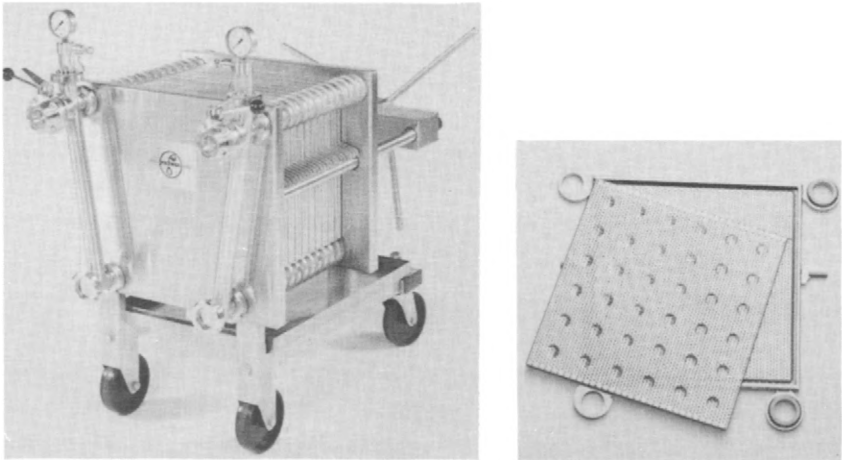

Figure 4.5. The sheet filter is like a conventional filter press but (a) of lighter construction with high quality finish, and (b) the plates easily dismantled for thorough cleaning.

hard face is used as the filtrate outlet, so that its finer pores can serve as a trap for any fibres that migrate through the sheet.

In the mid 1970s their composition was revolutionised to eliminate the health-threatening asbestos that they had contained since their origin in the early 1890s. The manufacture of sheets containing asbestos by the sole British producer, Carlson Filtration, is reported to have ceased in 1988[4].

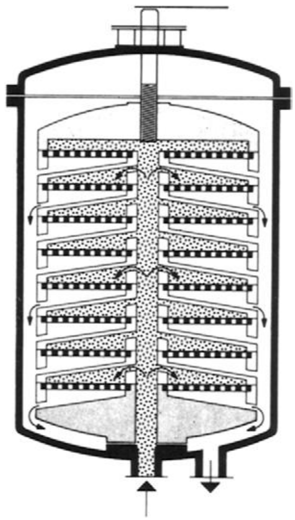

Figure 4.6. Seitz 'Radium' type A horizontal plate filter.

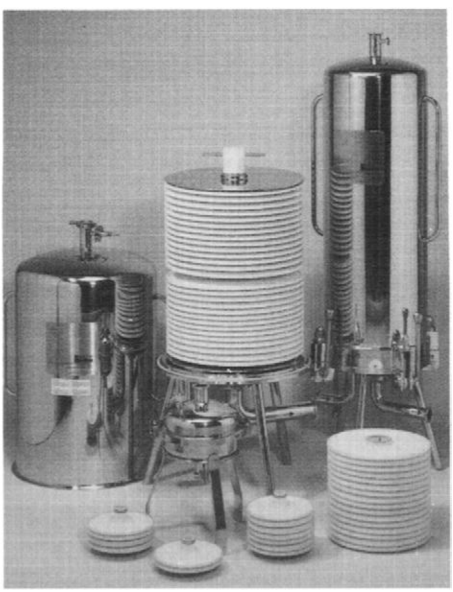

Figure 4.7. Zeta Plus filter cartridges.

4.5.1 History of filter sheets

Until quite recently, all commercially available filter sheets were derived from a mixture of cellulose and asbestos fibres that was first developed in Germany by the Seitz brothers early in the 1890s. In these sheets, the crucial component was the asbestos, which was found to be an exceptionally efficient filter medium, while the cellulose fibres controlled the structure and provided mechanical strength. These filter sheets contained 5–45% of asbestos, depending on the intended application. The fineness of the fibres could be varied to give very high surface areas of about 15 000–35 000 cm^2/g. Another important variable was the extent of fibrillation of the cellulose fibres, since increasing it increased the density of the sheet and reduced its porosity and permeability.

Incorporation of a bulky material such as diatomaceous earth provided another option for changing the permeability, while the thickness of a sheet was also significant. By exploiting these variables, a wide range of sheets could be produced, with gradations in both throughput rate and clarifying power, including harder and tighter sheets for low viscosity liquids such as water, and soft open sheets for very viscous liquids. In practice, performance depended on the duration of contact between the fibres and particles, which is a function of both the thickness of a sheet and the flow rate per unit area, as well as on the characteristics of the material being filtered.

Special grades of sheet incorporated reagents for specific ancillary functions, one example being polyvinyl pyrrolidone, the absorptive capacity of which for polyphenols stabilizes beers against chill and oxidation haze.

Of the various types of asbestos minerals, the one of importance in filtration was white asbestos, a hydrated magnesium silicate. It occurs in veins running through rocks of volcanic origin and is mined by open cast methods; the lumps so obtained are disintegrated and processed to separate the asbestos fibres from each other. These fibres are very fine, much finer than human hair, and generally are from 1.5 to 40 mm long but occasionally may be as long as 300 mm. A characteristic of them, which was only recognized and fully understood relatively recently, is that their surface carries a positive electrostatic charge (zeta potential), which imparts to asbestos fibres their unusual filtering properties (and is discussed in more detail later in this section).

