HANDBOOK OF FILTER MEDIA

Second Edition

Derek B. Purchas and Ken Sutherland

Preface

The appearance of a second edition of a technical handbook is a sign of the publisher's confidence in its value to its readers. This confidence is bred from the success of the first edition, but it must also involve the changes and additions to the second edition that make it an advancement upon the first. A purpose of this preface is to highlight some of those changes.

The first edition was written entirely by Derek Purchas, the doyen of consultants in the technology of filtration, certainly in the UK, and probably in the world. In its preparation Derek had the assistance of inputs from media manufacturers of all kinds, sizes and geographical bases. That assistance is no less a part of the second edition, and another purpose of this preface is to acknowledge that assistance.

The Handbook remains very much as Derek first wrote it, in terms of style, structure and content. Partly this is because the technology of filter media is very well established, so that a great deal of the material of the first edition embodied timeless features of the technology. The basic designs of filter have been in existence for over a century, and the six or so years since the first edition have not seen any major changes in filtration equipment.

However, there are significant changes in this second edition, of both structure and content, and, not surprisingly with a different main author, of style. The least of these is that the chance has been taken to make some textual corrections. Some additional emphasis is placed on air and gas filtration throughout the Handbook, especially in the more utility uses for such techniques.

The arrangement of the Handbook is similar to the first edition, although there are now two extra chapters, one formed by splitting one of the earlier chapters ('Textiles') into two, and the other being new ('Standards').

In terms of filter media technology, this second edition notes the following trends:

- the increased requirements for hot gas cleaning, involving advanced polymeric, metallic and ceramic media;
- the continuing development of membrane media, with an ever wider range of polymer compositions available;
- the rapid growth of cross-flow filtration as a process option;
- the increased use of composite media;

- the growth in availability of the various non-woven media made by spinning molten polymers; and
- the expansion of those media once thought of as restricted to reverse osmosis and ultrafiltration, i.e. those used for molecular separations, into the microfiltration range (and the parallel appearance of nanofiltration as a separate technology).

A technological change of a very different kind has been the appearance of the World Wide Web on the Internet, with many suppliers taking advantage of its existence to design and publish Web pages of their own. These sites vary enormously in quality, from little more than a company's name and address, to a complete inclusion of a product catalogue running to hundreds of pages and being a joy to read.

Although not a technological change, mention must also be made of the far-reaching changes in the corporate structure of the filter media marketplace. Many of the companies named in the first edition no longer exist as separate entities, if they exist at all. Of the 73 companies that advertised in the first edition over one-quarter no longer exist under those names (or have undergone major changes in their interest in filtration media).

Many of the specified media in the first edition are now available from a different supplier (or differently named at least). To some extent, this process is limiting the range of media available to the end user or filter OEM, although small companies are also appearing to make up the numbers.

A quick skim through the Handbook will show that it includes a considerable amount of proprietary information. This has been made available by the various manufacturers, in the interests of value to the reader, and the authors and publisher are exceedingly grateful to the manufacturers concerned. Acknowledgement is duly made in the text of the source of such material. Acknowledgement is also made to those members of staff of filter media manufacturers who have given their time in the identification of important new ideas in materials and media.

Some suppliers ignored requests to help, and some even expressly declined to contribute. To those companies, it is hoped that this edition will provoke regret that they did not take part in the exercise. Perhaps the appearance of a second edition may spur other suppliers to take an interest in the future.

There is no wish by authors or publisher to make this Handbook into a buyers' guide of filter media. Accordingly, no attempt is made to mention or even list all the suppliers of any particular type of medium. Those suppliers and their media referred to are deemed sufficiently representative of the type under discussion - but they are also among the limited range of suppliers who responded favourably to a request for help for this edition.

As to the authors: Derek Purchas, now effectively retired, was introduced earlier as the author of the first edition of this Handbook. He also wrote a classic textbook on solid/liquid separation processes, and co-edited a textbook on equipment scale-up. Ken Sutherland is a consultant, mainly in industrial marketing, specializing in the filtration equipment and materials sector. He is a co-author of Elsevier's Decanter Centrifuge Handbook (and of a textbook on industrial market research). So that the reader will know where to place the blame for any errors in this edition, it is only fair that this Preface should be signed by

Ken Sutherland
1 May 2002

Foreword to the First Edition

'I worked hard at altering the arrangement of the first three chapters of the third volume. What labour it is to make a tolerable book, and how little readers know how much the ordering of the parts has cost the writer!'

These heart-felt words were written in his diary on 6 February 1854 by the eminent historian Lord Macaulay, at a time when he was struggling to make further progress with his monumental (and highly readable) multi-volume book The History of England.

Almost a century and a half later, that entry in Macaulay's diary struck a sympathetic chord as I sought relaxation at the end of another gruelling day's wrestling with the dry and unromantic desiderata of filter media. So apposite did it at once appear that I noted it for inclusion, in due course, in this brief foreword which was then no more than a one-word title, to be expanded when the pain and agony of the serious writing had been completed. In quoting it now I am emboldened to couple it with a few lines from An Essay on Criticism by that earlier bitingly witty author Alexander Pope:

> The perfect Judge will read each word of Wit
> With the same spirit that its author writ:
> Survey the Whole, nor seek slight faults to find
> Where nature moves, and rapture warms the mind.

In reality, a technical book is inevitably and very properly likely to be subjected to critical assessment and comment at all levels, including both its breadth of concept and its minutiae – the more so where the book is offered as the first attempt to provide a comprehensive overview of the entire spectrum of industrial filter media. A corollary of this touch of realism is recognition that the resultant book must regrettably contain a variety of errors, oversights or deficiencies; notification of any of these would be welcomed, so that corrective action can be taken in future editions.

As will be evident from the very many acknowledgements throughout the book, compiling it has been made possible only by the generous cooperation of many companies and of the even more numerous individuals, some of whom have patiently responded to an almost endless flow of faxes, letters and telephone calls. In expressing my thanks to all of these, I would like to add an apology for any errors which, due to faults of misinterpretation, omission or commission on my part, may have crept into the printed text derived from the information they supplied.

Amidst the legion of those who have contributed to my endeavours since the first words were entered into my word computer on 8 February 1995, there is one person to whom special acknowledgement must be made. This is my wife Margaret, whose patient support has once again enabled us happily to survive the trials and tribulations which are the inescapable birth pangs associated with producing a book.

Derek B Purchas
5 September 1996

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CHAPTER 1

An Introduction to Filter Media

The process of filtration is widely used throughout industry, commerce and domestic life. It covers the production of potable water by reverse osmosis, through the protection of delicate components from the impact of large solid particles, and the clarification of beer, to the separation of waste sewage sludges. Filtration involves the physical separation of one or more components from a suspension or solution in a fluid, by passage of that fluid through or across a barrier that is permeable only to some of these components.

The key element in this description is the barrier, permeable only to part of the feed suspension or solution. This barrier is the filter medium, and a filter is then any mechanical structure that holds the medium in the most efficient way.

1.1 Definition of Filter Medium

It has rightly been said that the heart of any filter is the filter medium. Unless it is fitted with an adequate medium, even the most ingenious filter is useless. So what exactly is a filter medium?

The, now ageing, *Filtration Dictionary and Glossary*(1) defined a filter medium as 'any permeable material used in filtration and upon which, or within which, the solids are deposited'. This definition was not broad enough for the first edition of this Handbook, because it surprisingly assumed that only solid particles are relevant, and therefore excluded the many instances where particles comprise droplets of liquid. The following improved definition was then suggested as sufficiently all embracing: 'A filter medium is any permeable material upon which, or within which, particles are deposited by the process of filtration'.

However, even that breadth of coverage is no longer enough, because a large proportion of filtration operations now concern molecular and ionic species in solution. Accordingly, a revised definition is suggested in this new edition of the Handbook, to take note of this additional need:

A filter medium is any material that, under the operating conditions of the filter, is permeable to one or more components of a mixture, solution or suspension, and is impermeable to the remaining components.

The retained components may be particles of solid, droplets of liquid, colloidal material, or molecular or ionic species in solution, while the permeate (or filtrate) will normally be the suspending fluid or solvent, possibly together with some of the other components.

The purpose of this Handbook is to describe the materials used to make filter media, to highlight their main characteristics, and to advise upon their selection and use.

1.2 Filters and Their Media

In the definition of filter medium given above, the nature of the filter itself is not defined. A filter is any device in which a separation is achieved among other components of a suspension or solution, in a fluid – which may be a liquid or a gas – where the separation is caused by mechanical means, without the involvement of a change in phase (such as the melting of a solid, or the evaporation of a liquid). Filtration is almost entirely a characteristic of the size of the particle, droplet or molecule being separated, whereas relative particle density is a more important feature in sedimentation.

As is often the case in attempting a perfect definition or classification, the boundaries involved in defining filtration in this way are less than absolutely precise. Thus, some membrane separations do involve a change in phase; some filtration processes involve electrical as well as mechanical forces; and some processes involve chemical forces as well as physical ones. Most significantly, the process of dry screening (sieving or sifting) involves the passage of part of a mixture of granular solids through a screen – the filter medium – with little or no passage of a fluid at all, yet this is clearly a filtration process.

That said, the bulk of filtration processes involve the removal of particles, droplets or molecules from a fluid, by means of a physical barrier, the filter medium, through which they will not pass by virtue of their size. A particular form of filter may be able to use a wide variety of filter media, to achieve the same, or different, separations.

1.2.1 Purposes of filtration

There are two main purposes in filtration:

- to remove impurities from a fluid, and
- to recover valuable materials from suspension in a fluid (usually a liquid).

The first of these ('clarification') normally employs finely porous filter media, and aims to remove as much of the impurity as possible, and preferably all of it. The second ('harvesting') also aims for as complete a recovery as possible of the wanted material, but uses coarser media, mainly because the cake of recovered solid does most of the filtering, and also is less concerned with the clarity of the filtrate.

Here again the division is not exhaustively precise: some harvesting processes remove waste solids for subsequent treatment, while some clarification removes only some of the suspended solids (ahead, for example, of a finer filtration process). Filtration may also be used to classify a suspended solid into two separate size fractions.

The choice of filtration equipment involves selection both of the right medium, and of the best type of filter in which to mount it. The harvesting processes are more limited in equipment choice, because of the need to remove accumulated solids in relatively large quantity, often leading to the need for complex types of filter. Clarification duties are much less concerned about solid removal, and so can be satisfied by simpler (and, therefore, cheaper) filters, with correspondingly simpler media formats.

1.2.2 Filtration mechanisms

In terms of the way in which a particle, say, is trapped by a filter medium, and so removed from the fluid, four basic mechanisms can be distinguished. Their distinctive characteristics are briefly outlined as follows.

(a) Surface straining. Here the particle that is larger in size than the pores of the medium deposits on the surface, and stays there until it is removed. Particles that are smaller in size than the pores pass through the medium. As shown schematically in Figure 1.1, this is the main operating mechanism for bar screens, and plain woven monofilament mesh. It also plays a major role in filtration with membranes.

(b) Depth straining. For media that are relatively thick by comparison with their pore diameters, particles will travel along the pore until they reach a point where the pore narrows down to a size too small for the particle to go any further, so that it becomes trapped. Felts and other non-woven fabrics utilize this mechanism, which is illustrated in Figure 1.2.

(c) Depth filtration. Now a particle can also be trapped in the depth of the medium, even though it is smaller in diameter than the pore at that point. Such

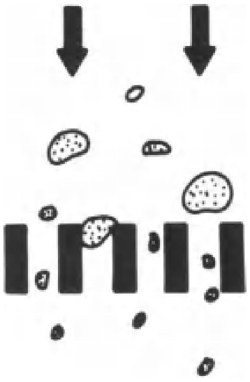

Figure 1.1. Filtration by surface straining(2).

behaviour involves a complex mixture of physical mechanisms. Particles are first brought into contact with the pore wall (or very close to it), by inertial or hydraulic forces, or by Brownian (molecular) motion. They then become attached to the pore wall, or to another particle already held, by means of van der Waals and other surface forces. The magnitude and efficacy of these forces may be affected by changes in factors such as the concentration and species of ions in an aqueous solution, or the humidity of a gas. This mechanism is illustrated in Figure 1.3, and is important for most media, but especially for high-efficiency air filters and in deep bed (sand) filters.

(d) Cake filtration. Here a thick layer or cake of particles accumulates on the surface of the medium, and then acts as the filter medium for subsequent filtration. If the particles (or some of them) are larger than the pores, then cake filtration may follow an initial period of surface straining. But cake filtration can occur even when the particles are all smaller than the pores (down even to about one-eighth of the pore diameter), especially if the solid concentration is relatively high (say, greater than 2% by weight in a liquid). This happens by the bridging of the particles across the entrance to a pore, as shown in Figure 1.4, to form a base upon which the cake will then grow.

Quite clearly, any real filtration process will probably involve a combination of two or more of the above mechanisms. The two straining processes will quickly

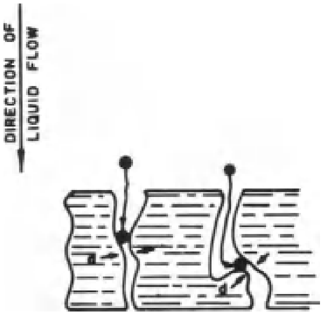

Figure 1.2. Filtration by depth straining(3).

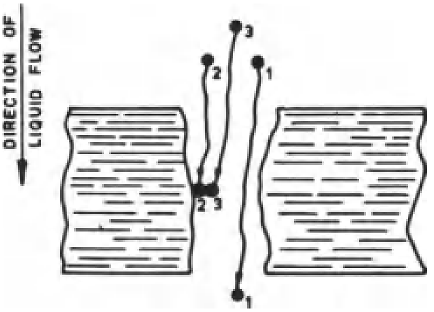

Figure 1.3. Depth filtration mechanism(3).

blind the medium, as the pores progressively block, requiring some kind of cleaning process to be implemented.

On the other hand, this simplified summary of a complex subject serves to emphasise that the mechanisms of filtration may result in the trapping of far smaller particles than might be expected from the size of the pores in the medium. The actual mechanism or combination of mechanisms pertaining in any specific instance is dependent on the characteristics both of the medium and of the suspension being filtered. The relationships between the four basic mechanisms and the two broad categories of practical filtration (clarification and harvesting) are summarized in Table 1.1.

It is important to realize that the fluid being handled can have a significant influence. For example, whereas a fine sintered metal medium will remove particles as small as 0.4 μm from a gas, the same sintered metal, when used to filter liquids, will not be effective below about 2 μm. Differences in performance also occur between aqueous and organic liquids, presumably because of their different electrical properties, which influence the build-up of static charges.

Special mention should be made of the mechanisms that commonly occur with woven fabrics. It is quite normal that a new, or freshly cleaned, fabric will initially allow some particles to pass through, whether used to filter a gas or a liquid. The clarity or quality of the filtrate will then improve progressively, as the characteristics of the fabric are altered by some of the solid particles, as they become embedded both between and within the individual yarns. Once this depth filtration has been completed, then surface or cake filtration proceeds.

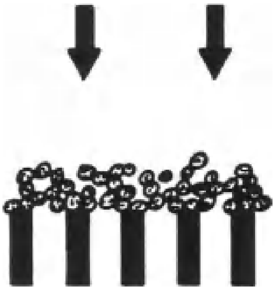

Figure 1.4. Cake filtration mechanism(2).

Table 1.1 The role of filtration mechanisms in practical filtration (× indicates a major role; + indicates a minor role)

Mechanism	Harvesting	Clarification
Surface straining	+	×
Depth straining		×
Depth filtration		×
Cake filtration	×	+

Similar in principle to this last process, the characteristics of the medium may be altered by an initial deposit of solids, or *precoat*, on the surface of the medium, in order to produce a less open medium. This precoating process is used either to prevent loss of valuable material in the initial stage of the filtration, or to prevent passage though the filter of material not wanted downstream of the filter. (Precoat material is often called a *filter aid*, which it clearly is, although the latter term is more correctly used for material added continuously to the feed stream of a filter to improve the filtration performance of the resulting cake.)

The mechanisms illustrated in Figures 1.1–1.4 are all variants of one major group of filtration processes, in which all of the fluid flows through the medium, leaving any separated material within or upstream of the medium. This is known as *through-flow* filtration (also as *dead-end* filtration). This is the traditional way in which filtration processes were operated. An alternative process now exists, as a significant part of the filtration business, in which the main fluid flow is directed across the surface of the medium, with only a portion of the fluid passing, at right angles to the main flow, through the medium. Material deposited on the upstream surface of the medium is then largely swept away by the fluid flow, which often runs in a recycle loop. This technique is known as *cross-flow* filtration (also as *tangential* or *parallel* filtration).

1.2.3 Types of filter

Although this Handbook make no pretence whatever to being a handbook of filtration technology, it is difficult to understand the spectrum of filter media without some reference to the range of types of filter within which they are used. Accordingly, Table 1.2 sets out a reasonably full list of the various types of filter, arranged schematically by nature. The wide range of types illustrated is mainly for liquid filtration, with a much smaller range used for gas filtration, as is indicated in Table 1.2.

Filter media of one kind or another are employed in all of these types of filter, and the various chapters of this Handbook will highlight which media are best suited to which type of filter. All filters exist for the 'simple' purpose of holding a piece of filter medium firmly across or parallel to a flow of fluid, but the way in which they perform this task can be very different from one type to another. Accordingly, filters differ very widely in complexity, from the simple tubular housing of a cartridge filter or strainer, to the complex machine that is a tower press or a rotary vacuum drum filter.

As has already been mentioned, the first group of equipment types in Table 1.2, screens, frequently operate with no fluid flow at all through the filter medium. Screening is mostly an operation at the coarser end of the filtration size spectrum.

The remainder of the items in Table 1.2 all involve fluid flow, and are used over the whole size spectrum, with filter media chosen to give the required degree of separation. The equipment type classification is intended as a help to understanding, rather than exhibiting precise divisions among the various types of equipment mentioned, and several examples exist where the equipment could be classified in more than one place.

Table 1.2 Types of filter

Screens			
	Stationary		
		In-line strainers[a]	
		Horizontal or slightly inclined	
		Curved ('sieve-bend')	
		Vertical	
	Moving		
		Continuous (vertical, or rotating drum)	
		Oscillating (vibrating or gyratory)	
Demisters[b]			
Depth filters			
	Pads and panels[a]		
	Thick cartridge[a]		
	Deep bed ('sand')		
Surface/cake filters			
	Vacuum		
		Batch	
			Nutsche (manual or scroll discharge)
			Rotary table
			Tilting pan (single or rotating/indexing)
			Leaf or tubular element
		Continuous	
			Rotary drum (range of discharge mechanisms)
			Rotary disc
			Indexing disc
			Belt (single or multiple chambers)
	Gravity		
		Flat bed (roll)[a]	
	Fluid pressure		
		In-line	
			Basket strainers
			Sheets
			Capsules[a]
			Pads and panels (cassettes)[a]
			Bags, sleeves and pockets[a]
			Cartridges (wide range of designs)[a]
			Other membrane filters (spiral wound, tubular, etc.)
		Pressure vessel	
			Tubular element (bag or candle filter)[a]
			Filter coalescers
			Flat elements (sheet, plate, leaf)
			Thickeners
			Rotary (drum, submerged drum, Fest, etc.)

Table 1.2 *(continued)*

	Filter press	
		Simple plate and frame
		Chamber press (membrane plate, plate press)
		Tower press (continuous medium)
	Variable volume (tube press)	
Mechanical pressure		
	Band press	
		Horizontal
		Vertical
	Screw press	

This list is mainly of filters used for liquid separations, except for those items marked:

[a] versions for gas and liquid filtration;

[b] gas filtration only.

1.3 Range of Filter Media

The number and variety of materials embraced by the definition of filter medium given in Section 1.1 are truly vast, ranging from metal plates with holes measured in centimetres, to microporous membranes, and from sheets of woven cloth to beds of sand. Filter media may be made from any material that can be rendered permeable or made into a permeable form, including:

- inorganic minerals
- carbon and charcoal
- glass
- metals
- metal oxides and other fired ceramic materials
- natural organic fibres
- synthetic organic fibres
- synthetic sheet material.

The materials can then be made up into filter media in a variety of forms: rod or bar, sheet, loosely packed or bonded fibres or granules, wire or monofilament, and so on.

A more comprehensive glimpse of this diversity is provided by Table 1.3, which has progressed through several evolutionary stages[4–6], since it was first devised by one of the authors in 1965, as a framework to impose some sort of order on the confusing multitude of options. It is a modified form of the 1981 version that is reproduced here, although the numerical values have been updated. In this table, media are arbitrarily arranged approximately in the order of decreasing rigidity; it is not suggested that this arrangement has any sort of fundamental basis, although rigidity is often a significant factor in matching media to their containing filters.

Close inspection of Table 1.3 quickly reveals the difficulty of dividing media into precisely defined types, on a consistent basis, with sharp divisions between categories. For example, this is especially true of modern membranes; in 1965, when the classification was first developed, these were only just emerging from their long-established role as a fragile tool in the research laboratory, and could reasonably be grouped together with other forms of plastic sheets. Now they are

Table 1.3 Classification of filter media, based upon rigidity

Main media type	Subdivisions	Smallest particle retained (μm)
Solid fabrication	Flat, wedge-wire screen	100
	Wire-wound tubes	10
	Edge-type	10
	Stacked discs	5
Metal sheet	Perforated	20
	Sintered woven wire	1
	Unbonded mesh	5
Rigid porous media	Ceramics and stoneware	1
	Sintered metal powder or fibre	1
	Carbon	1
	Sintered plastic powder or fibre	< 1
Cartridge	Yarn wound	5
	Bonded granule or fibre	1
	Pleated sheet	< 1
Plastic sheet	Perforated	10
	Sintered woven filament	5
	Woven mono- or multifilament (Membrane)	10
Membrane	Ceramic	< 0.1
	Metallic	< 0.1
	Polymeric	< 0.1
Woven media	Staple fibre yarn (polymeric filament)	5
Non-woven media	Dry-laid (felts)	10
	Wet-laid (papers)	2
	Wet-laid (sheets)	0.5
	Special polymeric (spun bonds, etc.)	0.1
Loose media	Fibres	1
	Powders	< 0.1

of major industrial importance, thanks to the availability of a continually expanding range of robust polymeric, metallic and ceramic membranes.

Clearly, not all permeable materials are necessarily usable as filter media, but certain of their inherent properties potentially enable them to be applied in this way, if they are combined with a compatible filter in an appropriate operating environment.

Neither is it necessarily true that a particular form of a material would be suitable as a filter medium in its original shape or format. For example, a loosely formed yarn of fibrous material is of no use as a filter medium, if it remains as a single yarn. However, once it is wound around a supporting core, with successive layers of yarn wound at an angle to the previous layer, then it becomes an excellent form of filter medium.

Such a construction represents one form of filter cartridge, and the medium only exists as such because of its particular format. It follows from this situation that the filter cartridge may be almost indistinguishable from the material from which the filter medium is itself made. Because of this indistinct boundary between media and filter elements (including filter bags and panels), this Handbook covers filter cartridges, and other replaceable elements, in addition to the bulk material from which any particular filter medium is made.

1.4 The Filter Media Business

The industrial context within which media are made and supplied to their end users deserves some comment at this point. The great variety of media, not surprisingly, leads to a considerable variety in the types of company involved with the supply of media. Some are devoted to its manufacture, while for others it may be only a small part of the total company activity.

Five main stages can be seen in the industry:

(i) the maker of the basic material from which the medium is to be made; a metal wire, a natural or synthetic fibre, a ceramic powder, an extruded plastic filament, and so on;
(ii) the conversion of some of these basic materials into a form in which they can be used to make filter media: the spinning of fibres or the twisting of filaments into a yarn, the crimping of a wire, etc.;
(iii) the formation of the bulk media: the weaving of a cloth or monofilament mesh, the moulding and sintering of a plastic or metal fibre or powder, the production of paper, the preparation and processing of a sheet of membrane (all together with any necessary finishing processes);
(iv) the conversion of the bulk medium material into pieces of the particular size and shape required for the medium to fit the filter (especially for makers of replacement media for existing filter units), which may include, for example, the pleating of flat material;
(v) the making of the filter itself, including the fitting or adapting of the medium to its position in the filter.

A sixth stage – the distributor or wholesaler – may exist at several inter-stage points in this series, or between the last and the final user. The creation of a stand-alone filter element, such as a cartridge, might be considered as part of stage (iv), or as a further stage between stages (iv) and (v) – and then bypassing stage (v), by direct sale to the end user.

Many companies in the industry exhibit combinations of two or more of these stages (vertical integration), but this may result in limitation of the markets for the products of the earlier stage.

Some media, of course, do not exhibit all these stages: sand filters go from the supplier of the graded sand straight to the deep bed filter maker. Most, however, show several, with some of the most common (woven fabrics, needle felts) exhibiting all of them. This complicated market structure obviously has its impact on a Handbook of this kind – which basically looks only at the products of stages (iii) and (iv).

1.5 Properties of Filter Media

A successful filter medium is likely to be required to combine many different properties, ranging from its filtration characteristics and its chemical resistance to its mechanical strength, the dimensions in which it is available, and its wettability. In fact, some 20 significant properties were identified by one of the authors(7) in exploring the extent to which these are, or could be, used for systematically selecting media for specific applications

These properties may be conveniently divided into three major categories:

- machine-orientated properties, which restrict the use of the medium to specific types of filter, such as its rigidity, strength, fabricability, etc.;
- application-orientated properties, which control the compatibility of the medium with the process environment, such as its chemical and thermal stability; and
- filtration-specific properties, which determine the ability of the medium to achieve a specified filtration task, such as its efficiency in retaining particles of a defined size, resistance to flow, and so on.

The three categories are listed in more detail in Tables 1.4–1.6. The significance and potential for quantifying the individual properties are discussed in turn in the following sections of this chapter, the components of Tables 1.4 and 1.5 being covered by the remainder of Section 1.5, and those of Table 1.6 by Section 1.6.

1.5.1 Machine-orientated properties

Those properties of a filter medium that are of particular concern to the mechanical implementation of the filter itself are described in this section.

1.5.1.1 *Rigidity*

It is virtually a subconscious reflex to use rigidity as a primary criterion of the possible compatibility of a filter medium with a specific type of filter; it was for this reason that rigidity was used as the basis of the general classification of media in Table 1.3. Nonetheless, it is relatively rare for the rigidity to be measured or for a value to be quoted.

The scientific basis of measurement is the Young's modulus of elasticity, values of which, for the basic material from which media are made, are available in appropriate reference books. In practice, these values are generally not directly applicable to filter media in their various fabricated forms.

The paper and textile industries each have their own standard procedures for measuring what is generally termed *stiffness*. The test for paper (BS 3748:1992) measures the force in grams to deflect a strip through a defined angle; the textile test (BS 3356:1961) is more empirical and records the *overhang length* of a strip necessary for it to bend through an angle of 41.5° from the horizontal, under its own weight. The textile data may be reported as *bending length*, which is half the overhang length, or as *flexural rigidity*, G, given by:

$$G = 0.00167ML^2$$

where M = cloth mass per unit area (g/m^2); L = overhang length (cm).

Table 1.4 Machine-orientated properties

1	Rigidity
2	Strength
3	Resistance to creep/stretch
4	Stability of edges
5	Resistance to abrasion
6	Stability to vibration
7	Dimensions of available supplies
8	Ability to be fabricated
9	Sealing/gasketing function

Table 1.5 Application-orientated properties

1	Chemical stability
2	Thermal stability
3	Biological stability
4	Dynamic stability
5	Absorptive characteristics
6	Adsorptive characteristics
7	Wettability
8	Health and safety aspects
9	Electrostatic characteristics
10	Disposability
11	Suitability for reuse
12	Cost

Table 1.6 Filtration-specific properties

1	Smallest particle retained
2	Retention efficiency
2.1	The structure of filter media
2.2	Particle shape
2.3	Filtration mechanisms
3	Resistance to flow
3.1	Porosity of media
3.2	Permeability
4	Dirt-holding capacity
5	Tendency to blind
6	Cake discharge characteristics

1.5.1.2 Strength

The strength of a material is generally characterized by generating stress/strain data using an extensometer. The main parameter thereby quantified is usually the tensile strength, but others frequently quoted are the rupture strength, the yield strength, the yield point, the elastic limit and the ultimate elongation.

With filter media, only limited use appears to be made of these basic mechanical properties. It is common practice for the literature of a supplier of monofilament meshes to include the *tensile strength* and *elongation* of the material from which the filaments are made. Tensile strength values are generally also supplied for sintered metals.

Whereas tensile strength would seem to be a useful parameter for porous ceramics, in practice the industry generally uses *cross breaking strength*, for which a standard test procedure is available (BS 1902 Part 1A:1966).

With other media, various strength criteria are preferred, sometimes involving misuse of a term such as tensile strength. For example, the standard test for paper (BS 4415:1969), whilst described as measuring tensile strength, omits reference to the thickness of the sample. For textiles, a similar standard test (BS 2576:1967) determines what is more aptly termed the *breaking load*.

Both the textile and the paper industries also have standard procedures for measuring the *resistance to tearing* and the *bursting strength*. The latter, which may be on either a wet or a dry sample, is an empirical value that depends on the diameter of the disc tested. It is readily measured using commercially available apparatus conforming to the appropriate standards (BS 3137:1972 for paper, BS 4768:1972 for textiles).

1.5.1.3 Resistance to creep/stretch

This property is of particular importance in respect of the use of textiles on certain types of filter, notably fabric dust filters and belt type filters for liquids. With this in mind, media manufacturers routinely use tensile tests primarily to predict cloth extension at loads that will be somewhat higher than those applied by the filter equipment. In the case of fabrics for dust collection applications, some equipment manufacturers actually indicate the stress–strain characteristic in their specifications, e.g. max. 2–2.5% extension at 5 kgf/5 cm. However, since this information is not always available, and since it is known that the force applied by equipment is in general quite low relative to the overall strength of the fabric, tests are usually carried out to indicate the material's extensibility at low loads, e.g. 2, 5 and 10 kgf/5 cm. Furthermore, since the stress–strain properties of textile fibres and filaments are affected by temperature, one media manufacturer (Madison Filter) has engaged a facility that will actually enable the tensile work to be carried out at elevated temperatures. Resistance to stretch is equally important in fabrics that are engaged in filter belt (liquid filtration) operations, where even relatively low loads could result in a belt extension up to and sometimes beyond the stroke of the filter's tensioning system.

1.5.1.4 Stability of edges

Whilst edge stability is clearly of importance with certain types of woven and non-woven media, there is no recognized method of assessment other than visual subjective judgment.

1.5.1.5 Resistance to abrasion

The ability of a filter medium to resist abrasion depends primarily on the hardness of the material from which the medium is formed (e.g. the hardness of nylon in a woven or non-woven fabric). Hardness may be measured in terms of various empirical scales, such as that which the mineralogist F Mohs devised in 1812, based on which material will scratch another, or one of those (Brinell, Rockwell, Shore, Barcol) involving measurement of the indentation caused by a loaded ball or pointer.

Direct empirical measurement of abrasion resistance is a common requirement in the textile industry. Examples of the techniques used are the Martindale wear tester, which counts the number of rotations of a rubbing abrasive surface until a hole is formed; and the Stolle tester which checks the number of flexings of a strip in close contact with a rod.

1.5.1.6 Stability to vibration

Whilst the stability of filter media to vibration can occasionally be of importance, no basis of guidance is available other than general structural considerations.

1.5.1.7 Dimensions of available supplies

The dimensions in which pieces of media are available are controlled by the techniques and machinery of the manufacturer. For example, woven fabric (including wire cloth) cannot be wider than the width of the loom: in practice, where the uniformity is critical, the usable width may be significantly less.

1.5.1.8 Ability to be fabricated

Combining a filter medium with a filter often demands the use of one or more fabrication techniques, such as cutting, bending, welding, adhesive bonding or stitching. Which of these is possible depends on the individual medium. Care must always be exercised in employing such techniques to ensure that their use does not create wider pores or other imperfections in the medium at a point where its filtration ability might be critical.

1.5.1.9 Sealing and gasketing function

The seal around the edge of a sheet of filter cloth is of critical importance, and often is partly dependent on the cloth itself acting here as a gasket, as in a conventional filter press. Effectively, the cloth is being required to be permeable in one area and impermeable in another. Natural fibres are soft, readily absorb liquids and deform easily; thus they tend to give a fairly good seal. Synthetic fibres, however, especially monofilaments, are relatively hard and have a low absorptive capacity, so that compression alone is less likely to make a good seal: a convenient answer to the sealing problem is to impregnate the appropriate area with a suitable impervious elastomer such as neoprene or nitrile rubber.

1.5.2 Application-orientated properties

The following notes describe those characteristics of a filter medium that are of particular importance in the system that involves the filtration process.

1.5.2.1 Chemical stability

The ability of a filter medium to withstand a specified chemical environment can generally be checked easily from published technical data, provided that the chemical nature of the medium itself is known. With synthetic fibres, this can in practice be a source of some difficulty, since the nature of the fibre may be hidden behind a trade name; the full measure of this problem is demonstrated by the list of some 5000 entries in a major glossary of fibre names, *The World Fibres Handbook*[8]. Some of the more common names are listed in Table 2.1 of Chapter 2.

1.5.2.2 Thermal stability

Although subject to the same potential difficulty of identifying the chemical nature of the fibre from which a filter medium is made, its compatibility with a specific operating temperature can be determined from published data. This may also depend upon the chemical environment.

1.5.2.3 Biological stability

This is generally of importance only with natural fibres (e.g. cotton), rather than synthetic materials, which are not usually susceptible to biological degradation.

1.5.2.4 Dynamic stability

The shedding of fibres, or the migration of fragments of filter media into the filtrate, is a matter of serious concern with certain types of critical applications, such as controlling the environment in a clean room, or producing ultraclean water for use in the electronics industry.

The more the medium contains small pieces of original material (fine fibres or powder), the greater the potential for shedding.

1.5.2.5 Absorptive characteristics

Absorption is typified by the ability of blotting paper to soak up substantial amounts of ink or other liquid into the depth of the paper. More precisely, it is defined as a physicochemical process in which a substance associates with another, to form a homogeneous mixture[1]: thus, a soluble gas is absorbed into a liquid to form a solution.

In the context of filter media, absorption of water causes the fibres of cellulose paper or cotton cloth to swell and the space between adjacent fibres to reduce, so that the filtration characteristics of the medium may change significantly.

1.5.2.6 Adsorptive characteristics

In contrast to absorption, adsorption occurs only at the surface of the solid or liquid adsorbent, producing there a high concentration of a particular component. The in-depth adsorption that occurs with activated carbon results from its microporous capillary structure, and its correspondingly very high internal surface area. The adsorption mechanism depends on intermolecular attractive forces (e.g. van der Waals forces).

With filter media, the adsorption of specific types of molecule or ion onto the surfaces of fibres may radically affect performance, especially of a medium that functions by depth filtration mechanisms. The tendency of a fabric to blind may also be affected.

1.5.2.7 Wettability

The practical significance of wettability is demonstrated by the relatively high pressure required to initiate the flow of water through a PTFE medium, because it is hydrophobic; by contrast, a liquid such as alcohol, which wets PTFE readily, will commence to flow at a far lower pressure.

Theoretically, whether or not a given liquid will wet a specific filter medium can be predicted from knowledge of the surface tension of the liquid against the solid, on the one hand, and against air (or the other gas in the system) on the other hand; wetting will occur if the surface tension against the solid is the greater. In practice, it is often difficult to use this simple relationship because of the absence of the necessary surface tension data; moreover, surface tension values may be altered dramatically by the presence of very small amounts of some impurity, either in the liquid or on the solid surface.

1.5.2.8 Health and safety aspects

One potential source of hazard is the risk of an electrostatic discharge, which is a recognized problem with dust filtration and can also occur under very different circumstances when filtering organic liquids; this is discussed in more detail in the next subsection. Other hazards may be of a more chemical or physical nature, notably in handling powdered filter aids, the inhalation of which can be harmful. Handling problems may also occur in disposing of used media, especially if contaminated with hazardous materials; disposability is also discussed separately below.

1.5.2.9. Electrostatic characteristics

Hazardous electric discharges can occur as a consequence of static generated by filtration through some types of filter media. This risk is best known in the application of fabric bag filters for dust collection from exhaust gases and air. The phenomenon is less common with liquid filtration, because of the high conductivity of water and aqueous solutions. But it can be significant with organic solvents and hydrocarbons, especially those with a very low conductivity(9,10); if this is combined with a low flash point, there may well be risk of an incendive discharge (i.e. a static discharge capable of causing ignition).

There is an important difference between gas/air filtration and liquid filtration that merits emphasis: this concerns the location of a static charge. A clean gas flowing through a filter medium cannot become charged, but a clean liquid can. With a gas, it is only any particles it contains that may become charged, not the gas itself; dust (or liquid droplets) collecting on a fabric bag may be charged, but there will be no charge in the filtrate unless it contains some particles.

By contrast, the liquid itself may become charged by filtration, and so will produce charged filtrate. Under normal circumstances, this charge will decay safely at a rate that depends on the electrical conductivity of the liquid, typically requiring a period of perhaps 30 seconds. Initially, however, a high voltage discharge may occur from the surface of the charged liquid, as it collects in a receiving vessel; this risk can be avoided by providing adequate dwell time in the piping system between the filter and the tank inlet. An alternative technique, which is standard practice for refuelling aircraft, is to dose the fuel with an antistatic additive at a concentration of about 1 ppm.

Antistatic fabrics, of relatively high electrical conductivity, are available to control the build-up of static in dust filters: some of these have metal fibres woven into the fabric, while others depend on a conductive coating of the polymeric fibres. This approach is of little benefit for liquids, which can be charged even by sintered metal and woven wire.

A totally different aspect of electrostatic behaviour is that in which fibres are intentionally charged, so as to improve the collection efficiency of particles by the medium. This is an important topic in filtration both of liquids and gases, and merits a key section later in this Handbook.

1.5.2.10 Disposability

Used and discarded filter media form part of the effluent from a plant, and must therefore receive appropriate attention to avoid causing pollution. For example, it is generally no longer possible simply to discharge precoat residues into the nearest sewer; a secondary filter may be required to collect and dewater these materials. Special arrangements may be necessary to dispose of contaminated filter cloths or cartridges.

An important feature these days is the need to recycle as much waste material as possible, and it is therefore becoming important that filter media and their appropriate housings, where these form a disposable cartridge, for example, should be made of the same material to enable simple recycling at the appropriate place after disposal.

1.5.2.11 Suitability for reuse

Some filter media can only be used once, and then must be discarded and replaced, while others have an indefinite life. Yet others fall somewhere in between, their useful life often depending on how they are used and cleaned. This factor can obviously have a profound cost implication.

1.5.2.12 Cost

Understandably, the cost per unit area of the myriad of different commercially available types and grades of filter medium varies 10,000-fold or more. This can be seen from the list of very approximate prices (£/m^2) assembled in Table 1.7; of course, these very rough figures by no means tell the whole story, since they take no account of the commercial realities of competitive tendering and bulk buying, nor of the substantial wastage from off-cuts imposed, for example, by the geometry of some filters. Even more pertinent is the impact if the medium can be repeatedly reused.

In practice, the cost of the filter medium may account for a substantial part, either of the capital cost or of the running cost of a filter, or even of both.

1.6 Filtration-specific Properties

Those properties of a filter medium that control its ability to undertake a filtration process are clearly the most important of its characteristics. These are now described in the following notes.

1.6.1 *Smallest particle retained*

The most obvious question to ask about a filter medium is: what is the smallest particle it will retain? Ideally, Table 1.3 should include a precise answer to this question for each of the types of media listed. Any attempt to do this immediately raises a host of difficulties about defining and measuring the 'smallest particle', in view of the diversity of the shapes of real particles, simple spheres being rare.

Therefore, whilst some 'smallest particle' figures are included in Table 1.3, it must be emphasised that they are intended only to provide a broad indication; they should be read in conjunction with the discussion that follows. What is much more meaningful is to characterize a filter medium in terms of its retention efficiency against particles of a standard test powder or aerosol.

1.6.2 *Retention efficiency versus particle size*

Figure 1.5 shows two typical grade efficiency curves relating to the filtration of a hydraulic fluid containing iron oxide; they demonstrate how the retention efficiency of a filter medium decreases as the size of the particles reduces. As illustrated, the actual shape of such curves may very widely; here, the felt and wire gauze both have a cut-off (i.e. 100% efficiency) at 35 μm, but the effectiveness of the wire gauze falls away rapidly, whereas the felt performs reasonably well down to a much smaller size.

The particle size corresponding to 100% retention (i.e. 35 μm for both curves in Figure 1.5) is generally known as the 'cut-off point', while the filter medium may be described as '35 μm absolute'. More usual practice is to rate a medium in terms of the particle size at which it has a somewhat lower efficiency, such as 98%; this immediately differentiates between the two examples in Figure 1.5.

Table 1.7 Typical costs of various types of filter media

Class	Type	Cost (£/m^2)
Cellulose paper	Resin impregnated	0.25–0.5
	Unimpregnated	0.15–0.25
Glass paper		0.4–0.8
Filter sheet	Asbestos free	4–6
Membrane	Acrylic copolymers	60–100
	Cellulose	45–75
	Cellulose esters	90–150
	'Nuclepore' polycarbonate	125–220
	Nylon	70–130
	Polyethersulphone	75–140
	PTFE on polypropylene substrate	400–500
	UF membranes	75–135
Mesh (monofilament)	Polyamide (5–200 μm)	20–95
	Polyester (5–200 μm)	20–100
	Stainless steel (5–100 μm)	35–175
Needle felt	Staple fibre	3–7
	Polyamide	5–7.5
	Polypropylene	4–5
Non-woven: spunbonded	Polyester	0.1–2.5
	Polyethylene	0.1–3
	Polypropylene	0.05–2
Non-woven: melt blown	Polyester	0.2–3
	Polypropylene	0.1–2.5
Porous ceramic	25 mm thick	200–300
Precoat powder	Coating 0.6 kg/m^2	0.25–0.4
Sintered stainless steel	Powder (1.6 mm thick)	260–380
	Metal fibre (0.8 mm thick)	250–360
	Mesh (5 layer)	700–1200
Woven fabric	Cotton	5–7.5
	Polyamide – multifilament	5–7.5
	Polyamide – staple	6–8.5
	Polyester – multifilament	4–6
	Polyester – staple	5–8.5
	Polypropylene – multifilament	4–6
	Polypropylene – staple	5–7.5
	Aramid (filament warp/staple weft)	12.5–15
	Glass (filament warp/staple weft)	5–8
	PTFE	35–40

It is important to note that any grade efficiency curve is strictly only valid for the test conditions under which it was generated. This restriction applies not only to factors such as the nature and concentration of the solid particles, but also to the properties of the liquid (e.g. its viscosity, pH, polarity, etc.), and to the filtration velocity (i.e. the flow rate per unit area).