Although some simple straining may also occur, these filter sheets primarily functioned by a depth filtration mechanism, whereby particles adhered, within the thickness of the sheets, to the positively charged surface of the asbestos fibres. It is this fact that explains the ability of the finest grades of sheet to trap particles well below 1 μm in effective diameter.

Once it was realized that asbestos particles represented a serious health hazard, whether inhaled as a dust, ingested in a liquid or injected into the body in a parenteral drug, there was a remarkably rapid switch by all the then competing suppliers to the asbestos-free alternatives that are now the international norm.

When asbestos filter sheets first came under attack, their manufacturers defended their use, especially for the filtration of micro-organisms down to virus size, and of highly concentrated protein solutions and other preparations with a high viscosity. This defence was based upon the non-availability of adequate alternatives, but material development soon resolved the problem. As early as 1974, Seitz introduced their own range of asbestos-free filter sheets to compete with novel media emerging from other manufacturers.

Carlson's development in turn of sheets based on (the then) ICI's Saffil alumina fibres, DuPont's potassium octatitanate Fybex fibres and calcined kieselguhr, all fell foul of the safety and health regulations concerning inhaleable dusts. In 1975 Carlson introduced their NA range of filter sheets that are not only asbestos-free sheets, but also contained no materials classified as dangerous.

4.5.2 Asbestos-free filter sheets

Carlson's original range of NA ('no asbestos') papers, based on natural kieselguhr, perlite and cellulose, has evolved over subsequent years to the seven grades listed in Table 4.16.

For filtering viscous fluids or those containing high levels of protein haze, Carlson produces the related BK series sheets detailed in Table 4.17, which have

Table 4.16 Carlson asbestos-free NA series filter sheets[a]

Grade	NA30	NA40	NA50	NA45	NA70	NA120	NA130
Thickness (mm)	2.65	3.50	4.90	4.00	3.80	4.40	4.30
Weight (g/m²)	775	1025	1500	1200	1250	1550	1600
Permeability (darcies)	0.270	0.153	0.106	0.068	0.044	0.029	0.018
Water flowrate (1/min/m² at 1 bar)	800	450	300	250	200	80	40
Mean pore size (μ)[b]	2.8	2.6	1.7	1.9	1.6	0.9	0.8
Max pore size (μ)[b]	3.7	3.4	2.4	2.7	2.3	1.5	1.3

[a] Carlson Filtration Ltd.
[b] Bubble point measurement.

Table 4.17 Carlson asbestos-free BK series filter sheets[a]

Grade	BK500	BK1000	BK1200	BK1500	BK2000	BK2500
Thickness (mm)	4.00	4.00	4.50	4.90	4.70	4.25
Weight (g/m²)	1125	1250	1450	1450	1450	1425
Permeability (darcies)	1.250	0.488	0.310	0.232	0.144	0.065
Water flowrate (1/min/m² at 1 bar)	2080	930	510	480	410	320
Mean pore size (μ)[b]	5.2	3.5	2.9	2.4	1.9	1.9
Max pore Size (μ)[b]	8.3	5.1	3.9	3.3	2.7	2.5

[a] Carlson Filtration Ltd.
[b] Bubble point measurement.

considerably higher throughputs than the NA series; with low density and high void volume, these are made from specially treated wood pulp.

Carlson's standard range of filter sheets is now the high-performance XE series, listed in Table 4.18. In addition to the basic formulation of cellulose with natural kieselguhr and perlite, XE sheets incorporate an advanced resin system, to give a higher total life with improved particle retention and clarity. With the exception of the XE170, 265, 350 and 375 versions, all the XE sheets are of the same carefully controlled thickness, enabling different grades to be readily interchanged in the same filter press configuration and seal thickness. Some typical performance data are given in Table 4.19. (The EE series matches the XE series, but is made from pure cellulose only, plus approved resins.)

Each of these three ranges of filter sheet can be supplied with increased wet strength (HH series), to enable them to cope with more demanding process requirements, or with reduced metal ion extractables (K series) or with both extra features (HHK series).

As well as these three ranges of sheets made for simple filtration, Carlson has three other types of sheet used for special processing purposes. The W2 media are used as support sheets either with a precoat, or where filter aid powders are used to increase the body of the filter cake. They are made of pure cellulose, with special resin binders, giving sheets of high wet strength, and corresponding durability. The other two types have solid particles held within the cellulose fibre matrix, to enable particular purification processes to be effected.

The Prop4 series of sheets contain PVPP (polyvinyl polypyrrolidone) powders, evenly dispersed throughout the sheet. PVPP has a particular affinity for polyphenols, and so can improve the stability of beer and wines. Once exhausted, the Prop4 sheets can be regenerated, *in situ*, by a chemical treatment, greatly extending the sheet's life.