Another form of expression used to quantify the relationship between particle size and retention efficiency is the beta ratio, which compares the size analysis of samples taken simultaneously upstream and downstream of the filter and is defined as:

$$\beta_n = N_u/N_d$$

where N_u = number of particles > n μm per unit volume of liquid upstream;
N_d = number of particles > n μm per unit volume of liquid downstream.

The major parameters that affect the retention efficiency, and hence, to a large extent, the filtration performance are: the structure of the medium; the shape of the particles; and the filtration mechanism.

1.6.2.1 *Structure of filter media*

This chapter commenced with one definition of a filter medium as: 'any permeable material upon which or within which particles are deposited by the process of filtration'. Implicit in this definition is the assumption that the medium comprises a mass of holes separated from each other by some kind of solid wall; it is also implicit that the medium has a finite thickness.

From these factors spring several possible variations, which alone or in combination can greatly affect the filtering characteristics. These are the size and cross-sectional shape of their holes; their morphology within the thickness of the

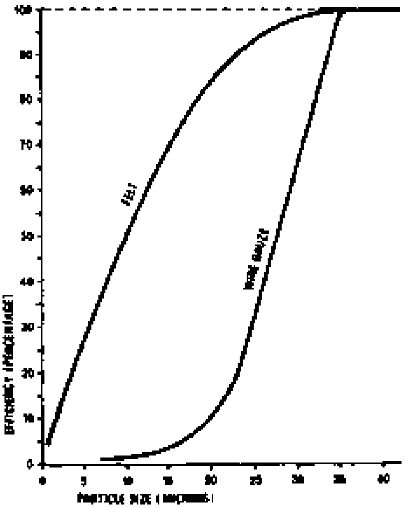

Figure 1.5. Grade efficiency curves for two media (felt and woven wire) with the same cut-off point at 35 μm but very different efficiencies against smaller particles.

medium (i.e. whether they are straight or tortuous, and whether they vary in size and shape within the medium); the number of holes per unit area; and the uniformity of each of these factors. The characteristics of a filter medium depend, in practice, partly on the intrinsic properties of the material from which it is made, and partly on the fabrication techniques employed in its manufacture. Thus, in the simplest case, a perforated metal sheet is made by drilling or cutting circular, rectangular or otherwise shaped holes in a solid sheet, so that the size, shape and spacing of the holes will be uniform within the limits of the engineering techniques used; similarly, the plate will be of uniform thickness, and each hole will usually pass directly through the plate by the shortest possible path. A plane weave wire cloth of light gauge will be broadly similar with approximately rectangular holes, although probably there will be more holes to permit flow and less metal to obstruct it than in a perforated sheet with holes of similar size.

This simple picture changes as the gauge of the wire becomes heavier, and as the weave is elaborated to give the more durable wire cloths generally used in filtration. As can be seen from Figure 1.6, the form of the holes becomes far more complex so that they can no longer be realistically described by the simple measurement of their plan view. Instead their *effective pore size* is determined by a performance test against particles of known size, or the *equivalent pore diameter* is determined by a *bubblepoint* test (using pressure to force air bubbles through the medium once it is immersed in a liquid).

Woven fabrics introduce further complications, since the more flexible nature of yarns makes it impossible to weave them with the same precision as wire; moreover, the yarns are often neither as uniform in diameter nor as smooth in surface as a wire, especially if they are of staple wool-like structure, spun from short fine fibres (Figure 1.7). An added complication then is the difference in flow path through the microstructure of such yarns as compared with that between adjacent yarns.

Even less definable structures occur with other media, such as needle felts (Figure 1.8), paper (Figure 1.9), porous ceramic (Figure 1.10), sintered metal (Figure 1.11) and polymeric membranes (Figure 1.12). With rare exceptions, it is almost meaningless to try to measure the size of the pores of these under a microscope, the practical choice being between a performance test and a bubble point test; membranes made by irradiation, such as Nuclepore, are an obvious exception, as Figure 1.13 illustrates.

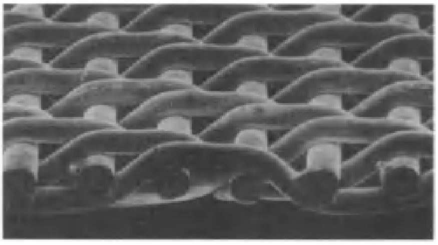

Figure 1.6. An example of woven wire mesh.

1.6.2.2 Particle shape

Despite the fact that it is common practice to refer to the size of particles by a single linear dimension (e.g. 10 µm), with rare exceptions this is an approximation that can be slightly or greatly misleading. It implies that the particles are spherical, which may be true of some bacteria and other organisms, of metal shot and of fly ash (although the latter often comprises a mixture of hollow spheres and fragments of shattered spheres). But in general, particles are more likely to be almost any shape other than spherical, ranging from plates and deformed blocks to needles.

A measure of the extent to which particles depart from the ideal sphere is given by the magnitude of their shape coefficients, K_a and K_v. Using these coefficients, the surface area and volume of a particle are related to its 'average' diameter, D_{av}, as follows:

surface area = $K_a d_{av}^2$
volume = $K_v d_{av}^3$

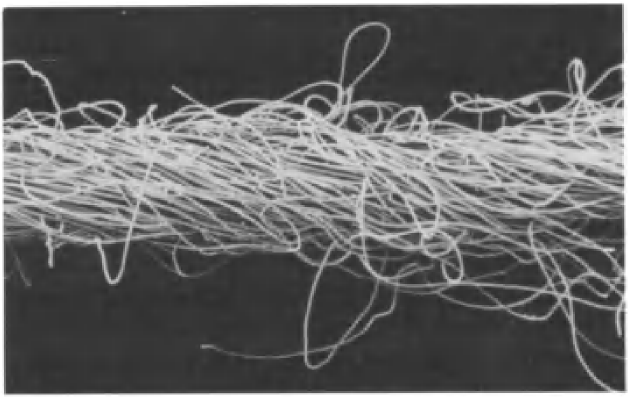

Figure 1.7. A spun staple yarn magnified.

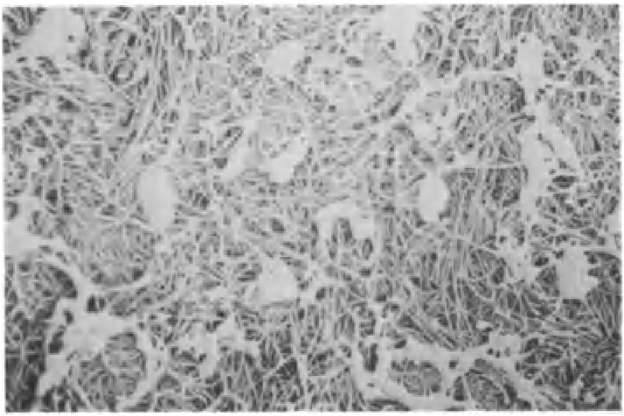

Figure 1.8. Magnified view of the surface of a needlefelt. The solid areas result from singeing.

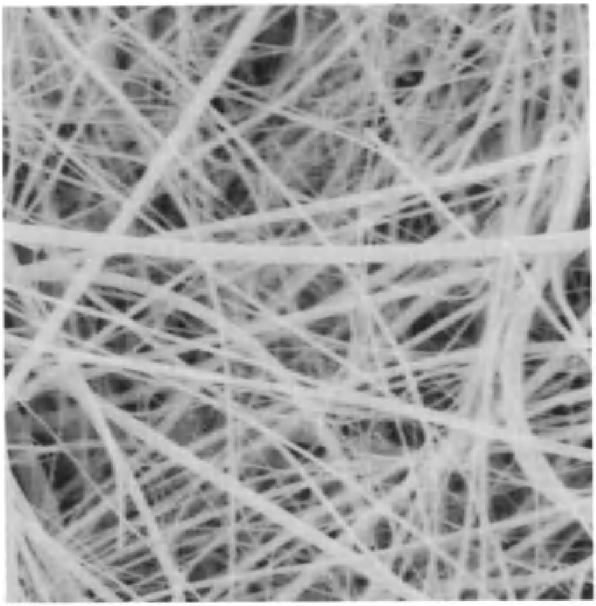

Figure 1.9. Paper of glass microfibres.

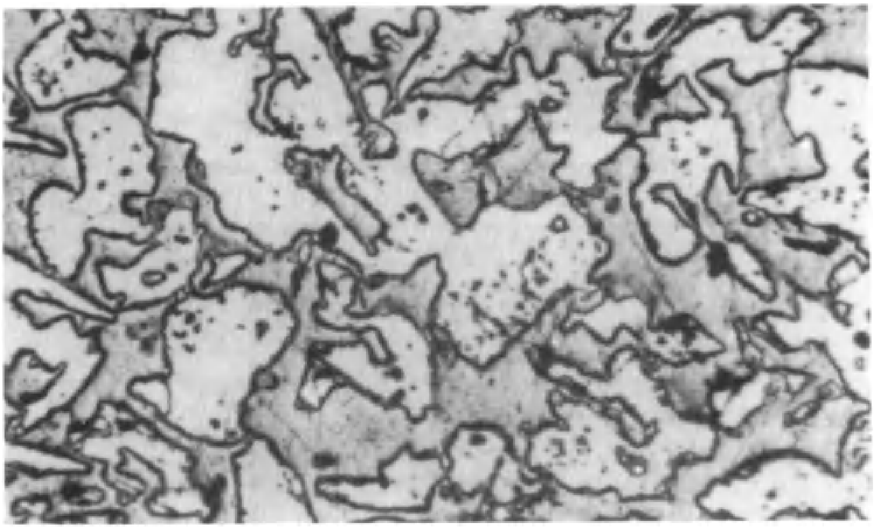

Figure 1.10. Photomicrograph of polished porous ceramic. Dark areas are pores.

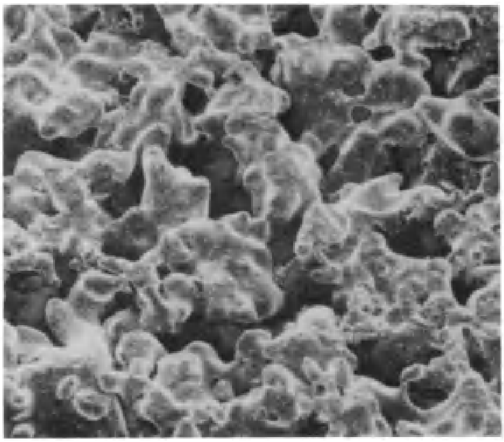

Figure 1.11. Photomicrograph of sintered metal powder.

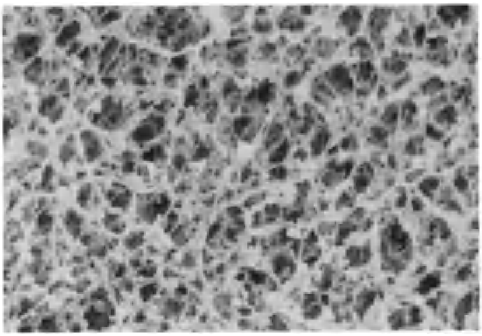

Figure 1.12. Photomicrograph of a typical polymeric membrane.

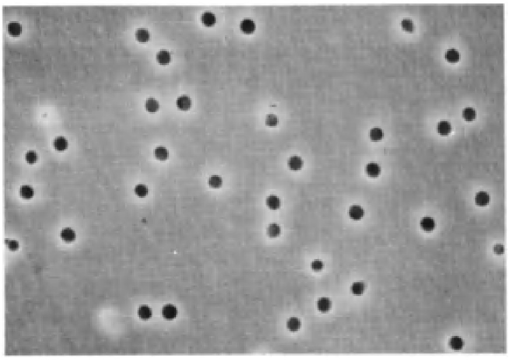

Figure 1.13. Photomicrograph of 'Nuclepore' track-etched membrane.

For spherical particles, $K_a = \pi$ (= 3.412) and $K_v = \pi/6$ (= 0.502). The few examples in Table 1.8 demonstrate the large variation that can occur with industrial particles[11].

1.6.2.3 Filtration mechanisms

The detailed examination of filtration mechanisms, both the way in which particles interact with the medium and the way in which the fluid flows through the medium, have been discussed in a previous section (Section 1.2.2). It is clearly of considerable importance to the filtering process as to which of the mechanisms of filtration is employed.

The practical effects of the differences in the structure of filter media, combined with the mechanisms of filtration, are well illustrated in Figure 1.5 above, which shows the filtering efficiencies of felt and wire mesh against particles with sizes ranging to above 40 μm. Both media have a cut-off point of 35 μm, above which they stop 100% of the particles. However, the effectiveness of the wire mesh falls away rapidly as the particles become smaller, because it functions only by surface straining. By contrast, felt continues to perform reasonably well down to a much smaller particle size, thanks to depth straining and/or depth filtration.

1.6.3 Resistance to flow (clean media)

The resistance to flow of a filter medium depends both upon the size of the individual pores and on the number of pores per unit area. The ideal medium would comprise a mass of holes divided by the thinnest possible walls, thus presenting the maximum open area through which fluid can flow. In practice the holes account for only a relatively small part of the surface, the exact proportion depending on the properties of the material from which the medium is made and the manufacturing process used. Very large differences in resistance to flow exist among the diverse ranges of available media.

This resistance can be of major importance in industrial applications, since it may affect both capital and running costs, so that considerable care may be required in selecting a medium for a specific duty. This can be made more

Table 1.8 Shape coefficients of typical particles

Particle	Area coefficient	Volume coefficient
Sphere	3.142	0.502
Copper shot	3.14	0.524
Sand	2.1–2.9	-
Worn sand	2.7–3.4	0.32–0.41
Pulverised coal, limestone	2.5–3.2	0.20–0.28
Coal	2.59	0.227
Mica	1.67	0.03
Aluminium flakes	1.60	0.02

complex by differences in definitions used to characterize the flow resistance of media, impeding a direct comparison of published data from different sources and for different media.

The actual resistance to flow of a fluid through a clean medium is a combination of the porosity of the medium material (i.e. the physical structure of the pores and surrounding material) and the permeability of the medium to the appropriate fluid (i.e. the ease or otherwise with which that fluid flows through the medium).

1.6.3.1 Porosity of media

With some types of media, direct measurement is possible of the relative areas of free and obstructed surface. While this does not give the actual resistance to flow, it is a simple and convenient mode of comparison, which quickly brings out the extent of variation that may occur. For example, the slot-shaped holes of a wedge-wire screen give a totally free area of only 5–10%, whereas the corresponding figure for perforated metal sheet with fine holes is typically about 30%. With square weave wire mesh, the free area decreases to 30–35% for the finest meshes: these are generally too weak mechanically for use in filtration, where instead use is made of dutch weave for which the free area is limited to 15–25%. Similar figures, but expressed as the percentage porosity, provide an interesting comparison among a wide diversity of media, and are summarized in Table 1.9.

The porosity of sintered metals, ceramics and stoneware is greatly affected by variations in the shape, size and size distribution of the particles used in the manufacturing process. Morgan has given a useful summary of the theoretical considerations, showing that the variations in porosity possible with spherical particles of both uniform and mixed sizes ranges downwards from a maximum of 47.6%(12). In practice, the influence of factors such as particle shape and bridging between particles makes it possible to produce certain grades of

Table 1.9 Typical porosities of filter media

	% free area
Wedge wire screen	5–40
Woven wire:	
twill weave	15–20
square	25–50
Perforated metal sheet	30–40
Porous plastics (moulded powder)	45
Sintered metal powders	25–55
Crude kieselguhr	50–60
Membranes	80
Paper	60–95
Sintered metal fibres	70–85
Refined filter aids (diatomite, perlite)	80–90
Plastic, ceramic foam	93

ceramics with porosities as high as 70%. Generally, both high porosity and fine pore size result from the use of finer particles, but at the expense of a decrease in mechanical strength.

Porous plastics made by sintering powders have porosities similar to those of sintered metal powders and ceramics. Polymeric membranes, which are made by very different processes, have very high porosities of about 80%, while figures up to 97% are reported for reticulated plastic foams.

In the case of precoats of irregular-shaped particles of materials such as diatomite, the porosity is generally 80–90% (although crude kieselguhr may be as low as 50%), whereas fibrous materials, such as cellulose paper and filter sheets, range up to about 90%.

1.6.3.2 Permeability

The permeability of a filter medium, a vital measure of the medium's capability for filtration, is determined experimentally, generally by observing the rate of flow of a fluid under a defined pressure differential. The immense variety of expressions formerly used for the permeability of filter media is illustrated by Table 1.10; this was originally assembled[5] in 1966, since when there has fortunately been considerable progress in standardization, so that permeabilities now are generally expressed in two main forms, even if in a considerable variety of units. The more common form, appropriate for sheets of media but effectively treating thickness as a constant, characterizes them in terms of the rate of flow of a specified fluid per unit area. A far less widely used form, which is more rigorous fundamentally and takes cognisance of the thickness, characterises a medium by its permeability coefficient.

Air and water (but especially air) are the two fluids most widely used in the assessment of permeability, although in certain fields other liquids such as oils are used. The techniques employed, and hence the data generated, vary from the one extreme of using a fixed rate of flow and observing the corresponding differential pressure, to the other of using a fixed pressure and observing the time required for the flow of the specified volume of fluid.

The most common form for expressing permeability disregards the thickness of the medium, so that the permeability is empirically quantified by the flow rate of air per unit area, under a defined differential pressure. An appropriate example of this method is the Frazier scale widely used internationally in the paper and textile industries; this is based on the flow of air and was formally specified as cubic feet per minute per square foot of material at a differential pressure of 0.5 inches water gauge. Metric versions require care since they may use various combinations of definitions of air volume (litres or cubic metres), time (minutes or seconds), area (square centimetres, decimetres or metres) and differential pressure (12.5, 20 or 25 mm water gauge or corresponding values in pascals).

A more fundamental expression is the permeability coefficient of the medium, K_p, which is defined by the Darcy equation describing flow through a porous layer:

$$P/L = Q\mu/AK_p$$

Table 1.10 Examples of the variety of permeability scales formerly used

Nature of medium	Type of permeability scale	Typical data
Sintered metals	gpm of water or cfm of air/sq ft at pressures in psi, through defined thickness (usually $^1/_8$ in) generally as graphs	5 μm pore. Δp1 psi – 25 cfm of air/ft^2 1.2 gpm of water/ft^2 20 μm pore. Δp1 psi – 48 cfm of air/ft^2 6.5 gpm of water/ft^2
Ceramics	(a) gpm of water or cfm of air at pressure in psi (b) mm Hg, either/ft^2 or per element: usually through defined thickness of about $^1/_2$ in	15–20 μm pore. (a) 100 scfm/ft^2 of air at 10 psig Δp=275 mm Hg (b) 5 gpm/ft^2 water, Δp=75 mm Hg
Woven metal	gpm of water/sq in at 1 psi	100 mesh square weave, 0.0045 in wire. 30% open area – 12.1 gpm/sq in. 47 μm dutch twill. 50 × 700–3.0 gpm/sq in
Woven fabrics	cfm of air/sq ft at 0.5 in WG	cotton twill – 3–15 cfm/ft^2 monofilament nylon – 300–900 cfm/ft^2 multifilament nylon – 5–500 cfm/ft^2 glass – 2–20 cfm/ft^2
Non-woven fabrics	(a) cfm of air/sq ft at 0.5 in WG (b) gpm of water/sq ft at 1 psi	(a) 0.5–230 cfm of air/ft^2 (b) 3–500 gpm of water/ft^2
Paper	(a) time for flow of e.g. 1000 cc water at pressure of e.g. 245 mm Hg (b) time for flow of fixed volume of air at defined pressure (c) litre of air per min/10 cm^2 at pressure of 10 cm WG (d) pressure needed to produce flow of e.g. 1 cfm/10 cm^2 (e) rate of air flow/unit area divided by pressure drop, e.g. cm/s/100 cm^2 divided by cm WG	(a) 4–100 s (b) $1^1/_2$–50 s (c) 40–400 l (d) 1–73 cm WG (e) 7.5–150
Sheets	gph of water either/ft^2 or/sheet at e.g. 10 psi	12–800 gph/ft^2
Filter aids	(a) graph showing cumulative flow/ft^2 versus time: using sugar and other solutions containing suspended solids on a batch test basis (b) expressed as ratio, relative to slowest in some range of products (c) darcies, based on water flow	(c) 0.05–5 darcies
Sand	Head loss, ft of water	

where A = area (m^2); Q = volumetric rate of flow (m^3/s); P = differential pressure (Pa); L = depth or thickness of the medium (m); μ = kinematic viscosity (Ns/m^2). When all of these parameters are expressed in SI units as shown, the permeability K_p is expressed in m^2.

However, K_p is frequently reported in inconsistent units, notably darcies, where viscosity is defined in centipoises, the differential pressure in atmospheres and the other parameters in centimetres and seconds, so that:

$$1 \text{ darcy} = 1(\text{cm}^3/\text{cm}^2/\text{s}).\ 1(\text{centipoise})/1(\text{atmosphere/cm})$$

These relationships are considered more fully in Section 11.2 of Chapter 11, which describes examples of equipment for measuring permeability and outlines the principles of standard testing procedures.

1.6.4 Dirt-holding capacity

An important performance parameter of filters, used either for the clarification of liquids or for gas and air cleaning, is the quantity of solids (i.e. 'dirt'), which can be collected without exceeding a defined pressure drop across the filter. A high dirt-holding capacity indicates a proportionally long on-stream time between either cleaning or replacing the filter element or medium.

Great differences in dirt-holding capacity occur between one type of medium and another, as illustrated in Figure 1.14; this is due both to the structure of the medium, and to the various filtration mechanisms by which they may function. Measurement of this capacity is frequently made as part of the challenge tests used to determine filtration efficiency; however, it is important to note that the measured capacity is strictly only valid for the test conditions used, since it depends not only on factors such as the nature and concentration of the solid particles, but also on the properties of the liquid (e.g. its viscosity, pH, polarity, etc.), and to the filtration velocity (i.e. the flow rate per unit area).

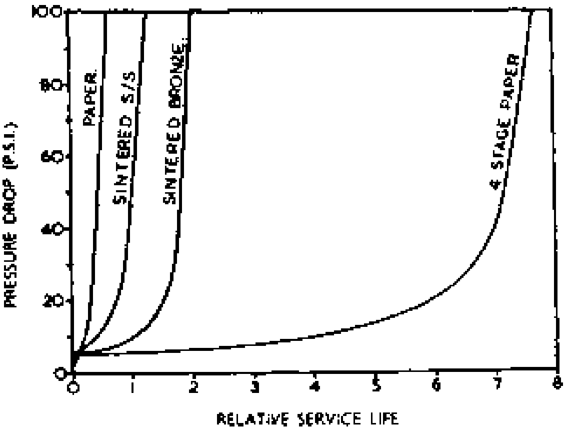

Figure 1.14. Rate of pressure rise determines the service life of media[13].

1.6.5 Tendency to blind

Unless the filter medium (or cartridge) is to be discarded at the end of a complete cycle, it is important that the accumulated solids be easily removed by a suitable cleaning procedure, whether the operation involves clarification or solids recovery by cake filtration. A medium is said to be blinded when cleaning fails to remove residual solids, which are adhering to it or embedded in it, so that its resistance to flow remains unacceptably high.

Useful empirical advice on the selection of filter cloths for liquid filtration is provided by Ehlers(14) in the form of tables; these include an indication of the order in which cloths are likely to blind, depending on the type of yarn, the structure of the yarn and the type of weave. They are reproduced in Chapter 2, as Tables 2.7–2.9. They indicate that a cloth less likely to blind is also likely to be such that it gives poorest clarity or the maximum amount of bleeding.

Rushton(15) points out that this analysis is not correct, since it ignores the division of flow, with part passing through the yarns (inter-fibre) and part around them (inter-yarn). If the proportion of the former is high, then solid particles are more likely to be carried into the depths of the yarns and to become firmly lodged, defying their removal by processes such as back-washing and increasing the likelihood of blinding. This distinction in flows was described by McGregor(16), who postulated that the split can be quantified as a factor B, which compares the actual permeability of the medium, K, with a notional permeability K_t, which would apply if the yarns were all solid filaments:

$B = K/K_t$ = actual permeability/notional permeability

For monofilament fabrics, $B = 1$, since no flow is possible through the yarns. As the value of B increases, this indicates an increasing proportion of the total flow to be passing through the yarns (inter-fibre flow), a condition that may arise due either to loosely twisted yarns or to a close weave, with various possible combinations of these giving the same B value. The 16 cloths characterized in this way by Rushton had B values ranging from 1 to 20; he concluded that a high B factor indicates a greater likelihood of blinding.

By application of the Kozeny equation, a relationship was developed whereby B can be calculated from the densities of the fibres (ρ_f), of the yarns (ρ_y), and of the medium (ρ_p), together with the number of fibres per yarn, N:

$$B = \left[1 + 1.34\left(\frac{\rho_p^2}{\rho_f^2 N}\cdot\frac{(\rho_f - \rho_y)^3}{(\rho_y - \rho_l)^3}\right)^{\frac{1}{2}}\right]^2$$

Even without the occurrence of blinding, it is frequently found that the resistance of the used medium is much greater than its original as-new value. Rushton(17) reports that, for monofilament fabrics, the combined or used cloth resistance, R_T, may be higher than that for a clean cloth, R_o, by factors as high as

6, depending on the ratio between the particle diameter and the combined dimensions of the pore and fibres in the monofilament cloths studied; smaller increases were observed with multifilament cloths, and yet smaller still with staple yarn structures.

In fact, over many years it has been realized that the overall resistance of a cake on a medium is greater than merely the sum of the resistances of the cake and the clean medium. Hatschek[18] attributed this difference to the resistance of the very first layer of particles deposited on or in the medium, and recognised that its magnitude varies with factors such as the relative sizes of the particles and pores, the shape of the particles, and the velocity of flow (which influences the orientation of the particles). The nature of this first layer has been the subject of considerable investigation in subsequent years, and the vital importance of concentration has been added to the other significant variables.

Tests with monofilament fabrics have shown that the clean cloth resistance, R_o, is only slightly increased provided that the particles are relatively large, i.e. if $D > (d_p + d_y)$, where D is the particle diameter, d_p is the pore diameter, and d_y is the filament size. Figure 1.15 depicts the usual relationship between R_T/R_o and $D/(d_p + d_y)$, and shows that, as D approaches d_p, the conditions for maximum flow resistance are obtained: this set of conditions is for 75 μm glass spheres on monofilament cloths.

The curve in Figure 1.15 may be divided into three parts (from right to left):

(a) in the first part, $D/(d_p + d_y) > 1.3$, resistance is low and cake forms on the surface of the medium;

(b) in the second part of the curve, penetration of particles into the pores occurs and resistance rises to a maximum; and

(c) in the third part of the curve, $D/(d_p + d_y) < 0.65$, bleeding occurs and resistance falls.

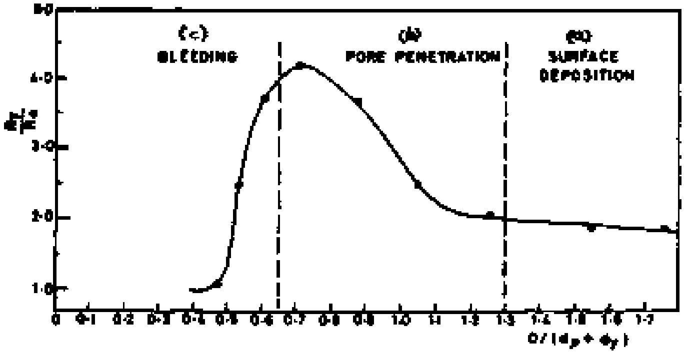

Figure 1.15. The increase in cloth resistance (as ratio used/clean) as a function of the ratio of diameters of particle and pore.

This work was extended to a few multifilament fabrics and a generalized expression developed to quantify the extent by which a clean cloth resistance R_o is increased:

$$R_T = \psi R_o$$

where

$$\psi = 1 + m(D/d_p)^{-n}$$

in which m and n are constants.

A summary of the resultant data is given in Table 1.11, which includes B values whereby the division of the flow between inter-yarn and inter-fibre modes may be seen. With admittedly scant data, it was suggested that there is a positive proportionality between B and m; in other words, a high value of B would imply a relatively large increase in the cloth resistance, R_o.

1.6.6 Cake discharge characteristics

Cake discharge characteristics are of particular importance with filter cloths used in conjunction with continuous filters such as rotary vacuum drum and disc filters, where successful continuous operation is highly dependent on the completeness with which cake is automatically removed from the working surface. The ability of a medium to discharge its cake depends very much upon the smoothness of the surface upon which the cake is residing, and hence upon the amount of fibrous material extending from the surface into the cake.

1.7 Guide to the Handbook

The bulk of this Handbook is now presented, arranged by broad class of medium material as far as possible. However, this arrangement is changed in two major sections, by the presentation of descriptions of:

- filters for air and gases, and
- cartridge filters.

Table 1.11 Influence of cloth structure on parameters in Equation 1.3

Cloth	Weave	B	m	n	Correlation coefficient between R_T and R_o
Monofilaments	Plain	1	2.25	1.65	0.98
Nylon A	Twill	2	6.30	2.07	0.98
Polyester D	Twill	2.66	9.86	2.13	0.91
Polyester B	Plain	> 20	15.78	1.30	0.97

These two are categorized by the provision of filter media in particular shapes or structures, as replaceable elements, where the element itself is the important feature.

The bulk of the text covers, in order:

- fabric media, divided into woven and non-woven (dry-laid);
- wet-laid media (papers);
- filters for air and other gases;
- screens and meshes;
- coarse porous sheet and tubular media (moulded, bonded or sintered);
- membranes (cellulose, polymeric, metallic and ceramic);
- cartridges and other replaceable filter elements: and
- loose media (powders, granules and fibres).

Where appropriate, some examples are given of the way in which filter media are used in practical embodiments of filters, and some guidance is given as to the way in which filter media might be selected for efficient use. However, it should be noted that this Handbook makes no attempt to cover the technology of filtration or centrifugation, nor to be a guide to filter selection and use – for that, the reader is referred to other standard texts(6,19–21).

The Handbook continues with two further chapters, one on filter media testing and one on filter media standards, before finishing with a glossary, a list of advertisers, and the editorial index.

1.8 References

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CHAPTER 2

Woven Fabric Media

The group of filter media that can be described as fabrics makes up the largest component of the media marketplace. Fabrics are made from fibres or filaments of natural or synthetic materials, and are characterized by being relatively soft or floppy, such that they would normally need some kind of support before they can be used as a filter medium.

The fibres or filaments can be made up into a fabric as they are, by means of some kind of dry-laying process, to produce a felt or similar material. Such 'non-interlaced' fabrics are generally referred to as 'non-woven', and they are covered in Chapter 3.

If the fibres or filaments are first spun into a continuous yarn, then the resultant yarn can be woven or knitted into a fabric, and such 'interlaced' materials are covered in the present chapter. If the material used in the weaving process is a single filament of wire or plastic, then the resultant material may be counted as a fabric, but is more often called a mesh, and as such is covered by Chapter 6.

2.1 Introduction

Textile fibres come from many sources:

Natural	vegetable	cotton, flax (linen), jute, wood cellulose
	animal	silk, wool, fur, hair
Artificial	natural resource	glass, ceramic, carbon, metal, reconstituted cellulose
	synthetic	thermoplastic polymers

Of the naturally fibrous materials, all have fibres that are extremely long by comparison with their diameters, except in the case of wood cellulose, where the manufacturing process produces fibres whose lengths are measured only in millimetres. Such fibres are too short to spin into a yarn, and are then only usable in wet-laying processes, to produce paper and related materials.

The remainder of the natural fibres have lengths measured in centimetres, and can be over 30 cm long in the case of wool, while silk can be produced as a single filament. The artificial materials can be produced as fibres of any length, or as continuous filaments.

Natural fibres have a diameter dictated by their source, and this is usually less than a millimetre. The artificial fibres and filaments are mainly formed by some kind of extrusion process from the molten state, such that their diameters can exist in a wide range, from much greater than those of natural products, to considerably finer.

The length and diameter of a natural fibre may be increased by converting the material into a yarn, although yarns may also be made up of filaments. Because of their much greater length, filaments may just be bundled together to make a yarn, although the bundles are usually twisted to give a reasonably constant diameter. The shorter, staple, fibres have to be twisted quite tightly, after being spun to line them up, in order to give adequate strength to the resultant yarn. ('Staple' was a term that related to natural fibres, but it has come to refer to any fibre of similar length, the synthetic fibre staples being produced by cutting the relevant filaments to the appropriate length.)

Yarns made from filaments are usually thin, smooth and of a lustrous appearance. Staple yarns are usually thicker, more fibrous (hairy) in appearance, and with little or no lustre. Yarns can also be made up from tapes of various kinds. In the case of filter media, these tapes would probably be fibrillated, or made of other perforated material.

Woven fabrics are then made up from single filaments, or multifilament yarns, or from twisted staple yarn. The last of these is normally used as a single strand, but two or more spun strands may be combined into ply yarns, where the strands are twisted together, usually (but not necessarily) in the opposite sense from the twist in each strand.

2.2 Properties of Yarns

Woven fabrics, then, are made up from yarns of one sort or another. It is usually the case that *warp* yarns (those running lengthways on the loom) are the stronger, while the *weft* yarns (those running across the loom) may be bulkier and less tightly twisted – weft yarns are often called filler yarns. It is quite common for the warp to be a single, relatively stout filament, while the weft is a yarn of some very different material. Equally, it is quite normal for both warp and weft to be made of the same filament or yarn.

The properties of a fabric, especially as regards its behaviour as a filter medium, depend very much on the way in which the yarns are woven together. Many properties, however, are intrinsic in the nature of the basic fibre or filament, and of the way in which it is made up into a yarn. The properties of the yarn are considered here, and those of the whole fabric in the next section. (The data given here on fibre properties are equally applicable to the same fibres when used in non-woven media.)

2.2.1 Chemical and physical properties of basic materials

The physical and chemical properties of a yarn are largely those of the fibres or filaments making up the yarn. In addition to the natural fibres (mainly cotton, but with some wool and silk), and a small, but growing, number of inorganic fibres, the bulk of filter fabrics is based upon an increasingly wide range of synthetic polymer fibres. The apparent range of synthetic fibres is the greater because of the very many trade names used for the same basic polymeric material. In order to simplify this complexity of names, Table 2.1 gives some of the more common trade names with their generic equivalents or basic polymers. Table 2.2 illustrates the basic chemical structures of the more common polymers used as fibres or filaments in filter media – the most widely used of these being polypropylene and polyesters. (The chemical nature of synthetic polymers is further explored in Chapter 8.)

A brief summary of the chemical resistances of cotton and the main polymers is given in Table 2.3, with much more detail of chemical solution behaviour given in Table 2.4.

A corresponding summary of basic physical properties for natural and synthetic fibres is given in Table 2.5. A major factor in the use of filter fabrics in gas cleaning is their ability to operate for considerable periods of time at moderately high (or even very high) temperatures. Table 2.6 recasts some of the physical and chemical data into a set of data for increasing operating temperatures.

2.2.2 Types and properties of yarns

The data of Tables 2.1–2.6 relate to the basic material of the fibres or filaments making up the yarns. There are also properties of the actual yarn to consider, namely strength, flexibility and tightness of twist.

There are, then, three basic types of yarn in wide use for filter media (Figure 2.1):

- monofilament, which is a single continuous filament of synthetic material (or silk);
- multifilament, which comprises a bundle of identical continuous filaments that may or may not be twisted; and
- staple, which is made from spun and twisted short fibres, either natural materials such as cotton and wool, or synthetic ones, which have been cut from extruded filaments.

There is a fourth, but much less common, type of yarn, made from fibrillated, or split-film, tape (such as the Fibrilon yarns of Synthetic Industries, shown in Figure 2.2).

The physical differences among these types of yarn have a significant effect on the filtration characteristics of any fabric woven from them. Thus, a multifilament or staple yarn offers filtration capability not only between adjacent yarns, but also within the yarn itself.

Table 2.1 Generic equivalents of some trade names for synthetic fibres.

	acetate	acrylic	cellulose	ceramic	modified acrylic	poly-amide	poly-aramid	poly-ester	poly-imide	poly-vinyl alcohol	poly-vinyl chloride	polyvinyl-idene dichloride	polyvinyl-idene difluoride	poly-ethylene	poly-propylene	poly-phenylene sulphide	polytetra-fluoro-ethylene
Acribel		●															
Acrilan	●																
Amilan						●											
Arnel	●																
Beratex														●			
Capolan							●										
Celanese																	
Chlorofibre											●						
Clevy T											●						
Conex							●										
Courlene															●		
Courtelle		●															
Cremona										●							
Creslan		●															
Cryol						●											
Dacron								●									
Diolen								●									
Dralon		●															
Dynel					●												
Eltexil														●			
Enkalon						●											
Fortrel								●									
Fluon																	●
Grillon						●											
Harlan												●					
Herculon															●		
Kapron						●											
Kodel								●									
Kynar													●				
Lilio							●										
Merkalon															●		
Mewlon										●							
Moplen											●						
Nextel				●													

Nitrilon	Nitron	Nylon	Nymerlon	Nomex	Orlon	P84	Perlon	Philon	Rastex	Rayon	Reevon	Retractyl	Rhovyl	Rovana	Ryton	Saran	Silon	Solef	Sulan	Sythofil	Tefaire	Teflon	Terylene	Tergal	Terital	Thermovyl	Trelon	Trevira	Trofil	Tyvek	Ulstron	Vestan	Verel	Viking	Vinal	Vinyon	Wolacryl	Zefran II
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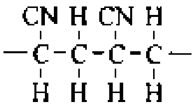
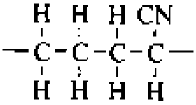
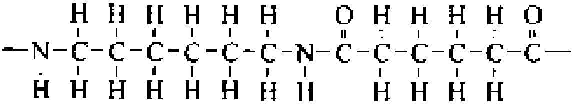
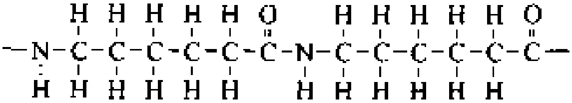
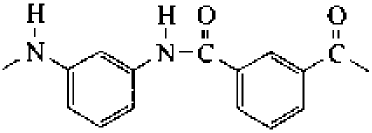
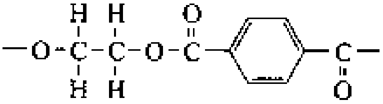
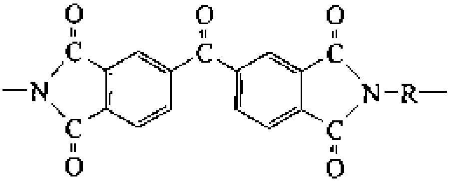
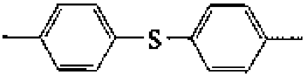
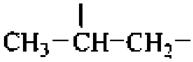
Table 2.2 Chemical nature of the major synthetic fibres

Name	Basic molecular unit	Comments
Acetate	Cellulose acetate	Derivative of natural cellulose
Acrylic	 $-\overset{CN}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{CN}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-$	At least 85% of these acrylonitrile units
Fluorocarbon	$-CF_2-CF_2-$	Polytetrafluoroethylene
Modacrylic	 $-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{CN}{\underset{H}{C}}-$	35–84% acrylonitrile
Polyamides	 $-\underset{H}{N}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\underset{H}{N}-\overset{O}{\overset{\Vert}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{O}{\overset{\Vert}{C}}-$	liphatic polyamides Nylon 66
	 $-\underset{H}{N}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{O}{\overset{\Vert}{C}}-\underset{H}{N}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{O}{\overset{\Vert}{C}}-$	Nylon 6
Polyaramid		Aromatic polyamide (Nomex)
Polyester		Ester of dihydric alcohol and terephthalic acid
Polythylene	$-CH_2-CH_2-$	PE
Polyimide		Derivative of tricarboxylic acid (P84)
Polyphenylene sulphide		PPS (Ryton)
Polypropylene	 $CH_3-\overset{\vert}{C}H-CH_2-$	PP
Polyvinyl chloride	$-CH_2.CHCl-$	PVC
Polyvinylidene dichloride	$-CH_2-CCl_2-$	PVDC
Polyvinylidene difluoride	$-CH_2-CF_2-$	PVDF

Equally important are the effects of changes in the structure of a specific type of yarn, in respect, for example, of its fineness or size (thickness or diameter), the extent to which it is twisted during spinning (or setting up as a multi-ply yarn), and the number of threads or filaments that it contains. Some guidance on how these various parameters affect the filtration characteristics of the fabrics made from them is given in Tables 2.7 and 2.8, which are derived from work published by Ehlers in 1961⁽¹⁾. Table 2.7 shows the overall effect of the type of yarn, as an order of preference of the three main types: staple, monofilament and multifilament, to achieve a specific filtration performance characteristic. Table 2.8 shows the effects on the same performance characteristics of the three yarn parameters: diameter, degree of twist and multiplicity of filaments.