In the Proc3 series, activated carbon granules are distributed throughout the sheet, enabling it to be used for removal of odours, colour, off-tastes and chlorine. Five grades are available, as shown in Table 4.20, differing in basis weight, carbon content and main sheet material. The LWT grades are suitable for lenticular cartridge manufacture, while versions are available with extra wet strength (HH versions) using special resins.

Seitz's quest for asbestos-free sheets has involved a major research programme, ultimately leading to a finely balanced combination of special procedures to upgrade cellulose fibres, the use of fine kieselguhr and perlite, and precisely dosed charge carriers which control the zeta potential. The company, now part of Vivendi/US Filter, consequently produces a very large range of filter sheets, comprising almost 100 different grades tailored to provide a precise answer to each specific application; their main standard grades are summarized in Table 4.21, while Table 4.22 provides guidance notes on the main categories, and examples of applications are given in Table 4.23.

Figures 4.8 and 4.9 indicate the size range of particles that, for practical purposes, can be removed by the various grades. The ability of appropriate grades to remove pyrogens and bacteria is illustrated respectively by Tables 4.24 and 4.25.

Table 4.18 Carlson asbestos-free BK series filter sheets[a]

Grade	XE5	XE10	XE20	XE50	XE70	XE90	XE150	XE170	XE200	XE265	XE280	XE350	XE400	XE675	XE1200	XE1700
Thickness (mm)	3.6	3.75	3.75	3.75	3.75	3.75	3.75	3.9	3.75	3.7	3.75	4.25	3.75	3.75	2.75	3.75
Weight (g/m^2)	750	100	1925	1125	1125	1200	1200	1325	1275	1300	1300	1540	1270	1350	1425	1450
Permeability (darcies)	1.79	0.74	0.49	0.2	0.16	0.11	0.068	0.055	0.047	0.040	0.035	0.027	0.025	0.015	0.008	0.006
Water flowrate ($1/min/m^2$ at 1 bar)	3500	1050	820	650	600	370	290	200	230	180	190	110	130	70	30	20
Mean pore size (μ)[b]	5.7	3.1	2.8	2.4	2.4	1.7	1.6	1.8	1.5	1.3	1.4	1.5	1.3	1.0	0.8	0.8
Max pore size (μ)[b]	7.2	4.2	3.6	3.2	3.4*	2.4	2.3	2.5	2.2	2.4	2.1	3.9	1.9	1.6	1.3	1.2

[a] Carlson Filtration Ltd.

[b] Bubble point measurement.

Capitalizing upon a wider understanding of the influence of the zeta potential upon filtration efficiency, (the then) AMF Cuno introduced the Zeta Plus range of filter media, in the early 1970s, composed of cellulose and inorganic filter aids, and carrying the positive charge implicit in their name. These media are now mostly used in the form of Cuno's lenticular cartridge filters, illustrated in Figure 4.7, but also available in depth cartridge format.

Because of the wide availability now of media using zeta potential as a contributing factor to high filtration efficiencies, it is appropriate to summarize here the theoretical origins of the concept. The term arises from a theoretical model developed to explain the stability of a colloidal suspension of particles in water. The particles remain dispersed because they are repelled from each other by similar (i.e. all negative or all positive) electrical charges on their surfaces. The source of these charges may be ionization of soluble crystals, imperfections

Table 4.19 Typical performance data of Carlson XE filter sheets[a]

Liquid	Sheet grade	Flow rate (l/min/m^2)	Cycle time (h)	Total throughput (m^3/m^2)
Whisky	XE5/XE35 (double)[b]	3–6	8–10	1.4–3.6
London gin	XE20–XE90	16–24	30–40	30–60
Deionized water	XE50	10–24	8–40	5–60
Eau de Cologne	XE90–XE200	12–16	4–8	3–8
Antibiotics	XE1700	0.3–1.5	Discarded after each batch	
Sera	XE1700	0.4–0.8	Discarded after each batch	
Syrups for soft drinks	PROC3	4–8	3–4	0.7–2
Malt vinegar	XE675	9–18	5–20	2.5–22
Photographic emulsions	XE5	3–12	4–8	0.7–6

[a] Carlson Filtration Ltd.
[b] Two-stage filtration in series.

Table 4.20 PROC3 activated carbon sheets[a]

Grade	Basis weight (g/m^2)	Carbon weight (g/m^2)	Other constituents[b]
PROC3	1300	585	C, K, R
PROC3 CX	1300	780	C, R
PROC3 LWT	1000	450	C, K, R
PROC3 CX LWT	1000	600	C, R
PROC F	900	225	C, K, R

[a] Carlson Filtration Ltd.
[b] C = cellulose, K = natural kieselguhr, R = resin.