It is very apparent from Tables 2.7 and 2.8 that no one type of yarn is perfect for all of the performance characteristics, and that an optimum choice will depend upon which of the performance factors is the most important in any one

Table 2.3 Summary of chemical resistance of fibres

Fibre type	Acronym or example	Chemical resistance rating against attack by the following					
		Biological agents	Mineral acids	Organic acids	Alkalis	Oxidising agents	Organic solvents
Cotton		Poor	Poor	Poor	Good	Poor	Good
Polyacrylonitrile	PAN	Excellent	Excellent	Excellent	Good	Excellent	Fair
Polyamide	Nylon	Excellent	Poor	Fair	Excellent	Fair	Good
Polyaramid	Nomex	Excellent	Fair	Good	Fair	Fair	Excellent
Polyester	PET	Excellent	Good	Excellent	Poor	Fair	Good
Polyethylene	PE	Excellent	Excellent	Excellent	Excellent	Fair	Fair
Polyimide	P84	Excellent	Excellent	Excellent	Poor	Fair	Fair
Polyphenylene sulphide	PPS	Excellent	Excellent	Excellent	Excellent	Fair	excellent
Polypropylene	PP	Excellent	Excellent	Excellent	Excellent	Fair	Fair
Polytetra-fluoroethylene	PTFE	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Polyvinyl chloride	PVC	Excellent	Excellent	Excellent	Excellent	Fair	Excellent
Polyvinylidene dichloride	PVDC	Excellent	Excellent	Excellent	Excellent	Fair	Fair
Polyvinylidene difluoride	PVDF	Excellent	Excellent	Excellent	Excellent	Good	Good

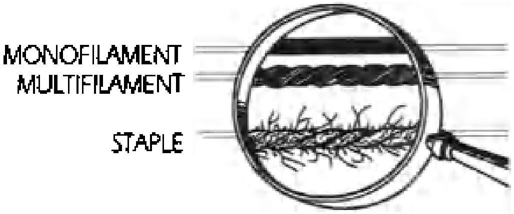


Figure 2.1. The three standard types of yarn.

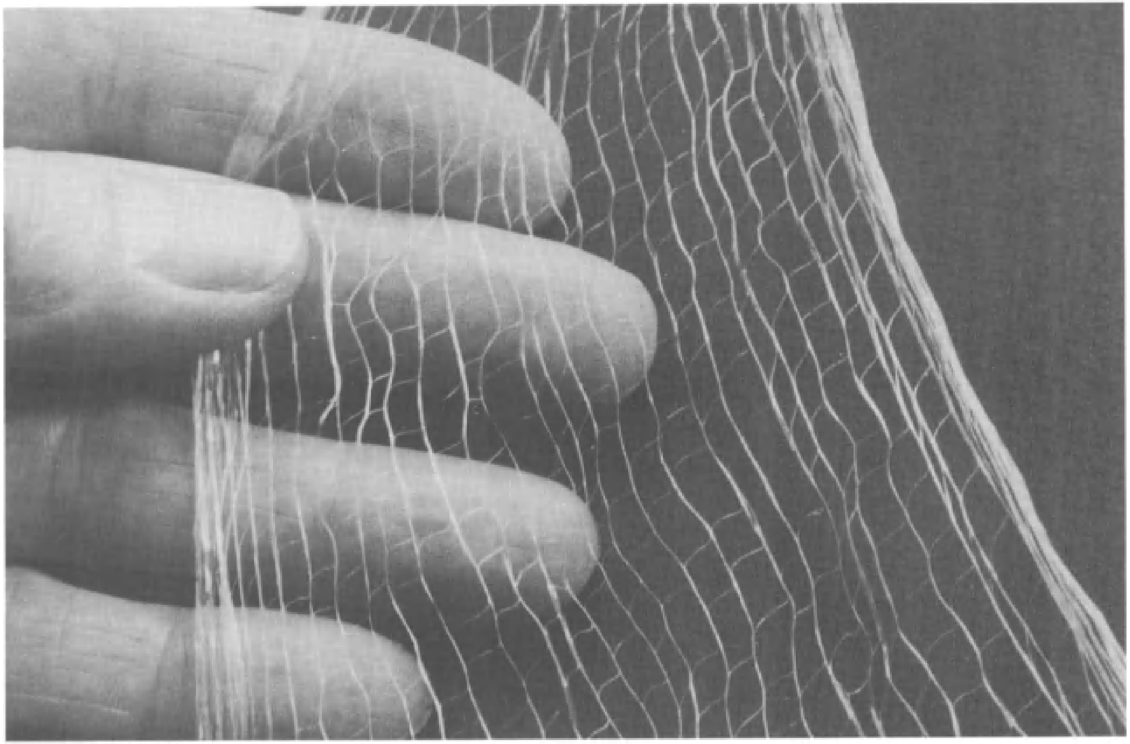


Figure 2.2. The fine structure of 'Fibrilon' fibrillated yarn. (Synthetic Industries, Inc.)(2)

Table 2.4 Fabric corrosion tables

Corrodent	Fabric											
	PET	PP	Nylon-6	Nylon-66	LDPE	HDPE	ETFE	ECTFE	Nomex	Cotton	PVDF	Felt
Acetaldehyde in water	R	R	NR	NR	R				NR			
Acetamide	NR	50	R	R	R	R	R	95	R	NR	NR	
Acetic acid, glacial	R	95	NR	NR	R	65	R	95	R	NR	55	NR
Acetic acid, 50–95%	R	95	NR	NR	R	65	R	95	95	NR	95	NR
Acetic acid, 10–50%	R	R	95	95	R	65	R	95	95	NR	R	NR
Acetic anhydride	NR	40	95	95	NR	NR	R	95	95		25	
Acetone	25	R	20		NR	50	R	65	40	R	NR	R
Acetyl chloride	25	NR	NR	NR	NR	NR	R	65	120	NR	50	
Acetophenone		NR	R	R	NR	NR	R	65	R		R	
Acrylonitrile	20	R	25	25		R	R	NR	40		50	
Acrolein	40	40	NR	NR		25			NR			
Acrylic acid	R	40	NR	NR					NR	NR		NR
Adipic acid		40			60	R	R	65		NR	R	NR
Allyl alcohol		60	25	25		60	R	R	40	R	95	R
Alum	65	105	NR	NR		60	R	R	NR		R	
Alum chrome		105	NR	NR		70	R	R	NR		R	
Alum potassium		105	NR	NR		60	R	R	NR		R	
Aluminium chloride	75	R	NR	NR	R	60	R	R	NR	NR	R	
Aluminium fluoride		R	25	25	NR	NR		150	40	NR	R	
Aluminium hydroxide	R	95	R	R	R	65	R	R	NR	R	R	
Aluminium nitrate		R	25	25		60	R	R	40	NR	R	
Aluminium potassium sulfate		R	NR	NR	NR	NR	R	R	NR	NR	R	
Aluminium sulfate	R	R	60	60	R	60	R	R	70	NR	R	NR
Ammonia, anydrous		105	25	25	NR	60	R	R	NR	NR	R	NR
Ammonia gas, dry	65	R	95	95	NR	60	R	R	65	NR	R	NR
Ammonium bifluoride		R				60	R	R		NR	135	NR
Ammonium carbonate	R	R	R	R	R	60	R	R	95	NR	R	NR
Ammonium chloride	75	R	NR	NR	R	60	R	R	NR	NR	R	NR
Ammonium hydroxide, saturated	R	R	R	R	R	60	R	95	95	NR	R	NR
Ammonium hydroxide, 10–25%	R	R	R	R	R	60	R	R	95	NR	R	NR
Ammonium nitrate	60	95	95	R	25	60	R	R	40	NR	R	NR
Ammonium persulfate	80	105	NR	NR		65	R	R	NR	NR	R	NR
Ammonium phosphate	60	105	25	25	25	60	R	R	65	NR	R	NR
Ammonium sulfate	75	95	NR	NR		25			NR	NR	R	NR
Ammonium sulfide		105				60	R	R		NR	R	NR
Ammonium sulfite	R	105	25	25	NR	60	NR	NR	40	NR	125	NR
Ammonium thiocyanate	25	60	25	25		60	R	R	25	R	R	
Ammonium thiosulfate		65	NR	NR					NR	R		
Amyl acetate	25	NR	65	65	NR	40	95	40	65	R	95	R
Amyl alcohol	R	95	95	R	R	60	95	R	25	R	135	R
Amyl chloride		NR	NR	NR	NR	NR	R	R	NR	NR	R	
Aniline	R	NR	NR	NR	NR	50	120	40	NR	R	20	R

Table 2.4 (*continued*)

Corrodent	Fabric											
	PET	PP	Nylon-6	Nylon-66	LDPE	HDPE	ETFE	ECTFE	Nomex	Cotton	PVDF	Felt
Antimony trichloride	R	R	NR	NR	NR	60	50	20	NR	NR	20	NR
Aqua regia	25	NR	NR	NR			40	40	65	NR	20	NR
Arsenic acid		R	20	20	NR	NR		R	40	NR	R	NR
Barium carbonate	R	R	25	25	R	60	R	R	120	R	R	R
Barium chloride	R	105	R	R	25	60		R	R	NR	R	NR
Barium hydroxide	NR	105	25	25	25	60		R	25	NR	R	NR
Barium sulfate	NR	105	25	25	25	60	R	R	95	NR	R	NR
Barium sulfide		R	25	25	25	60		R	95	NR	R	
Benzaldehyde	NR	25	65	65	NR	NR	95	95	65	R	70	R
Benzaldehyde in water	R	R	R	R	R			20	R	R		R
Benzene	NR	NR	R	R	NR	NR	95	95	R	R	50	R
Benzene sulfonic acid	R	R	NR	NR	NR	50	NR	95	NR	NR	25	NR
Benzoic acid	R	80	25	25	25	70	50	120	95	NR	120	NR
Benzoyl chloride	25	25	NR	NR		25		65	NR	NR	50	
Benzyl acetate	R	R	R	R	R	65		65	R	NR		
Benzyl alcohol	25	50	95	R	NR	NR		95	R	R	R	R
Benzyl chloride	R	NR	R	R	R	65	120	40	R	NR	R	NR
Bismuth acetate	R	R	R	R	R	65		65	R	R		R
Bismuth subcarbonate	R	R	R	R	R	70			R	R	R	R
Boric acid	95	95	NR	NR		60	55	25	40	R	R	R
Bromic acid		60				60		120		NR	105	NR
Bromine, liquid	25	NR	NR	NR	NR	NR		65	NR	R	60	
Bromine, water, saturated	NR	20	100	R	NR	NR	95	40	R	R	R	
Bromacetic acid	R	25	NR	NR	25	40			NR	NR	NR	
Bromobenzene	R	25	R	R	25	40		20	R	R	R	
Butyl acetate	R	R	R	R	R	R	125	40	R	NR	60	NR
Butyl alcohol	50	95	95	R	R	60	50	R	120	R	135	R
Butyl phthalate		80	R	R					R	R	25	
Butyric acid	R	80	NR	NR	NR	NR	50	120	NR	NR	115	NR
Cadmium chloride	R	R	R	R					R	NR		NR
Calcium acetate	R	R	25	25	R	R			95	NR	135	NR
Calcium bisulfite	NR	95	65	65	20	60		R	95	NR	R	
Calcium carbonate	R	R	R	R	60			R	R	R	R	R
Calcium chlorate		115				60		R			R	NR
Calcium chloride	R	105	R	R	R	60	R	R	R	NR	R	
Calcium hydroxide	R	105	65	65	R	60		R	NR	NR	R	NR
Calcium hypochlorite, saturated	R	R	NR	NR	R	60	50	R	NR	NR	R	NR
Calcium nitrate	75	105	NR	NR		60		R	NR		R	
Calcium oxalate	R	105	NR	NR	R	R			NR			
Calcium oxide	20	115	25	25	20	60		R	40		R	R
Calcium sulfate	75	105	25	25	60	R	R	R	65	R	R	R
Caprylic acid	R	60	R	R	25	60		65	R	NR	105	NR
Carbolic acid (phenol)	NR	80	NR	NR	NR	NR	R	95	NR	NR	105	NR
Carbon bisulfide (disulfide)	20	NR	25	25	NR	NR	R	95	120		NR	

Table 2.4 *(continued)*

Corrodent	Fabric											
	PET	PP	Nylon-6	Nylon-66	LDPE	HDPE	ETFE	ECTFE	Nomex	Cotton	PVDF	Felt
Carbon tetrachloride	R	20	R	R	NR	NR	95	95	R	R	R	R
Carbonic acid	100	115	40	40	20	60		R	R	R	R	R
Castor oil		140	25	25	R	65		R	65	R	R	R
Cellosolve	NR	95	R	R	NR	NR	95	95	R	R	R	R
Cetyl alcohol	R	R	R	R	R	R			R	R		R
Chloroacetic acid	25	80	NR	NR	NR	NR	50	120	NR		95	
Chloroacetic acid, 50% water	NR	25	NR	NR	NR	NR		95	NR		100	
Chloric acid 20%	NR	60	NR	NR	25	60		65	NR			
Chlorine dioxide 15%		NR			NR	NR	NR				95	
Chlorine gas. dry	20	NR	NR	NR	NR	25	120	115	NR		100	
Chlorine gas. wet	20	NR	NR	NR	NR	65	95	95	NR		100	
Chlorine liquid		NR	NR	NR	NR	NR		120	NR		105	
Chlorine water. saturated	20	95	NR	NR	NR	NR	40	40	NR		105	
Chlorobenzene	R	40	R	R	20	20	R	65	R	R	105	R
Chloroform	R	40	50	R	NR	NR		95	R	R	100	R
Chlorosulfonic acid	NR	NR	NR	NR	NR	NR	95	95	NR	NR	40	NR
Chlorox bleach sol. 5.5% chlorine		80	NR	NR					NR	R	115	R
Chormic acid 50%	R	65	NR	NR	60	60	40	120	NR		115	
Chromic acid 30–50%	R	65	NR	NR	60	60	NR	R	NR		115	
Chromic acid 10%	R	105	NR	NR	60	60	50	120	NR		115	
Chromic chloride	25	R	NR	NR	R				NR			
Chromyl chloride		60									50	
Chromium trioxide	NR	40	NR	NR	NR				NR		75	
Cinnomylic acid	R	40	R	R	20	60			R	NR		NR
Citric acid	R	105	20	R	R	60	50	R	R	NR	120	NR
Cresol	NR	60	NR	NR	NR	NR	R	95	NR		105	
Cresylic acid	R	40	NR	NR	NR	NR		NR	NR	NR	105	NR
Crude oil	75	60	65	65		60	95	95	95	R		R
Cupric carbonate	R	R	R	R	R	60			R		125	
Cupric chloride	R	R	NR	NR	R	60	R	R	NR		R	
Cupric cyanide	R	R	20	20	R	60			65		R	
Cupric fluoride		105			20	60		R		NR	R	NR
Cupric sulfate	95	105	NR	NR	20	60		R	NR	NR	R	NR
Cyclohexane	NR	NR	R	R	NR	25		R	R	R	R	R
Cyclohexanol		70	R	R	NR	60		65	R	R	105	R
Cyclohexanone	R	40	R	R	NR	NR	150	20	R	R	50	R
Cyclopentanone	R	NR	R	R	NR	NR			R	R		R
Cymene	R	25	R	R	NR	NR			R			
Detergents	60	115	40	40	R	65	R	95	R	R		R
Detergent solution, heavy duty	50	65	40	40				R	R	R		R
Dextrose		105				65		120		R	105	R

Table 2.4 *(continued)*

Corrodent	Fabric											
	PET	PP	Nylon-6	Nylon-66	LDPE	HDPE	ETFE	ECTFE	Nomex	Cotton	PVDF	Felt
Diacetin (glycerol acetate)	R	R	R	R	R	R			R			
Diallyl phthalate	R	NR	R	R	NR	NR			R	NR		NR
Dibutly phthalate	20	30	25	25	NR	NR			65	NR	NR	NR
Dibenzylamine	R	NR	R	R		25	NR		R	NR		NR
Dibenzylketone	R	R	R	R		25			R	R		R
Dibromobenzene	R	40	R	R		25			R			
Dibutylamine	R	40	R	R		25	NR		R	NR		NR
Dichloroacetic acid	40	40	NR	NR		40			NR	NR	60	NR
Dichlorobenzene	R	60	R	R	NR	25		20	R	NR	50	NR
Dichloroethane (ethylene dichloride)	NR	25	20	20	NR	NR		R	65		R	
Dichlorotheylene		80	25	25	NR	NR	30	20	65		50	
Diesel fuels	75	40	R	R	25	60	95	95	R	R	R	R
Diethanolamine	R	R	R	R	R	65	NR		R			
Diethylamine		40	R	R	NR	NR	NR	20	R		50	
Diethylene glycol	R	R	R	R	R	65	50	20	R	R	NR	R
Dimethylaniline		70	R	R		25	R	95	R		105	
Dimethylformamid	20	60	R	R	20	60	95	40	R		NR	
Dimethyl pthalate	R	60	25	R	NR	NR	R	95	R		40	
Dinitrobenzene	R	20	R	R	NR	NR			R			
Dioctylphthalate	20	NR	60	60	NR	NR	R	R	80		25	
Dioxane	20	60	R	R	NR	60	95	95	R		NR	
Diphenyl (dowtherm)	NR	NR	R	R	NR	NR	R	95	R			
Diphenylacetic acid	R	R	25	25	R	65						
Diphenylamine	R	NR	R	R	NR	NR	NR		R			
Disodium phosphate		95			R	R		R		R	70	R
Epichlorohydrin	R	70	R	R	25	65	R	95	R		115	
Ethyl acetate	NR	60	95	R	NR	NR	75	95	R	R	60	R
Ethyl alcohol	R	R	R	R	60	R		R	R	R	100	R
Ethyl benzene	R	NR	R	R	R				R	R		R
Ethyl benzoate	R	R	25	25		R	50			NR		NR
Ethyl carbamate (urethane)	R	40	R	R	R	65			R			
Ethyl carbonate	R	R	R	R	R	65			R			
Ethyl chloride	R	R	R	R	R	60	95	R	R		R	
Ethyl chloroacetate	R	25	20	R	NR	NR	95	65	R	R	60	R
Ethyl phenylacetate	R	R	R	R	R	60		20	R	NR	R	NR
Ethyl ether	R	25	20	R	NR	NR	95	65	R	R	60	R
Ethyl propionate	R	25	R	R	25	50			R			
Ethylene bromide	R	NR	R	R	NR	NR	65	R	R		R	
Ethylene chloride	NR	NR	R	R	NR	NR	50	R	95		R	
Ethylene chlorohydrin		95	NR	NR	NR	NR		20	NR		80	
Ethylene diamine		60	NR	NR		60	30	NR	NR	NR	25	NR
Ethylene dichloride	NR	NR	20	20	NR	NR	95	95	95		R	
Ethylene glycol	95	R	95	95		60	95	95	95	R	R	R
Ethylene oxide	20	NR	40	40	NR	NR	95	95	65	R	100	R

Table 2.4 *(continued)*

Corrodent	Fabric											
	PET	PP	Nylon-6	Nylon-66	LDPE	HDPE	ETFE	ECTFE	Nomex	Cotton	PVDF	Felt
Fatty acids	95	95	NR	NR	NR	50	50	95	20		R	
Ferric ammonium sulfate	R	R	NR	NR	R	60			NR	NR		NR
Ferric chloride	R	R	NR	NR	R	60	20	95	NR	NR	R	NR
Ferric chloride 50% water		105	NR	NR			95	95	NR		R	
Ferric hydroxide					R	R				R		R
Ferric nitrate	75	95	NR	NR	25	60	50	R	NR		R	
Ferric sulfate	75	95	20	20		65	50	R	25	NR	R	NR
Ferrous chloride	R	R	NR	NR	R	60	50	R	NR		R	
Ferrous nitrate		95			R	65		R			R	
Ferrous sulfate	R	R	NR	NR	R	60		R	NR		R	
Fluorine gas, wet	20	NR	NR	NR	NR	NR	NR	NR	NR		25	
Fluoboric acid	20	R	NR	NR		60		20	NR		R	
Formaldehyde 35–50% solution	R	R	95	R	R	60	95	95	R		R	
Formic acid, anhydrous	NR	80	NR	NR	NR	60	95	120	NR	NR	60	NR
Formic acid 10–85%	R	R	NR	NR	R	60		95	NR	NR	115	NR
Fuel oil	65	70	25	25	NR	NR	R	R	40	R	R	R
Furfural	20	NR	NR	NR	NR	NR	95	40	NR		40	
Furfural alcohol	R	25	R	R	25	65			R			
Gallic acid	R	R	20	20	R	60		65	40		50	
Gasoline	R	NR	R	R	NR	NR	95	95	R	R	R	R
Gasoline	R	NR	R	R	NR	NR	95	95	R	R	R	R
Gelatin	95	R	NR	NR	R	65		120	NR	R		R
Glucose (corn syrup)	20	R	20	20	R	65		R	25	R	R	R
Glycerine (glycerol)	R	R	R	R	R	60	50	R	R	R	R	R
Glycolic acid		R			R	65	95	40			50	
Glycols	20	R	R	R	R	65		95	R	R	R	R
Heptane	20	NR	R	R	NR	60	95	40	R	R	R	R
Hexachlorobenzene	R	40	NR	NR	20				NR			
Hexane	R	40	R	R	NR	NR	115	95	R	R	R	R
Hydraulic oils	95	65	20	20	NR	NR		40	25	R		R
Hydraulic oils (water base)	95	65	20	20	NR	NR		40	25	R		R
Hydrobromic acid dilute to 50%	R	95	NR	NR	R	R	R	R	NR	NR	R	NR
Hydrochloric acid 50%	R	40	NR	NR	60	60	R	95	NR	NR	R	NR
Hydrochloric acid 25–38%	25	95	NR	NR	R	65	R	95	NR	NR	R	NR
Hydrochloric acid dilute to 20%	R	95	NR	NR	R	65	R	95	NR	NR	R	NR
Hydrocyanic acid	20	105	NR	NR		65			NR	NR	R	NR
Hydrofluoric acid 50–100%	NR	95	NR	NR	20	20	20	120	NR	NR	100	NR
Hydrofluoric acid dilute to 40%	NR	105	NR	NR	R	60	R	120	NR	NR	120	NR
Hydrogen chloride gas, dry		R			60	60					R	
Hydrogen fluoride					NR	NR						

Table 2.4 *(continued)*

Corrodent	Fabric											
	PET	PP	Nylon-6	Nylon-66	LDPE	HDPE	ETFE	ECTFE	Nomex	Cotton	PVDF	Felt
Hydrogen peroxide 90%	20	50	20	20	NR	35	50	65	25		55	
Hydrogen peroxide 50%	20	50	20	20	NR	40		65	25		115	
Hydrogen peroxide dilute to 45%	50	50	20	20	NR	60		65	25		120	
Hydrogen sulfide, dry	20	105	NR	NR	25	60	R	95	NR		R	
Hydrogen sulfide, wet	20	105	NR	NR	20	60	R	95	NR		R	
Hydrogen sulfide, aqueous solution		80	20	20	20	60		65	40		105	
Hydroquinone		60				R		120		R	120	R
Hydrochlorous acid		60				60		R		NR	R	NR
Iodine	R	R	NR	NR	NR	NR	R	120	NR		70	
Iodine solution, water		20	NR	NR	NR	NR	120	120	NR	R	70	NR
Iodine solution, alcohol	20	NR			NR	NR		95		R		R
Isopropyl alcohol	NR	95	NR	NR	R	80	50	20	NR	R	125	R
Isopropyl ether		NR	20	20	NR	NR		20	25	R	25	R
Jet fuel, JP 4 and JP 5	20	20	35	35	R	70	50	R	40	R	100	R
Kerosene	95	40	R	R	NR	NR	R	R	R	R	R	R
Ketones, general	NR	NR	65	65	NR	NR	95	95	95	R	40	R
Lactic acid	R	R	95	R	NR	NR	R	R	95	NR	40	NR
Lanolin		R			R	R	R	R		R	R	R
Lanolin oil		R			R	R	R	R		R	R	R
Lauric acid		75				60		120			115	
Lead acetate	R	95	40	40	R	95		R	R	NR	R	NR
Lead chloride	R				25	60		R				
Lead sulfate			20	20	25	65		R	95	R	120	
Linoleic acid		60	NR	NR	NR	NR		120	NR		120	
Lithium bromide					25	60		65		R		R
Lithium chloride	R	R	R	R	R	60	50		R			
Magnesium carbonate	40	105				65	50	R		R	R	R
Magnesium chloride	R	R	R	R	R	65	R	R	R	NR	R	NR
Magnesium hydroxide	NR	120	20	20		65	50	R	NR	R	R	R
Magnesium nitrate		120	20	20		65	50	R	40		R	
Magnesium sulfate	75	105	20	20	60	65	50	R	40		R	
Maleic acid	NR	105	NR	NR	60	65		120	20		R	
Malic acid		50	NR	NR	60	65		120	20		R	
Mercuric chloride		105	NR	NR		65	50	120	NR		120	
Mercuric cyanide		105			60	65		120			120	
Mercuric nitrate		105			60	65		120			120	
Mercurous nitrate		60			60	65	50	120			110	
Mercury	75	105	60	60	60	65		R	60		R	
Methanol (methyl alcohol)	R	R	65	R	R	60	50		R	R	R	R
Methyl acetate	R	40	R	R	25				R	NR		NR
Methyl bromide	NR	NR	NR	NR	NR	NR		R	NR		R	
Methyl bromoacetate	R	R	R	R	R	60			R			
Methyl cellosolve		105					R	R		R	R	R

Table 2.4 (*continued*)

Corrodent	Fabric											
	PET	PP	Nylon-6	Nylon-66	LDPE	HDPE	ETFE	ECTFE	Nomex	Cotton	PVDF	Felt
Methuyl chloride	20	95	20	20	NR	NR		R	25		R	
Methyl ethyl ketone	R	60	R	R	20	25	R	65	R	R	NR	R
Methyl isobutylketone	NR	NR	40	40	NR	20	R	40	65	R	40	R
Methyl methacrylate										R	50	R
Methyl urea	R	R	R	R	R	60			R			
Methylene chloride	NR	NR	NR	NR	NR	NR	R	20	NR		40	
Mineral oil	R	R	95	R	NR	65	R	R	R	R	R	R
Monoacetin (glycerol acetate)	R	40	25	25	20	60			40	R		R
Morpholine		65	R	R	60	60	40	40	R	R	NR	R
Naphtha	R	50	R	R	NR	NR	R	R	R	R	R	R
Naphthalene	20	20	25	25	NR	25	R	R	40	R	R	R
Nickel chloride	NR	105	NR	NR		60	50	R	NR		R	
Nickel nitrate		105				60	50	R			R	
Nickel sulfate	R	R	R	R	R	60	50	R	R		R	
Nitric acid anhydrous		NR	NR	NR	NR	NR	NR	50	NR	NR	65	NR
Nitric acid 70%	20	NR	NR	NR	NR	60	NR	50	NR	NR	65	NR
Nitric acid 50%	20	60	NR	NR	NR	60	NR	50	NR	NR	65	NR
Nitric acid, 5–40%	20	50	NR	NR	NR	60	NR	100	NR	NR		NR
Nitric acid, red fuming		NR			NR	NR	NR	100	NR	NR		NR
Nitrobenzene	R	20	95	R	NR	NR	R	40	R	R		R
Nitrobenzoic acid	R	40	NR	NR	20	25						
Nitrotoluene	R	R	R	R	NR	NR			R			
Nitrous acid		NR	NR	NR	NR	NR			NR	NR		NR
Nitrus oxide		NR	NR	NR	NR	NR		20	NR	NR	NR	
Octyl alcohol	R	R	R	R	R	65			R	R		R
Oleic acid	R	75	75	R	NR	NR	50	120	R	NR		NR
Oxalic acid	R	50	NR	NR	R	60		65	R	NR		NR
Ozone	R	NR	NR	NR	NR	NR	50	R	NR		R	
Palmitic acid	75	70	20	20		20		120				
Paraldehyde	R	R	R	R	R	70			R			
Peracetic acid 40%		NR	20	20	NR	NR				NR		NR
Perchloroethylene	95	NR	95	R	NR	NR	95	95	R		R	R
Perchloric acid 70%	NR	NR	NR	NR	NR	NR	95	95	NR	NR		NR
Perchloric acid 10%	NR	60	NR	NR	NR	20	95	95	NR	NR		NR
Petroleum ether	R	20	R	R	70	60			R			
Phenol (carbolic acid)	NR	80	NR	NR	NR	NR	R	95	NR	NR		NR
Phenoxyacetic acid	R	R	25	80	R	60				NR		NR
Phenol ether	R	NR	R	R	NR	NR			R	R		R
Phosphoric acid 10–85%	R	95	NR	NR	R	60	120	95	NR	NR	R	NR
Phosphorous oxychlorine		NR			NR	NR	60					
Phosphorous pentoxide		70				60		120				
Phosphorous trichloride	R	NR	NR	NR	NR	20	R	95	NR			
Phthalic acid (aqueous)	R	R	20	20	R	60		65		NR		NR
Picric acid	NR	60	NR	NR		60		20	25	80		80
Potassium acetate 50%		95	95	95		20		20	R			

Table 2.4 (*continued*)

Corrodent	Fabric											
	PET	PP	Nylon-6	Nylon-66	LDPE	HDPE	ETFE	ECTFE	Nomex	Cotton	PVDF	Felt
Potassium bicarbonate	60	110	20	20	20	65			65		R	
Potassium bichromate	NR	110	NR	NR	25	65		120	NR		R	
Potassium bisulfate	R	R	25	25	R	70		120	40	NR		NR
Potassium bromide	20	110	NR	NR	25	65	NR	R	NR		R	
Potassium cabonate	NR	R	R	R	R	65		R	R	NR	R	NR
Potassium chlorate	20	110	NR	NR		65	NR	R	NR		R	
Potassium chloride	75	110	20	20	65	R	R	20	40		R	
Potassium chlorite	R	R	R	R	R				R			
Potassium chromate		110				65		R			R	
Potassium cyanide	20	110	20	20		65		R	65		R	
Potassium dichromate	R	110	NR	NR	20	65		R	NR		R	
Potassium ferricyanide	75	110	20	20	60	65		R	25		R	
Potassium hydroxide 5–90%	R	60	R	R	R	60	50	110	NR	NR	75	NR
Potassium hypochlorite		70			NR	NR					95	
Potassium nitrate	75	110	20	20		65		R	40		R	
Potassium permanganate	R	60	NR	NR	NR	65	40	40	NR		R	
Potassium sulfate	20	110	60	60		65		20	R		R	
Potassium sulfide		110	20	20		65			95		R	
Propionic acid	R	25	R	R	20	40	50		R			
Propyl alcohol	20	110	NR	NR		65			NR	R	50	R
Propylene glycol	NR	R	R	R	20	60	50		R		125	
Pyridine	R	80	20	20	20	60	115	95	40		NR	
Resorcinol	R	110	20	20	20	60	50		40			
Salicylic acid		60	20	20		60	50	65	65	NR	100	NR
Silver cyanide		110				65		R			100	
Silver nitrate		95	20	20		65	50	R	40		R	
Sodium acetate	R	R	R	R	R	70	50	R	R		R	
Sodium benzoate	R	R	20	20	R	60	50	R	40		R	
Sodium bicarbonate	40	110	95	95		55	R	R	40	R	R	R
Sodium bisulfate	R	R	20	20	R	65		R	40		R	
Sodium bisulfite	R	R	20	20	R	65		R	40		R	
Sodium borate	20	80	20	20		65		R	40		R	
Sodium bromide	R	R	R	R	R	65		R	R		R	
Sodium carbonate (soda ash)	R	R	R	R	R	65	R	R	65	NR	R	NR
Sodium chlorate	20	110	NR	NR	R	65		R	NR		R	
Sodium chloride	R	R	R	R	R	65	R	R	R	R	R	R
Sodium chlorite		50			NR	NR					115	
Sodium cyanide	R	R	20	20	R	65		R	40		R	
Sodium dichromate	20	60	NR	NR		65		60	NR		95	
Sodium ferricyanide		110				65					R	
Sodium ferrocyanide	75	50				60					R	
Sodium fluoride		110	NR	NR		65			40		R	
Sodium hydroxide (caustic soda) 70%	NR	R	R	R	R	65	50	65	NR	NR	60	NR

Table 2.4 (*continued*)

Corrodent	Fabric											
	PET	PP	Nylon-6	Nylon-66	LDPE	HDPE	ETFE	ECTFE	Nomex	Cotton	PVDF	Felt
Sodium hydroxide (caustic soda) 50%	NR	R	R	R	R	65	120	120	65	NR	100	NR
Sodium hydroxide (caustic soda) 10–30%	55	R	R	R	R	65	120	95	65	NR	130	NR
Sodium hypochlorite	70	120	NR	NR	20	65	95	95	NR		R	NR
Sodium nitrate	R	R	70	70	R	80		R	40		R	
Sodium nitrite		110				65		R			R	
Sodium peroxide		100	20	20		60		R	40		R	
Sodium silicate	20	110	25	25		65		R	40		R	
Sodium sulfate	R	R	R	R	R	65	R	R	R	NR	R	NR
Sodium sulfide	R	R	R	R	R	80	R	R	R		R	
Sodium sulfite	25	50	95	R		60		R	R		R	
Sodium thiosulfate	20	60	20	20	20	60	R	R	40		R	
Stannic chloride	75	110	20	20		65		R	40		R	
Stannous chloride	75	110	NR	NR		65		R	NR		R	
Stearic acid	20	80	60	60		60	50	65	95		R	
Stoddard solvent (mineral spirits)	R	40	R	R	20	35	R	R	R	R	120	R
Succinic acid	R	60	20	20	20			120	65		120	
Sulfamic acid	NR	R	NR	NR	R				NR	NR	95	NR
Sulfur dioxide (dry)	75	70	NR	NR	20	70	NR	R	20		100	
Sulfur dioxide (wet)	25	70	20	20		40	R	R	20		100	
Sulfur trioxide	20	NR	NR	NR	20			20		NR	NR	
Sulfuric acid 100%	NR	NR	NR	NR	NR	NR	R	R	NR	NR	NR	NR
Sulfuric acid 10–98%	NR	50	NR	NR	NR	NR	R	R	NR	NR	65	NR
Sulfuric acid 80%	NR	70	NR	NR	NR	NR	R	120	NR	NR	95	NR
Sulfuric acid 70%	NR	70	NR	NR	NR	60	R	R	NR	NR	110	NR
Sulfuric acid 60%	NR	95	NR	NR		60	R	R	NR	NR	110	NR
Sulfuric acid 10–50%	70	95	NR	NR		60	R	R	NR	NR	105	NR
Sulfurous acid		110	NR	NR		60		120	NR	NR	100	NR
Tannic acid	65	110	20	20	25	65		120	40		110	
Tanning liquors		60	20	25	25	60		120	40			
Tartaric acid	75	110	60	60	20	60	50	120	95		120	
Tetrachloroethylene	R	25	R	R	20		50		R	R		R
Tetrachloroethane	20	95	R	R					R		120	
Tetrahydrofuran (THF)	NR	NR	R	R	NR	NR	R	40	R		NR	
Thiocarbamide (thio urea)	R	25	R	R	20				R			
Titanium tetrachloride		40	20	20	NR	NR	50		65		65	
Toluene	R	NR	95	R	NR	NR	110	95	R	R	95	R
Tribromobenzene	R	25	25	25	25				40			
Tributyl phosphate	NR	50	60	60	20	60		20	65		50	
Trichloroacetic acid	R	60	NR	NR	R	30	R	40	20	NR	60	NR
Trichloroethylene	R	NR	R	R	20	30	95	40	R	R	125	R
Triethylamine	20	NR	25	25		25		NR	25	NR	50	NR
Trisodium phosphate	20	110	30	30		60	R	95	40		R	
Turpentine	65	40	65	65	NR	NR	95	95	R	R	R	R

Table 2.4 (*continued*)

Corrodent	Fabric											
	PET	PP	Nylon-6	Nylon-66	LDPE	HDPE	ETFE	ECTFE	Nomex	Cotton	PVDF	Felt
Urea	20	110	40	40		60	50	120	65		120	
Valeraldehyde	R	NR	NR	NR	NR				NR			
Water, demineralized, distilled, salt, and sea	R	R	20	20		60	R	R	R	R	R	R
Xylene	R	NR	95	R	NR	NR	95	95	R	R	100	R
Zinc chloride	95	R	NR	NR	R	70	50	95	R		R	
Zinc sulfate	R	R	20	20	R	60	50	R	R		R	

Key to tables

R=recommended for use up to maximum operating temperature (°C) allowable for the fabric
200=recommended only to this indicated temperature
NR=not recommended
blank=no data available

Summary of fabrics

Abbreviation	Generic equivalent	Maximum operating temperature (°C)
PET	Polyester	150–175
PP	Polypropylene	120–125
Nylon-6	Polyamide	105–125
Nylon-66	Polyamide	95–120
LDPE	Low density polyethylene	65–75
HDPE	High density polyethylene	95–110
ETFE	Polytetrafluoroethylene	120–150
ECTFE	Polychlorotrifluoroethylene	150–160
Nomex	Polyaramid	190–205
Cotton	Cellulose	120–135
PVDF	Polyvinylidene fluoride	140–150
Felt	Wood	95–120

General notes

1. All of the chemicals listed in the tables are assumed to be in the pure state or in a concentrated or saturated aqueous solution unless otherwise indicated. Concentration percentages are weight percentages.
2. When a maximum temperature is shown it indicates the highest temperature for which data is available. Higher operating temperature may be possible but tests would have to be conducted.
3. Recommended operating temperatures relate only to the chemical compatibility at these temperatures. Mechanical considerations must also be taken into account.

application. Mixed yarns, as noted below, may provide the answer to the need for the optimum performance from the fabric.

Although the normal metric system is perfectly good enough for the measurement of fibre or filament diameters, the actual numbers are rather small. The textile industry has developed two independent, although similar systems, for the specification of thread and yarn sizes. Both involve weights of a length of the material, and so depend upon density as well as size.

The *denier* system was originally developed from a system used for specifying silk filaments (and which enumerated the size in terms of drams per thousand yards). The denier number is the weight in grams of 9000 m of filament or yarn, the smaller the denier number, the finer being the filament. So, 9000 m of 20-denier yarn weigh 20 g. (The 9000 m figure presumably comes from its near equivalence to 10 000 yards.) The denier is widely used to specify silk, and artificial filaments, but is not convenient for use with staple yarns, because of their much greater weight.

The *tex* system is more recent (late nineteenth century), and is a universal system for specifying the size of staple fibre yarns, although it can also be used for filament yarns. The tex figure is the weight in grams of 1000 m of the yarn, so that 1 tex = 9 denier. This simple definition is then complicated by the textile industry's use of the term *decitex* (written dtex) to be the weight in grams of 10 000 m of yarn, so that 1 dtex = 10 tex. Analogy with other uses of the deci-prefix suggests that this relationship is the wrong way round, but the usage is very well established. It follows that 1 dtex = 90 denier.

The diameter of a particular yarn may be calculated from its tex number as follows:

$$D = 0.036 \times [(\text{tex})/(\text{density})]^{0.5}$$

Table 2.5 Physical properties and natural and synthetic fibres

Fibre temperature	Maximum safe continuous temperature (°C)	Specific gravity	Absorbency for water (% wt)	Wet breaking tenacity (g/den)	Elongation at breaking (%)	Resistance to wear
Acetate	99	1.3	9–14	0.8–1.2	30–50	Poor
Acrylic	135–150	1.14–1.17	3–5	1.8–3	25–70	Good
Cotton	93	1.55	16–22	3.3–6.4	5–10	Fair
Glass	290–315	2.50–2.55	Up to 0.3	3–6	2–5	Poor
Modacrylic	70–82	1.31	0.04–4	2–4	14–34	Fair
Polyamide	105–120	1.14	6.5–8.3	3–8	30–70	Excellent
Polyaramid	205–230	1.38	0.1–3.3	4.1	14	Excellent
Polyester	150	1.138	0.04–0.08	3–8	10–50	Excellent
Polyimide	260	-41	3	4.2	30	Good
Polyfluoro carbon	260–280	2.3	Nil	0.9–3.3	10–25	Fair
Polyvinyl chloride	65–70	1.38	2	1–3	11–18	Fair
Polyvinylidene dichloride	82–85	1.7	0.1–1.0	1.2–2.3	15–30	Fair
Polyvinylidene difluoride	140–160	1.78	<0.04		80	Excellent
Polyethylene						
Low density	65–74	0.92	0.01	1–3	20–80	Good
High density	93–110	0.92	0.01	3.5–7	10–45	Good
Polypropylene	120	0.91	0.01–0.1	4–8	15–35	Good
Polyphenylene sulphide	180–200	1.37		3.5	35	Good
Rayon	100	1.50–1.54	20–27	0.7–4	6–40	Poor
Wood	82–83	1.3	16–18	0.76–1.6	20–35	Fair

Table 2.6 Fibres for high temperature dust filtration

Fibre	Acronym or example	Max. temperature (°C)		Resistance to attack by oxidizing			
		Continuous	Surge	Agents	Acids	Alkalis	Abrasion
Cotton		80	95	Fair	Poor	Good	Good
Wool		95	110	Fair	Good	Poor	Good
Polyamide	Nylon	95	120	Fair	Poor	Good	Fair
Polypropylene	PP	95	105	Good	Excellent	Excellent	Good
Polyacrylonitrile	Dralon	130	140	Excellent	Excellent	Fair	Fair
Polyester	Dacron	150	180	Good	Fair	Poor	Excellent
Polyphenylene sulphide	Ryton	190	230	Good	Excellent	Excellent	Good
Polyaramid	Nomex	200	240	Poor	Poor	Good	Excellent
Polyimide	P84	240	260	Excellent	Fair	Good	Good
Polytetra-fluoroethylene	Teflon	260	280	Excellent	Excellent	Excellent	Fair
Glass		280	300	Excellent	Poor	poor	poor
Inconel 601	Bekinox	550	600	Excellent	Excellent	excellent	good
Ceramic, metal oxides	Nextel	760	1200	Excellent	Good	good	good

Table 2.7 Effect of type of yarn on filter fabric performance (1 = best)

Performance characteristic	Order of preference		
	1	2	3
Maximum filtrate clarity	Staple	Multifil	Monofil
Minimum resistance to flow	Monofil	Multifil	Staple
Minimum moisture in cake	Monofil	Multifil	Staple
Easiest cake discharge	Monofil	Multifil	Staple
Maximum fabric life	Staple	Multifil	Monofil
Least tendency to blind	Monofil	Multifil	Staple

Table 2.8 Effect of yarn structure on filter fabric performance (1 = best)

Performance characteristic	Structure parameter[a]								
	Yarn diameter			Twists/cm			Fibres/yarn		
	1	2	3	1	2	3	1	2	3
Maximum filtrate clarity	L	M	S	Lo	M	H	H	M	Lo
Minimum resistance to flow	S	M	L	H	M	Lo	Lo	M	H
Minimum moisture in cake	S	M	L	H	M	Lo	Lo	M	H
Easiest cake discharge	S	M	L	H	M	Lo	H	M	Lo
Maximum fabric life	L	M	S	M	Lo	H	M	H	Lo
Least tendency to blind	S	M	L	H	M	Lo	Lo	M	H

[a] L = large, M = medium, S = small, Lo = low, H = high.

where D = diameter in mm. For example, a 16 tex polypropylene fibre (1.6 dtex or 144 denier), which has a density of 0.91 g/cm^3, has a diameter of 0.15 mm, or 150 µm.