Table 4.21 Seitz asbestos-free filter sheets

Designation	Weight per unit area[a] ($g\,m^{-2}$)	Thickness[a] (mm)	Specific weight[a] (g/cm)	Max ash content (%)	Bursting strength[b] (10^2 kPa)	Permeability[c] ($l/mm/m^2$)	Test for bacteria retention capability (*E. coli* in 0.9% NaCl solution) (CFU/cm^2)	Cations, soluble in 0.05 N H_2SO_4 solution (mg/m^{-2})[d] (not applicable for the low-ion grades)			
								Ca^{2+}	Mg^{2+}	$Fe^{2+/3+}$	Al^{3+}
SEITZ-EKS	1350	3.7	0.36	60	≥2.0	30	10^9	<2000	<500	<75	<400
SEITZ-EK 1	1300	3.7	0.35	53	≥2.0	40	10^8	<1500	<500	<75	<400
SEITZ-EK	1300	3.7	0.35	50	≥2.0	70	10^7	<1500	<400	<75	<400
SEITZ-KS 50	1300	3.7	0.35	50	≥2.0	90	0.5×10^7	<1500	<400	<75	<300
SEITZ-KS 80	1300	3.7	0.35	50	≥2.0	110	10^6	<1500	<400	<75	<300
SEITZ-K 100	1300	3.7	0.35	50	≥2.0	150	–	<1500	<400	<75	<300
SEITZ-K 150	1300	3.9	0.33	48	≥2.0	190	–	<1500	<400	<75	<300
SEITZ-K 200	1300	3.9	0.33	48	≥2.0	220	–	<1500	<400	<75	<300
SEITZ-K 250	1300	4.0	0.32	48	≥2.0	520	–	<1000	<300	<75	<300
SEITZ-K 300	1250	4.2	0.30	48	≥2.0	800	–	<1000	<300	<75	<250
SEITZ-K 700	1250	4.1	0.30	48	≥2.0	950	–	<1000	<300	<75	<200
SEITZ-K 800	1250	4.1	0.30	48	≥2.0	1300	–	<1000	<300	<75	<200
SEITZ-K 900	1250	4.3	0.29	48	≥2.0	1700	–	<1000	<300	<75	<200
SEITZ-T 120	850	2.9	0.29	45	≥2.0	230	–	<750	<200	<50	<250
SEITZ-T 500	800	2.7	0.30	40	≥2.0	450	–	<750	<200	<50	<200
SEITZ-T 750	800	2.7	0.30	42	≥2.0	550	–	<750	<200	<50	<150
SEITZ-T 850	800	2.7	0.30	42	≥2.0	950	–	<750	<200	<50	<150
SEITZ-T 950(a)[h]	800	2.8	0.29	42	≥2.0	1700	–	<750	<200	<50	<150
SEITZ-T 1000	950	3.6	0.26	35	≥2.0	3500	–	<750	<200	<50	<100
SEITZ-T 1500	800	3.7	0.22	35	≥2.0	7500	–	<750	<200	<50	<100
SEITZ-T 2100	700	3.3	0.21	17	≥2.0	10 200	–	<750	<200	<50	<100
SEITZ-T 2600	700	2.9	0.24	1	≥2.0	10 200	–	<750	<200	<50	<100
SEITZ-T 3500	850	4.6	0.18	17	≥2.0	13 000	–	<750	<200	<50	<100

Table 4.21 (*continued*)

Designation	Weight per unit area[a] (g m^{-2})	Thickness[a] (mm)	Specific weight[a] (g/cm)	Max ash content (%)	Bursting strength[b] (10^2 kPa)	Permeability[c] (l/mm/m^2)	Test for bacteria retention capability (*E. coli* in 0.9% NaCl solution) (CFU/cm^2)	Cations, soluble in 0.05 N H_2SO_4 solution (mg/m^{-2})[d] (not applicable for the low-ion grades)			
								Ca^{2+}	Mg^{2+}	$Fe^{2+/3+}$	Al^{3+}
SEITZ-T 5500	700	4.5	0.16	1	≥2.0	25 000	–	<750	<200	<50	<100
SEITZ-EK ABF[e]	1300	3.7	0.35	50	≥2.0	70	10^7	<1500	<400	<75	<400
SEITZ-EKB ABF[e]	1350	4.0	0.34	52	≥2.0	90	10^7	<1500	<400	<75	<400
SEITZ-KS 50 ABF[e]	1350	4.0	0.34	52	≥2.0	115	0.5×10^7	<1500	<400	<75	<300
SEITZ-KS 80 ABF[e]	1350	4.0	0.34	52	≥2.0	170	10^6	<1500	<400	<75	<300
SEITZ-K 100 ABF[e]	1350	4.0	0.34	52	≥2.0	200	–	<1500	<400	<75	<300
SEITZ-K 150 ABF[e]	1300	4.1	0.32	52	≥2.0	350	–	<1500	<400	<75	<300
SEITZ-K 200 ABF[e]	1300	4.1	0.32	52	≥2.0	500	–	<1500	<400	<75	<300
SEITZ-P 20[f]	1250	4.0	0.31	17	≥5.0	350	–	<750	<200	<50	<150
SEITZ-P 30[f]	1250	4.0	0.31	17	≥4.0	300	–	<750	<200	<50	<150
SEITZ-0/400a[h]	900	3.5	0.26	1	≥5.0	4250	–	<400	<100	<30	<100
PERMADUR	900	3.5	0.26	1	≥5.0	4250	–	<200	<100	<30	<100
SEITZ-KS 50 C[g]	1300	3.7	0.35	50	≥2.0	90	0.5×10^7	<350	<100	<75	<300
SEITZ-KS 80 C[g]	1300	3.7	0.35	50	≥2.0	110	10^6	<350	<100	<75	<300
SEITZ-K 100 C[g]	1300	3.7	0.35	50	≥2.0	150	–	<350	<100	<75	<300
SEITZ-K 150 C[g]	1300	3.9	0.33	48	≥2.0	190	–	<350	<100	<75	<300
SEITZ-K 250 C[g]	1300	4.0	0.32	48	≥2.0	520	–	<350	<100	<75	<300
SEITZ-K 700 C[g]	1250	4.1	0.30	48	≥2.0	950	–	<350	<100	<75	<200
SEITZ-K 800 C[g]	1250	4.1	0.30	48	≥2.0	1300	–	<350	<100	<75	<200
SEITZ-K 900 C[g]	1250	4.3	0.29	48	≥2.0	1700	–	<350	<100	<75	<200
SEITZ-SUPRAdur 50	1250	3.6	0.35	25	>5.0	110	–	<800	<200	<75	<100