2.2.2.1 Staple yarns

Staple yarns were, of course, the first yarns used in the manufacture of filter fabrics, made from natural fibres, long before any synthetic fibre was available. Even with synthetics, staple yarns were the first used in industrial filtration on a

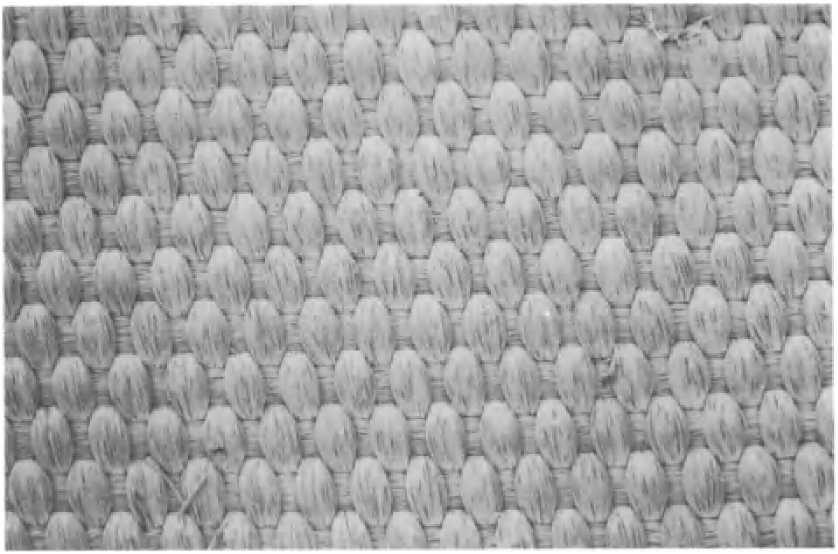


Figure 2.3. A plain weave multifilament fabric.

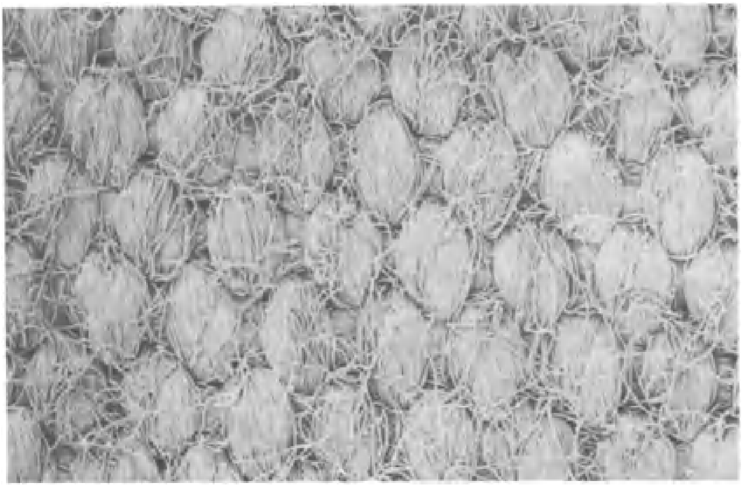


Figure 2.4. A plain weave staple yarn fabric.

large scale, since they made possible the production of the heavy-duty, durable fabrics needed for traditional filter presses and leaf filters.

Natural fibres, supplied in bulk, must first be cleaned to remove foreign matter (and grease, in the case of wool). Natural fibres, after cleaning, and artificial fibres, after cutting to the appropriate length, are *carded* by means of an array of spikes, which separates the individual fibres, and lays them parallel, as a thin sheet of uniform thickness. This sheet is then drawn together to produce a thick, continuous and untwisted *sliver* (if the sliver is given a loose twist, it becomes *roving*). Before the carding, the fibres may be mixed by blending in different lots of material, usually to ensure the production of a uniform yarn.

An additional process, called *combing*, may follow carding. This process removes short fibres, and produces a sliver made up of long fibres, lying parallel, which is smoother and more lustrous than uncombed sliver. At any given yarn diameter, a combed yarn is stronger than an uncombed one.

Slivers (or roving) are then processed in *spinning* machines, which stretch the strands and twist them to the required degree, both to hold the fibres together, and to give the necessary strength to the yarn. The direction of twist can result either in S-twist or Z-twist, with a slope increasing with the tightness of the twist: the opposite direction of twist is then normally used for converting the single yarn into a two- (or more) ply yarn. Within reason, the greater the degree of twist the stronger the yarn – but also the less useful it is in a filter fabric, when flow through the yarn is required.

A major difference between staple yarns and other types is the 'hairier' finish. This can readily be seen by comparing Figures 2.3 and 2.4. The impact of this difference is the greater difficulty in removing a filter cake from a fabric made with staple yarn than is the case with fabrics made up from silk or polymeric filaments.

The spinning processes used to make staple yarns are developed either from the spinning of cotton (with relatively short fibres, in the region of 40 or 50 mm), or the spinning of wool (with considerably longer fibres, perhaps 2–3 times the length of cotton, and much more crimped). Synthetic fibres are cut from the extruded filaments of polymer in lengths to suit whichever of these two spinning systems is to be used.

As a general guide, yarns from woollen spinning systems are bulkier than those from cotton systems, while the fibres within wool-spun yarns can move more easily within the yarn assembly. It is thus claimed that wool-spun yarns are better for filtration than either cotton-spun staple yarns or multifilament yarns, by permitting a higher throughput, and by being less prone to blinding.

2.2.2.2 Monofilament yarns

It is perhaps strange to call a monofilament a yarn in view of the latter's normal multifibrous connotation. Nevertheless, monofilaments are used in significant quantity in filtration fabrics, either as the only yarn or as a warp yarn with the weft of some different (and usually bulkier) yarn. A large proportion of fabrics made only with monofilament are better called meshes – and as such are covered in Chapter 6.

Monofilament yarns consist of a single continuous filament made by extruding molten polymer through a specially engineered die, or *spinneret*, to give the filament its required diameter and cross-sectional shape. After leaving the spinneret, the filament is drawn through a series of rollers, which improve the alignment of the polymer molecules, and so develop the desired tensile strength.

Although a whole variety of cross-sectional shapes is possible, as illustrated in Figure 2.5, woven monofilament fabrics nearly always employ filaments of cylindrical cross-section, and in diameters ranging from 0.1 to 0.3 mm, but occasionally up to 0.8 mm, or even greater. (Filaments of other shapes are used in non-woven fabrics.)

Madison's Filterlink is an interesting construction for monofilament fabrics, which was developed originally for papermaking machines. Preformed spirals of monofilaments, which run in the warp direction (MD or machine direction) are enmeshed and linked together by a series of straight monofilaments in the weft direction, across the machine (Figure 2.6). The spirals are pulled tightly into the straight filaments during a special heat-setting process, which imposes a heavy crimp, and effectively locks the structure, as is shown in the enlargement of Figure 2.6(b). The tight packing of the spirals results in exceptional width stability, and gives the fabric excellent resistance to bowing and distortion. The filaments are relatively large in diameter, being in the range 0.6–0.9 mm.

Netlon and similar meshes appear to be of monofilament construction. However, they are not woven, but made by a special, extrusion process, the products of which range from fine mesh to heavy-duty netting and robust perforated tubes. Such products are discussed in Chapter 6.

2.2.2.3 Multifilament yarns

Multifilament yarns begin in much the same way as a monofilament, except that the spinneret has a multiplicity of finer holes, so as to produce simultaneously a corresponding number of fine filaments, of about 0.03 mm in diameter. There is now little concern about the strength of the individual

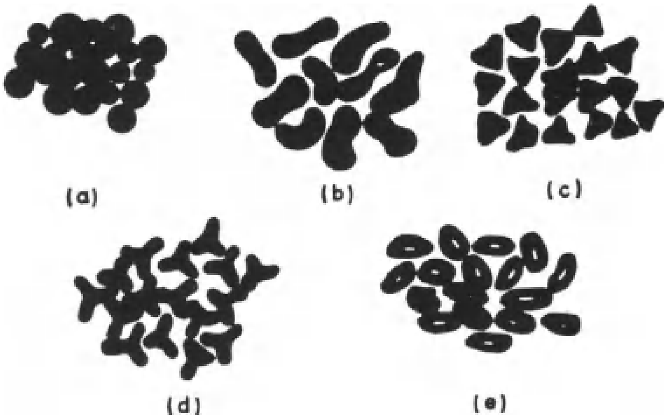


Figure 2.5 Variations in cross-sectional shape of synthetic fibres: (a) polyester – circular; (b) cellulose acetate; (c) polyester – triangular; (d) polyester – star like; (e) polyester – hollow.

filament, so the bundle is immediately compacted, and then twisted to a preset amount (which is expressed in terms of twists/cm). The twisting not only strengthens the yarn, and makes it more rigid, but also helps to protect it from abrasion, both during weaving, and in subsequent use.

The amount of twist is also important in respect of the filtration characteristics of the final fabric, since it partly determines the proportion of the fluid flow that passes through the yarns, as compared with the flow between adjacent yarns. With a very tightly twisted yarn, little if any flow will go through it. Moreover, as the amount of flow though low-twist yarns increases, so also does the tendency for particles to become embedded within the yarn, and so trapped, thereby making cleaning more difficult, and increasing the tendency of the fabric to blind.

2.2.2.4 Fibrillated tape yarns

A fibrillated film or tape is one that has been processed so that its structure includes fine short fibres, or *fibrils*, and corresponding holes. Polymer film is fibrillated, either by special cutters and pins, or by more sophisticated methods involving the stretching of the film to cause it to split into multiple localized ruptures. It is then cut into tapes, which are rolled or bundled into yarns (also called split-film yarns).

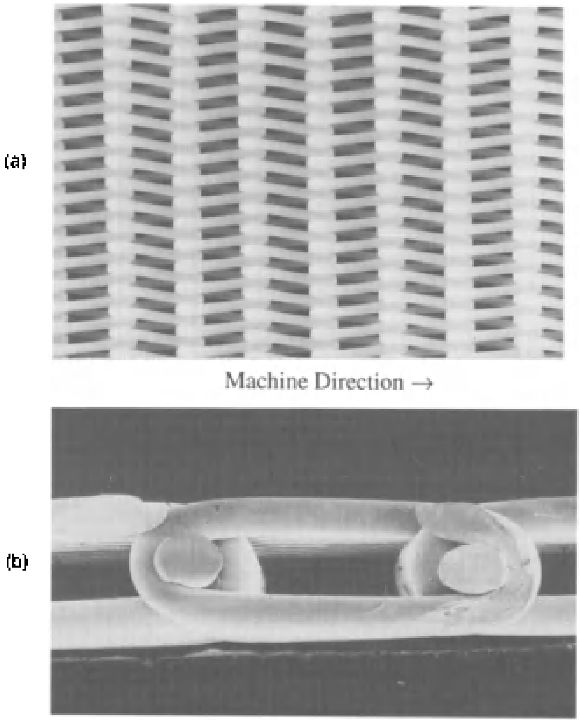


Figure 2.6. P & S Filtration's 'Filterlink' fabric belt (a) at ×4 magnification, (b) longitudinal section at ×20 magnification.

These yarns are normally made from highly orientated polypropylene, since its non-polar nature and the low intermolecular forces between the long linear polymer chains lend themselves well to the fibrillation process. This involves embossing the film with a pattern by pressurized contact with rollers, which have surfaces that have been photo-etched (as in gravure printing). The embossed film is then heated and stretched in one or more directions, thus causing the indentations to rupture. Variations are possible in film thickness, embossed pattern, and stretching process, which enable the manufacture of a wide variety of products, either as yarns, or in sheet form, and as netting.

Fibrillated yarns are widely used in the textile industry, but mainly to make heavy-duty industrial fabrics, for applications such as bulk container bags, carpet backing, geotextiles, and agricultural uses. They have only a limited use in filtration, mainly to produce coarse open fabrics used as support or drainage cloths beneath finer grades of filter fabric. An example of a support cloth is shown in Figure 2.7.

Yarns of this kind are available in many different grades, the product range of the Fibrilon yarns, produced by Synthetic Industries Inc, extending from 250 up to 10 000 denier or more. An elegant illustration of their delicate structure is shown in Figure 2.2.

2.2.2.5 Mixed yarns

The above discussion of types of yarn has assumed that the yarn will be used as both warp and weft in any fabric woven from them. However, instead of using identical yarns, a combination of different yarns can be very beneficial.

One common combination is the use of multifilament yarn for the warp, with staple yarn for the weft, an example of which is shown in Figure 2.8. The higher tensile properties of the warp give strength to the fabric, while its filament

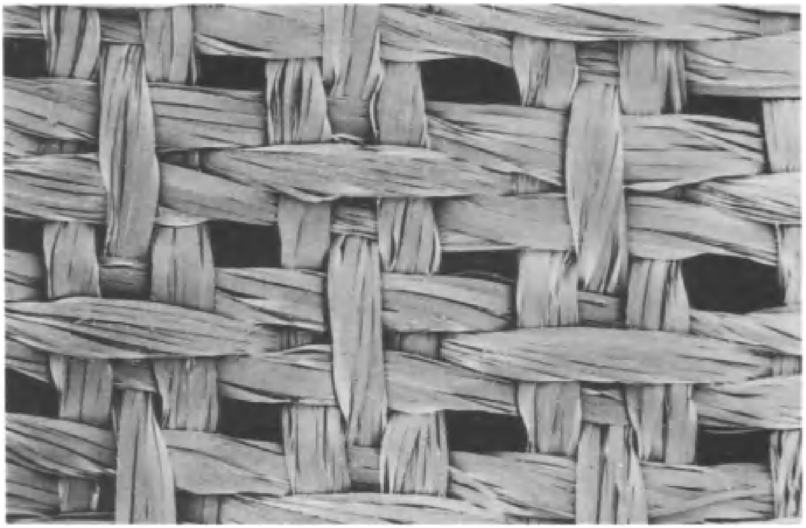


Figure 2.7. A support of backing cloth made from fibrillated yarn in mock-leno weave.

structure gives a reasonably smooth surface. The contribution from the weft is bulk, which improves the filtration efficiency and the durability of the fabric.

A different combination is to use a monofilament warp, which aids cake discharge, with a multifilament weft, with its better collection efficiency. Alternatively, the main weft yarn may be combined with a secondary one, to act as a filler, thereby increasing the bulk of the fabric.

2.3 Woven Fabric Media

The basic material of a woven fabric (filament or fibre) and the way that this material is formed into a yarn are major parameters in the choice of a fabric as a filter medium. The third such parameter is the way in which the yarns are laced together, i.e. the type of *weave*, together with any *finishing* process applied to the fabric. These are now considered, together with the properties of the resultant fabric.

2.3.1 Types of woven fabric

The variety of available woven fabrics is virtually unlimited even if only the materials from which the filaments or yarns, and the complexity of the yarn are considered. To these must then be added the structure of the woven fabric itself: the way in which the yarns are woven together, and the finishing process (if any) applied to the fabric after weaving.

In common with all industrial textiles, filter fabrics have to meet quite rigid specifications as to width, weight per unit area, weave and yarn structure, strength and elongation, thickness and chemical properties. Flexibility may be an important requirement, and the necessary porosity certainly is. There are, of

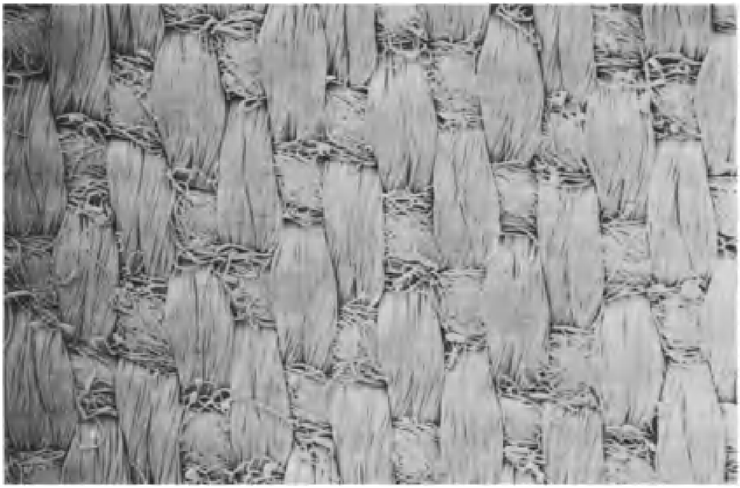


Figure 2.8. A mixed yarn reverse-satin weave fabric, with multifilament warp and staple weft.

course, many other properties of fabrics that are of no concern to their use as filter media.

Woven fabrics are made up from yarns that are interlaced in a particular and regular order called a *weave*. The component yarns, warp and weft, need not be parallel to each other nor cross at right angles, but this is the case in most fabrics, and certainly it is so in filter media. The key features of a woven fabric come from the geometrical regularity of its components, and because these components are held in place, not by any rigid bonding, but by friction at their points of contact.

2.3.1.1 Types of weave

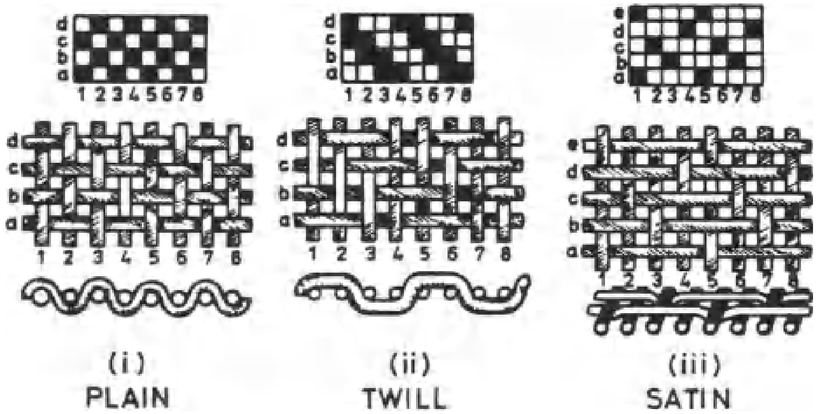
The binding system, or weave, is the basic factor that determines the character of the woven fabric. There are three main types of weave:

- plain,
- twill, and
- satin,

that are used in industrial textiles, as illustrated in Figure 2.9, although there are many other more complex systems, some deriving from hand manipulation, and others from mechanical changes in the loom. Examples of such complex patterns include the creation of a pile, or the formation of a gauze – the latter having some importance in filtration fabrics (as a *leno* weave).

The differences among the weaves depend upon the pattern formed as the weft yarns are woven over or under the longitudinal warp yarns. In the diagrams of Figure 2.9, the warps are numbered 1, 2, 3, etc., and the wefts are identified as a, b, c, etc. A white square, such as a2, corresponds to the passage of the weft over the warp.

In *plain* weave, the weft yarn passes over and then under each succeeding warp yarn across the loom, as shown in Figure 2.3. The return weft then passes the opposite way, under then over succeeding warps, such that each weft is held securely in place by the interlocking of the warp yarns. If necessary, each



2.9. The three basic weaves generally used for filter cloths.

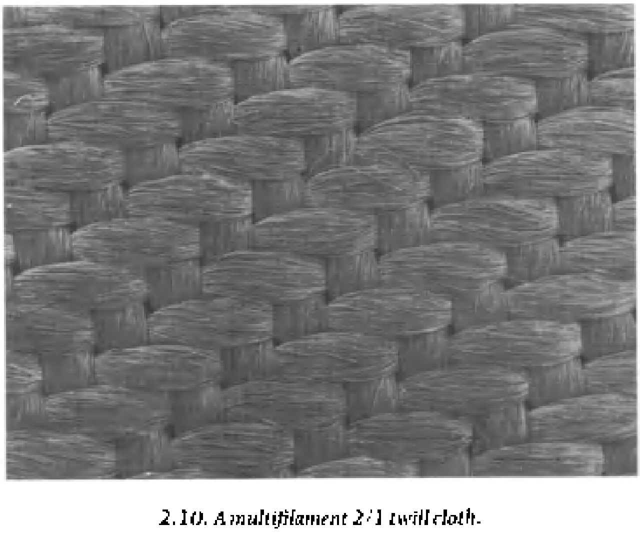
succeeding weft yarn is beaten into place, to reduce the distance between weft yarns along the fabric. Plain weaves can give the tightest fabric, with the highest filtration efficiency, as well as the most rigid.