Table 4.21 (*continued*)

Designation	Weight per unit area[a] ($g\,m^{-2}$)	Thickness[a] (mm)	Specific weight[a] (g/cm)	Max ash content (%)	Bursting strength[b] (10^2 kPa)	Permeability[c] ($l/mm/m^2$)	Test for bacteria retention capability (*E. coli* in 0.9% NaCl solution) (CFU/cm^2)	Cations, soluble in 0.05 N H_2SO_4 solution (mg/m^{-2})[d] (not applicable for the low-ion grades)			
								Ca^{2+}	Mg^{2+}	$Fe^{2+/3+}$	Al^{3+}
SEITZ-SUPRAdur 100	1250	3.6	0.35	1	> 7.0	170	–	< 700	< 200	< 50	< 50
SEITZ-SUPRAdur 200	1200	3.8	0.32	1	> 4.0	400	–	< 700	< 200	< 30	< 50
SEITZ-SUPRAdur 500	950	3.6	0.26	1	> 4.0	1500	–	< 700	< 200	< 30	< 50
SEITZ-SUPRAdur 3000	600	2.3	0.26	1	> 4.0	1000	–	< 200	< 100	< 30	< 50
SEITZ-SUPRA EK 1 P	1300	3.5	0.37	52	≥ 2.0	70	10^7	< 2000	< 400	< 30	< 400
SEITZ-SUPRA 80 P	1300	3.7	0.35	52	≥ 2.0	170	10^5	< 1500	< 400	< 75	< 300
SEITZ-EKS P	1350	3.7	0.36	60	≥ 2.0	30	10^9	< 2000	< 500	< 75	< 400
SEITZ-KS 50 P	1300	3.7	0.35	50	≥ 2.0	90	0.5×10^7	< 1500	< 400	< 75	< 300
SEITZ-K 300 P	1250	4.2	0.30	48	≥ 2.0	800	–	< 1000	< 300	< 75	< 200
SEITZ-AKS 4[i]											
With protective paper	1050	3.6	0.29	20	≥ 2.0	250	–	< 1500	< 300	< 75	< 250
Without protective paper	1050	3.6	0.29	20	≥ 2.0	1450		< 1500	< 300	< 75	< 250

[a] The figures quoted should be regarded as a guideline.
[b] Bursting strength determined on a dry sample of area 10 cm^2.
[c] Water permeability refers to differential pressure of $\Delta p = 100$ kPa (1 bar).
[d] By means of the method elutration with 0.05 N H_2SO_4 all soluble and for practical purposes relevant ions are extracted.
[e] SEITZ-IK ABF through to SEITZ-K 200 ABF are special grades for the filtration of beer.
[f] SEITZ-P 20/SEITZ-P 30 filters are used for beer stabilization.
[g] SEITZ-K 900 C through to SEITZ-KS 50 C represent grades low in calcium and magnesium for the filtration of spirits.
[h] SEITZ-T 950(a) and SEITZ-0/400a are special grades with a very high wet strength.
[i] SEITZ-AKS4 sheets contain activated carbon, for removing colour, taste, lipids, etc.

of the lattice structure of crystals. or absorption of ions from the liquid phase. What is commonly known as the DLVO theory (from Derjaquin and Landau[5], and Veerfey and Overbeek[6]) postulates that this results in the electrical double layer model shown in Figure 4.10.

Table 4.22 Guidance notes on application of Seitz filter sheets

Seitz designation	Comments
K series	Standard cellulose/kieselguhr sheets for general use.
T series	Cellulose only sheets with low content of soluble Ca, Mg, Fe, Al ions. T120 to T950 have positive zeta potential and high adsorptive capacity. T1000 to T5500, which have no zeta potential, are for coarse filtration, high throughput, high dirt holding capacity. Good for viscous fluids and gel particles.
P series	For pharmaceutical industry, guaranteed low in pyrogens. EKSP is preferred choice for maximum removal of organisms. Two SUPRA grades primarily used for retention of pyrogens.
SUPRAdur	Up to 40% polyolefine fibres, high mechanical and chemical resistance to aggressive materials. Functions mechanically.
PERMADUR	High proportion of polyolefine fibres, high wet strength regeneratable sheet for supporting precoats.

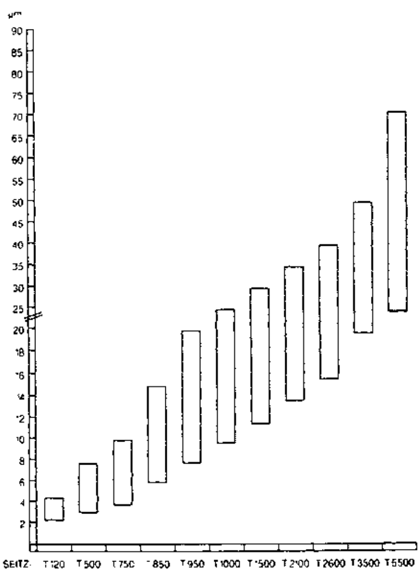

Figure 4.8. Nominal particle retention characteristics of Seitz T-series filter sheets for general industrial duties.

Table 4.23 Typical applications of Seitz filter sheets

Product	Separating task. Type of turbid matter	SEITZ depth filters
Aftershave	Removal of terpenes	SEITZ-K 300 – SEITZ-K 150
Agar-agar	Undissolved components	SEITZ-K 150
Alkyd resin	Gel corpuscles, swelling substances	SEITZ-T 5500
Ammonia water	Turbid matter, iron hydroxide	SEITZ-K900 and kieselguhr dosage
Bath extract (camomile)	Fine turbid matter in larger quantities	SEITZ-K900 and kieselguhr dosage
Beer	Normal turbid matter	SEITZ-K200 ABF – SEITZ-K 700
	Kieselguhr	SEITZ-0/400 Fa. PERMADUR
	Stabilization	SEITZ-P 29/SEITZ-P 30
Utility water	Normal turbidity	SEITZ-T 1500
Caprolactam melt	Removal of manganese dioxide	SEITZ-K 900 – SEITZ-K 700
Collagen solution	Final filtration prior to filling	SEITZ-K 900
Sodium hypochlorite	Impurities	SEITZ-SUPRAdur 100
Disinfectants (alkaline)	Fine turbid matter, colloids	SEITZ-EKS
Eau de Cologne/ Eau de Toilette	Removal of terpenes after the cooling process	SEITZ-KS 80 – SEITZ-KS 50
Electro-immersion lacquer	General polishing	SEITZ-T 5500 – SEITZ-T 2600
Enzyme solution (containing cellulaze)	Polishing filtration	SEITZ-SUPRAdur CF 900 – SEITZ-SUPRAdur CF EKS
Epoxy resin	Swelling components	SEITZ-K 900
Vinegar	Filtration after precoat filter	SEITZ-K 250 – SEITZ-K 150
Liquid fertilizer	General polishing	SEITZ-K 900
Tissue culture solution	Sterilization	SEITZ-EKS
Face lotion	Removal of terpenes	SEITZ-EKS
Glycerine, 30%	Retention of activated carbon (Carboraffin)	SEITZ-K900 – SEITZ-K300
Gum arabic	Removal of non-soluble components	SEITZ-T 2600
Resin melts	Overpolymerized overcondensed components, swelling and gel corpuscles	SEITZ-T 5500 – SEITZ 850
Cough syrup	Insoluble extract components	SEITZ-K 300 – SEITZ-K 250
Invert sugar solution	Retention of activated carbon	SEITZ-K 100
Coconut butter	Pressing residues, slimy substances	SEITZ-T 950
Camomile pressings	Filtration of the alcoholic decantate	SEITZ-K 700 – SEITZ-K 300
Cheese rennet	Colloidal impurities	SEITZ-K 300
	Organism reduction	SEITZ-EK 1
Catalysts, e.g.: Raney Nickel	Residual catalysts	SEITZ-K 900 – SEITZ-KS 50
Clear lacquer	Colloidal impurities	SEITZ-K 900
Copper chloride solution with HCl	Residues from coatings	PERMADUR

Table 4.23 (*continued*)

Product	Separating task. Type of turbid matter	SEITZ depth filters
Molasses	Foreign bodies	SEITZ-K 150
Olive oil	Fine particles from pressing residues and traces of H_2O	SEITZ-L 800
Plant pesticides	Fine clarification to protect nozzles from blocking	SEITZ-T 1500
Plant extracts	Prevention of subsequent clouding	SEITZ-K 250 – SEITZ-KS 80
Phosphoric acid	Clarification	SEITZ-SUPRAdur 100
Ointment bases	Prefiltration	SEITZ-K 300
Soup seasoning	Final filtration	SEITZ-T 550
Wine	Normal turbid matter	SEITZ-K 900 through to SEITZ-EKS
Tin tetrachloride	Removal of hydrolized components	SEITZ-SUPRAdur 500

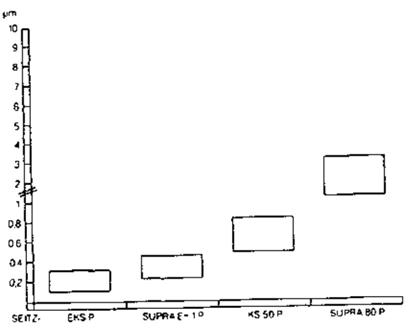

Figure 4.9. Nominal particle retention characteristics of Seitz P-series filter sheets for pharmaceutical duties.

The surface charge (negative in Figure 4.10) of the solid particle is balanced by a tightly held layer of ions of opposite charge (positive in Figure 4.10). Beyond this is an outer layer through which the ionic concentration (and hence the charge) decays with increasing distance, until the equilibrium conditions of the bulk of the liquid are attained. As a particle moves, or as a liquid flows past it, it continues to retain the tightly held layer of (positive) ions, but leaves behind the outer layer, separating from the latter at the plane of shear indicated in Figure 4.10. It is the potential at this plane that known as the zeta potential (ζ).

The magnitude of the zeta potential of a given filter medium, and therefore its adsorptive power, is not a fixed value but is dependent on a variety of related electrochemical phenomena, such as the nature and concentration of ions in the liquid being filtered. For example, Figure 4.11 is reproduced[7] to demonstrate how the performance of the sample of Zeta Plus is affected by changes in the pH, peaking in this example between pH 5 and 7.5.

Table 4.24 Pyrogen removal capability of Seitz-Supra EK1P filter sheets

Depth filter	Pyrogen content (EU ml^{-1})[a]		Logarithmic pyrogen	Pyrogen challenge (EU cm^{-2})	Total pyrogen retention (EU cm^{-2})
	Unfiltrate	Filtrate			
SEITZ-	60	0.06	3	282	282
SUPRA	600	<0.06	>4	3.11×10^3	3.11×10^3
EK 1P	6000	<0.06	>5	3.14×10^4	3.14×10^4
	6×10^4	<0.06	>6	3.14×10^5	3.14×10^5
	6×10^5	6×10^5	0	3.14×10^6	3.14×10^6

Lipopolysaccharide: *E. coli* 055:B5 Filtration velocity: 460 $l\,m^{-2}\,h^{-1}$

Pyrogen reduction: $\dfrac{\text{EU ml}^{-1}\text{ unfiltrate}}{\text{EU ml}^{-1}\text{ filtrate}}$

Pyrogen retention: $\dfrac{(\text{EU ml}^{-1}\text{ unfiltrate} - \text{EU ml}^{-1}\text{ filtrate}) \times \text{ml filtrate quantity}}{\text{cm}^2\text{ filter area}}$

Sensitivity of reagent: 0.05 EU ml^{-1} medium: pure water

[a] EU = endotoxic units.

Table 4.25 Bacteria removal capability of Seitz filter sheets

›Depth filters	Filtration medium: 0.5% peptone solution		Filtration medium: physiological saline solution		Test organism
	Specific organism challenge (CFU cm^{-2})[a]	Titer reduction[b]	Specific organism challenge (CFU cm^{-2})[a]	Titer reduction[b]	
SEITZ-EKS	5.2×10^9	8.9×10^7	2.1×10^{10}	1.7×10^9	*Pseudomonas diminuta*
SEITZ-EK 1	5.2×10^9	2.0×10^7	4.7×10^9	5.0×10^8	ATCC 19146
SEITZ-EK	7.9×10^8	2.5×10^7	2.6×10^8	6.4×10^8	*Serratia marcescens*
SEITZ-KS 50	2.1×10^8	4.2×10^6	2.6×10^9	1.1×10^7	ATCC 14756
SEITZ-KS 80	2.1×10^8	1.7×10^5	6.1×10^8	1.6×10^6	

[a]CFU=colony forming units.

[b]Titer reduction$=\dfrac{\text{No. of organisms unfiltrate}}{\text{No. of organisms filtrate}}$ specific filtration velocity: 450 $l\,m^{-2}\,h^{-1}$.

A good illustration of the electrokinetic contribution to the filtration efficiency of Zeta Plus is provided by Figure 4.12. The upper curve shows the capture rate by Zeta Plus 90S for particles of sizes ranging downwards from 1.2 μm; the lower curve resulted after the charge on the medium had been destroyed by treatment with strong alkali.

Table 4.26 Characteristics of different formulations of Zeta Plus[a]

Zeta Plus code	Comments
A	Composed of cellulose+resin.
C	Composed of cellulose+inorganic filter aids+resin. Suitable for chemical sterilization.
S	Composed of cellulose+inorganic filter aids+resin. Suitable for sterilization by autoclaving or in-line steaming to 131°C
HT	Composed of cellulose+inorganic filter aids+resin. HT indicates 'high tensile' and 'high throughput'. Suitable for sterilization by autoclaving or in-line steaming to 131°C.
AP, C, SP	Pharmaceutical versions of A, C and S grades. Manufactured to procedures registered in the US FDA Drug Master File, with full tractability of all components.
LP	Low endotoxin response cellulose+inorganic filter aids+resin. Pharmaceutical product as for AP, etc., above.
CA, LA, SA	Low aluminium extractable versions of C, S and LP grades.
Delipid	For lipid removal. Composed of cellulose+inorganic filter aids+resin.
Delipid LP	Pharmaceutical versions of Zeta Plus Delipid grades. Manufactured to procedures registered in the US FDA Drug Master File, with full traceability of all components.
U	Composed of cellulose+resin. For filtration of utility oils.
UW	Composed of cellulose+resin+water-absorbent layer. For filtration of utility oils.
Zeta Carbon	Composed of activated carbon+cellulose+resin.

[a] Cuno Incorporated.

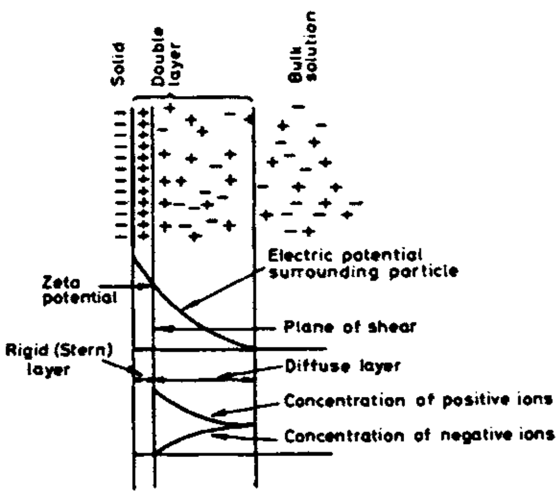

Figure 4.10. The electrical double layer model showing charges assembled around a negatively charged solid surface submerged in water.

Zeta Plus is available in a range of nine nominal grades of fineness, between roughly 10 and 0.1 μm as indicated by Figure 4.13. There are various formulations as summarized in Table 4.26.

4.6 Selecting Wet-laid Media

The media described in this chapter have had two major uses: as filters in the laboratory for analytical purposes, and for industrial-scale filtration. The laboratory filters are available in cellulose or glass, and their behaviour and applications are well described in Sections 4.2.1 and 4.3.2.

The industrial filters employ paper media largely for air and gas filtration, and for liquid filtration the choice is usually for filter sheets rather than paper,

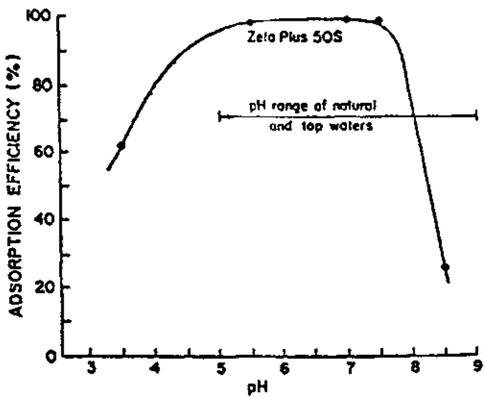

Figure 4.11. Influence of pH on the absorption efficiency of Zeta Plus 50S.

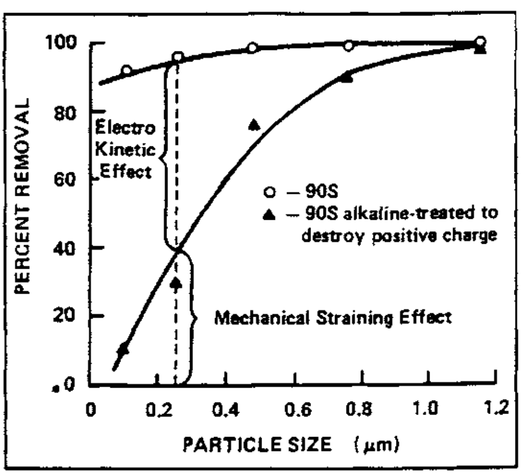

Figure 4.12. Demonstration of electrokinetic contribution to the filtration efficiency of Zeta Plus.

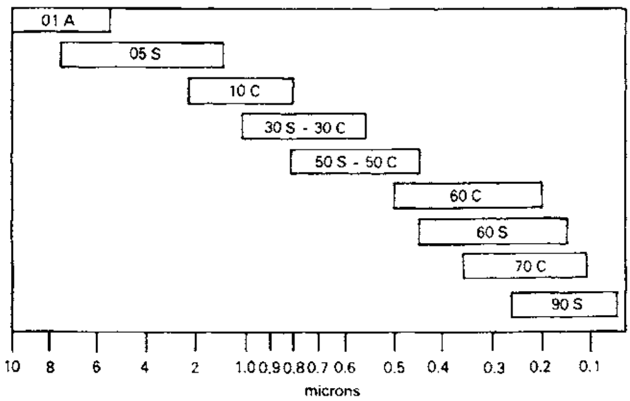

Figure 4.13. Nominal particle retention characteristics of Zeta Plus media.

although some automotive uses exist for papers in liquid filtration. Guidance to use of sheets is given in Tables 4.22 and 4.23.

The air media are most often employed in the pleated state, to increase useful filter area per unit volume of filter, and such filters are now increasingly using non-woven media, rather than paper. The choice among the available media is therefore largely a matter of cost.

4.7 References

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