Twill weaves are characterised by a strong diagonal pattern. They are formed by the passage of the weft yarn over two or more warps at a time, and then under one or more, in a regular pattern across the loom. The next weft thread follows the same pattern of over-and-under, but displaced by one warp yarn. The twill weave illustrated in Figure 2.9 is a '2/2' pattern showing two over followed by two under. The section of the weft yarn above a set of warps is called a *float*, and a fabric showing a predominance of warps floating on the face is called *warp faced*, and the one with weft floats dominating is *weft faced*.

The essential feature of a twill weave is its regularity, leading to its diagonal pattern. Most twill weaves are uneven in their split between warp and weft, which causes the float effect. Figure 2.10 shows a 2/1 twill weave, employing multifilament yarns. In a twill weave, more weft threads can be packed in to the fabric per unit length, which gives the fabric more bulk. Compared to a plain weave with the same yarns, twill fabrics are more flexible, and therefore easier to fit into a filter.

Satin weave extends further the concept of the twill weave, by having wider spacings between points of interlacing. Satin weave does not have the regular shift of weave pattern that twill has, and the result is an irregular appearance, smooth faced, with relatively long floating warp yarns. Most satin fabrics are made from smooth, lightly twisted yarns, thereby enhancing the visual effects.

Fabrics with a satin weave are still more flexible than the other two types of weave, because of the increased ease of yarn-to-yarn movement: this reduces the likelihood of particles becoming trapped in the structure. The longer floats allow insertion of proportionally more warp threads, thereby further improving the surface smoothness, resulting in easier cake discharge. However, unless the



2.10. A multifilament 2/1 twill cloth.

threads in both warp and weft directions are packed tightly together, satin weaves do not generally achieve high filtration efficiencies, while the long floats are more susceptible to abrasive wear.

The impact of weave on filtration performance of the resultant fabric is shown in Table 2.9, with the same layout as Tables 2.7 and 2.8, and also derived from Ehlers's work in 1961(1).

2.3.1.2 Fabric finishing processes

Fabrics of all kinds have to be treated after manufacture (non-woven as well as woven). The most common treatment will be some kind of cleaning process; bleaching may be needed to remove an unwanted natural colour. In the case mainly of woven fabrics, the material has to be inspected for imperfections, and any necessary repairs made.

Hardman[2] has identified three main reasons for carrying out finishing processes on fabrics that are to be used as filter media (there being several other such processes required for textiles for other end uses):

- to ensure stability of the fabric;
- to modify the surface characteristics; and
- to regulate the permeability of the fabric.

Stabilization may be necessary to counteract the tensions that are imposed on a fabric throughout the whole of the production process; as these tensions subsequently relax, movement and changes in the fabric dimensions may occur, so that, for example, eye holes in prepared filter press cloths may not align accurately with the ports of the press plates. To avoid such problems, it is common practice to subject a fabric to either a hot aqueous or dry setting process, at a temperature and for a duration suited to the particular polymer.

Another reason for stabilization is to anticipate the tensions that will be imposed on the fabrics in use, for example on belt filters and vertical automatic filter presses. In this case treatment involves stretching the fabric at a carefully controlled temperature; in addition to reducing the tendency of the fabric to stretch further during use, this prestretching process also ensures better tracking by equalizing any tension variations that may exist across the width of a belt.

Table 2.9 Effect of weave pattern on filter fabric performance

Performance characteristics	Order of preference		
	1	2	3
Maximum filtrate clarity	Plain	Twill	Satin
Minimum resistance to flow	Satin	Twill	Plain
Minimum moisture in cake	Satin	Twill	Plain
Easiest cake discharge	Satin	Twill	Plain
Maximum fabric life	Twill	Plain	Satin
Least tendancy to bind	Satin	Twill	Plain

Surface treatment is designed to adjust the characteristics of the surface of the fabric so that it is better suited to its particular purpose. Among the processes involved in treating a fabric surface are calendering, singeing, and napping.

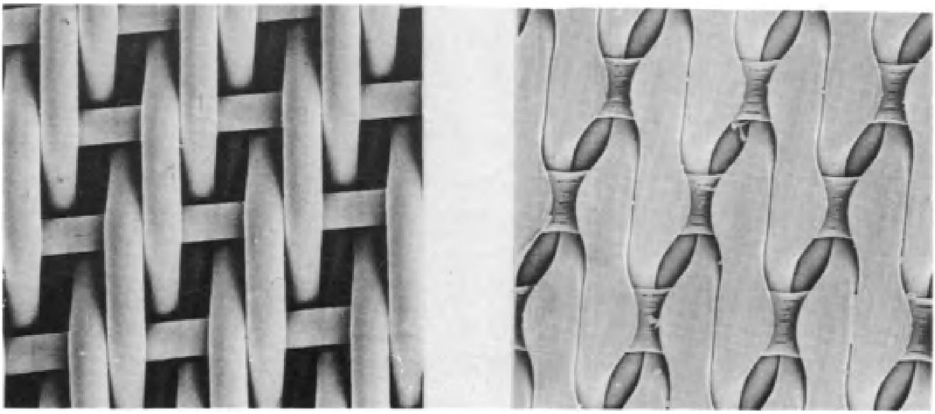
Calendering is the most frequently used of the surface treatment processes, and involves passing a fabric between heated pressurized rolls, with the temperature, pressure and speed through the rolls suited to the particular fabric. As illustrated in Figure 2.11, the effect is both to improve the surface smoothness (and hence cake discharge), and to regulate its permeability (and hence the filtration efficiency).

Singeing is a treatment process specific to the fibrous surface of fabrics made from staple yarns. The short protruding fibres, which can impede cake discharge, are removed by a rapid contact with either a gas flame or a very hot metal strip. This is usually followed by contact with a wet surface in order to stop any smouldering. The effects of singeing are illustrated in Figure 3.5 in Chapter 3, there applied to a non-woven felt.

Napping is the use of a fine steel comb to raise a soft fuzz on the face of a fabric (one or both sides), which may be followed by shearing to cut the raised fibres to a uniform length. This can improve the ability of the cloth to retain fine particles, and can also increase its dirt-holding capacity, but it will decrease the ability of cake removal from the material. It is a finish that is frequently used for dust filtration fabrics.

Permeability regulation is a vital process for the fabrics intended as filter media. It takes two basic forms: alteration of the surface, and adjustment of the relative positions of the integral yarns. Surface alteration includes calendering, as already mentioned, and the application of some kind of coating. Surface coatings are a special form of permeability regulation treatment, and are included below in the discussion of composite fabrics.

Mercerization is a process applied to cotton and some cotton blends, mainly to improve characteristics not of concern to filtration (such as lustre and affinity for dyes), but it does also improve strength. The process, which may be applied at the



(a) Before calendering (b) After calendering.

2.11. Effect of calendering on the surface of a 2/2 monofilament twill cloth.

yarn or fabric stage, involves immersion under tension in a caustic soda solution, followed by neutralization with acid. The treatment produces permanent swelling of the fibre, and hence changes the permeability of the fabric.

Tentering is a final process used to set the warp and weft of woven fabrics at right angles to each other, and to stretch and set the fabric to its final dimensions. Tentering stretches the fabric under tension by the use of a tenter frame, which travels on tracks through a heated chamber, to remove creases and wrinkles, to straighten the weave, and to dry the fabric to its final size. When the process is applied to synthetic fibres it is sometimes called *heat-setting*, a term also applied to the permanent setting of pleats, creases, and special surface effects.

2.3.1.3 Composite fabrics

When a second layer of fabric is joined to a first to make a *composite fabric*, then an element of confusion enters into the definition, as to whether the second material enhances the filtration performance of the first, or whether it completely changes the filtration regime of the resultant medium, with the second layer taking over the filtration function. The latter situation is exemplified by the laying down of a membrane layer over a woven substrate, such that the membrane does all of the filtration, and the woven material is only a support for the membrane. Composite fabrics of the second kind, which are effectively membrane media with woven fabric supports, are discussed in Chapter 8. The present section concentrates on coated woven fabrics, and multi-layer woven materials.

Surface coatings have become an important part of the woven fabric media business. The coating, which may be sprayed on as a liquid, or laid down as a thin sheet that is then bonded to the fabric, or even pushed into it, is primarily there to modify the surface permeability, but may also have other beneficial properties. (See also Section 3.3.1.2 for more information on coatings.)

Microporous polymer coatings can be applied to the face of woven and non-woven fabrics, both to achieve finer filtration, and to improve cake discharge. Examples of this format are provided by the various Ravlex coatings, supplied by Ravensworth; MP and HP grades are made from tetrafluoroethylene terpolymers, applied in liquid form, to provide a very robust coating with 5–8 μm pores. The scanning electron micrograph in Figure 3.6 in Chapter 3 shows a Ravlex coating on a non-woven fabric.

A polyurethane coating on a substrate of woven polyester is the basis of Madison's Primapor fabrics, introduced for use on process filters such as rotary drums and filter presses, shown in Figure 2.12. A development of this, the Azurtex coatings, again of polyurethane, on a polypropylene or polyester substrate, are impressed into the fabric. This gives a more durable finish, although the pore size is higher (6 μm, compared to 2.5–4 μm for Primapor). Madison also has a Tuf-Tex finish, of specially formulated resin, for woven (and non-woven) fabrics, although this is intended as an abrasion-resistant coating rather than permeability changing.

Laminated fabrics involve two or more layers of woven material, fixed together, either firmly or loosely. It is common practice in filtration to assemble several layers of different fabric on top of each other, with the finest on top as the main filtration medium, and those below of increasingly open and robust construction to provide mechanical strength and stability. It is much less common for the reverse system to be employed, where the coarsest material faces the feed, with the finest material last in the series – this might be used, for example, if the feed contains particles of widely differing particle sizes. The latter arrangement is an example of depth filtration, and is more widely used with non-woven media (as well as in loose media systems, such as sand beds).

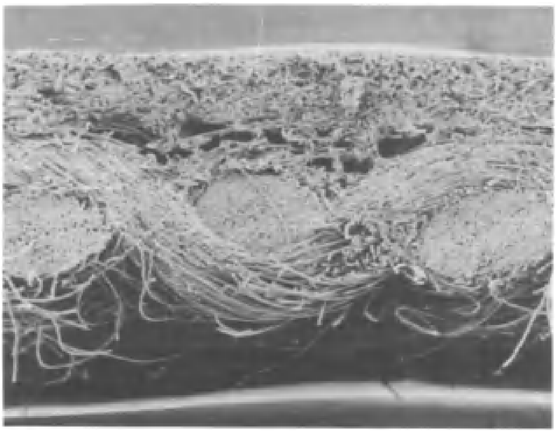
As has already been implied, a significant use for woven fabrics in filtration lies in their use as supports for membranes. Where a heterogeneous medium of this kind can be accepted, than woven fabrics can provide very strong support as membrane substrates.

Multi-layer weaving has been developed as a sophisticated weaving process by Sefar[4]. It enables the production of the Tetex multi-layer fabrics in one operation, the resultant media being very suitable for filter belts; an example is illustrated in Figure 2.13. Special looms are used that can handle several different warp and weft systems, involving around 10 000 filaments, simultaneously: this may include combining different warp and weft threads (e.g. monofilaments with ultrafine multifilaments). Equally specialized are the subsequent heat-setting/finishing processes, and the stretching and relaxing machines coupled with calendering. Belts may be 10–30 m long, and between 0.8 and 3 m wide; some belts are required to have different permeabilities in different regions, such as at the sides.

For the filtration of machine tool coolants on flat bed filters, traditionally done with disposable paper (or paper-like) media, the long life of double layer polyester belts, with nominal pore ratings of 40–120 µm, makes them an economic alternative.

2.3.2 Properties of woven fabric

The properties of woven fabrics that make them valuable as filtration media include their regular structure and their relative strength, both mechanical and



2.12. A section through a 'Primapor' coated fabric.

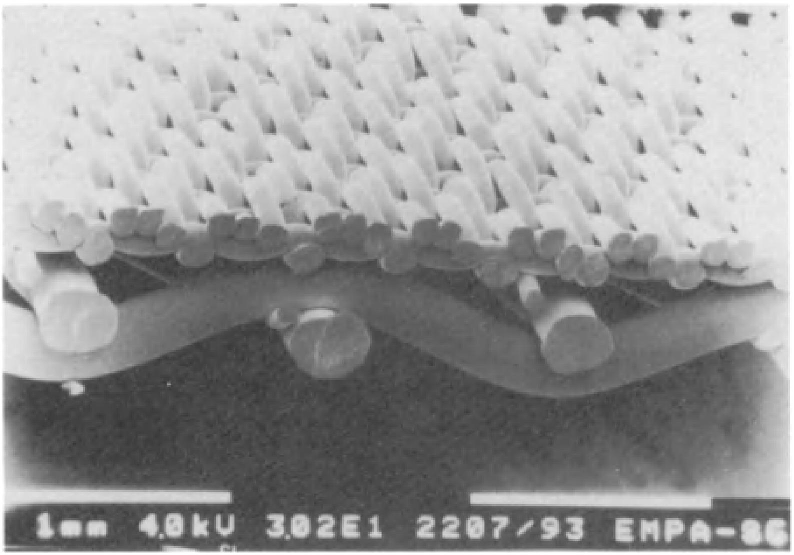
chemical. Fabrics from staple yarns are available in a wide range of materials, cotton and wool obviously, but also all thermoplastic polymers can be made into staple yarn, and used for fabrics.

A typical range of staple yarn filter fabrics is described in Table 2.10, which shows a preponderance of twill weaves. They are available with quite a wide range of permeabilities. Weights of fabrics based on staple spun yarns are generally in the range 400–700 g/m^2, the majority, in polyamide, polyester or polypropylene, are for liquids: those for dust filtration are in aramid, polyester or sulfar (PPS).

Plain weave monofilament fabrics range from lightweight cloths, with apertures of about 5 μm, up to heavy meshes with apertures as large as 5 mm; the corresponding fabric weights are typically in the range 40–400 g/m^2. The lighter grades are relatively flexible, but this gives way to stiffness and then rigidity as the filament size increases. The resultant format is more of a screen than a fabric, and they find a wide diversity of uses as sifters, sieves, strainers and screens. The media with precise, even if very fine, spacings between the woven filaments, are classified as screens and covered in more detail in Chapter 6.

A wide variety of grades of monofilament fabrics is available in each of the main synthetic polymers, as illustrated in Tables 2.11–2.14, which list representative selections from the Nytal (nylon), Estel (polyester), Propyltex (polypropylene), and Fluortex (PTFE) precision textiles of Sefar. The Fluortex fabrics can be supplied in various different commercial fluorocarbon polymers, the distinctive properties of which are listed in Table 2.15.

Rather than the plain weave used for screen-like monofilament fabrics, satin and, to a lesser extent, twill are the usual weaves of monofilament fabrics used for vacuum and pressure process filters for liquids. For smaller filter presses,



2.13. Section through a double layer woven 'Tetex' filter belt.

pressure leaf filters, horizontal belt filters, tipping pans, and both disc and drum vacuum filters, fabrics are usually in the weight range 200–450 g/m^2. For larger scale, heavy-duty operations, the weight range may extend to 1500 g/m^2. Examples of polyamide, polyester and polypropylene filter cloths in the lighter category, based on warp and weft yarns of various finenesses, are listed in Table 2.16, which are the principle qualities produced by one leading manufacturer.

The Madison Filterlink material, described above, has an exceptionally smooth surface, which has a far greater contact area than that of standard fabrics, thereby aiding filtration and extending fabric life by reducing mechanical wear. These fabrics have found particular use for the highly stressed operating conditions of multi-roll compression belt filters (belt presses), in the dewatering of flocculated sludges, for example; the absence of a mechanical seam in belts made from link fabric is of significant benefit, since this is often the weak link in conventional belts, and is frequently the first point of failure. These fabrics are typically well in excess of 1000 g/m^2 by weight, as indicated in the data of Table 2.17. Although they are effectively only available in polyester, it will be seen that a few grades contain some polypropylene, which is incorporated with the cross wires as a filler.

Table 2.10 Woven staple yarn cloths[a]

Fibre	Quality code	Weave	Weight (g/m^2)	Permeability to air[b]	Tensile strength[c]	
					Warp	Weft
Cloths for filtering liquids						
PA	NX463-44	Twill	460	95	180	120
PA	NX563-44	Twill	560	100	200	140
PA	NX473-48	Twill	570	100	200	140
PA	NX713-45	Twill	710	40	350	130
PA	NX713-46	Twill	710	13	350	130
PE	AM543-07	Twill	540	10	270	110
PE	AM543-44	Twill	540	60	280	110
PE	AM543-49	Twill	540	10	280	110
PE	AM573-32	Plain	575	5	380	280
PP	PX243-41	Plain	240	70	140	100
PP	PX373-42	Twill	375	100	220	140
PP	PX413-45	Twill	410	35	220	140
Cloths for filtering gas/dust						
Aramid	AX319-51	Twill	315	95	200	90
PE	AM299-32	Twill	290	155	160	130
PE	AM439-75	Twill	435	360	160	90
PE	AM509-75	Twill	500	205	220	140
Sulfar	SU349-04	Twill	290	120	160	60

[a] Madison Filtration Ltd.

[b] Air permeability.

[c] Tensile strength, kgf/5 cm.

Table 2.11 Examples of 'Nytal' nylon precision monofilament textiles[a]

Reference no.	N4000	N2000	N1000	N800	N600	N500	N390	N300	N224	N100	N80	N56	N35	N20	N15HD	N10HD	N5HD
Aperture (μm)	4000	2000	1000	800	600	500	390	300	224	100	80	56	35	20	15	10	5
Warp meshes/cm	2.0	3.64	7.57	9.26	11.9	13.9	17.6	22.7	29.1	57.8	67.8	101	100.5	185	185	190	200
Weft mesh/cm	2.0	3.64	7.57	9.26	11.9	14.3	17.6	22.7	29.1	66.7	81.3	101	128.2	185	185	190	200
Thread dia. (μm)																	
Warp	1000	750	320	280	240	220	180	140	120	60+ 2×50	50+ 2×43	43	43	34	39	42	2×43
Weft	1000	750	320	280	240	200	180	140	120	50	43	43	2×43	34	39	42	2×43
Thickness of fabric (μm)	2440	1580	630	505	445	390	325	250	220	105	92	71	97	45	43	40	80
Open area (%)	64	53	58	55	51	50	47	47	43	38	35	32	16	14	8	4	1
Weight (g/m^2)	395	395	160	140	133	119	105	76	80	35	35	37	49	32	32	32	60
Permeability to air[b]	–	–	6000	5800	5760	5340	5370	5100	4710	3390	2200	2130	1500	510	320	180	30
Permeability to water[c]	–	–	–	–	–	–	–	–	–	492	460	420	334	130	60	48	5.4
Bursting pressure[d]	–	–	17.5	20.5	19.5	19.5	17.5	15.0	15.5	6.0	6.5	8.5	10.0	7.5	7.5	7.5	15.5

[a] Sefar.

[b] Air permeability, l/dm^2/min @ 20 mmWG.

[c] Water permeability, l/dm^2/min @ 500 mmWG.

[d] Bursting pressure, kg/cm^2.

Table 2.12 Examples of 'Estal' polyester precision monofilament textiles[a]

Reference no.	PE5000	PE4000	PE2000	PE1000	PE800	PE600	PE500	PE390	PE300	PE224	PE105	PE80	PE55	PE15	PE20	PE10
Aperture (µm)	5000	4000	2000	1000	800	600	500	390	300	224	105	80	55	15	20	10
Warp meshes/cm	1.6	2.0	3.6	7.6	9.1	11.9	13.9	17.5	22.2	29.1	56.2	76.9	95.2	105.5	95.0	95.0
Weft meshes/cm	1.6	2.0	3.6	7.6	9.1	11.9	13.9	17.5	22.2	29.1	56.2	76.9	95.2	115.5	166.7	166.7
Thread dia. (µm)																
Warp	1000	1000	800	320	290	240	220	180	150	120	73	50	50	2×40	2×40	2×40
Weft	1000	1000	800	320	290	240	220	180	150	120	73	50	50	40	40	40
Thickness of fabric (µm)	1900	1900	1450	615	500	480	410	357	250	195	130	80	82	44	95	65
Open area (%)	70	64	51	57	55	51	48	47	44	42	35	38	27	17	7	2
Weight (g m⁻²)	355	430	520	175	145	160	155	120	104	103	66	42	51	45	55	65
Permeability to air[b]	–	–	–	–	10750	9450	8550	8600	8000	7150	5400	5825	3412	1722	550	50
Permeability to water[b]	–	–	–	–	–	–	–	–	–	–	857	–	737	542	50	10
Bursting pressure[c]	–	–	–	–	–	21.5	24.0	21.5	14.0	17.0	11.5	7.5	8.5	9.5	10.0	10.0

[a] Sefar.

[b] Air permeability, l dm⁻² min⁻¹ at 20 mm WG. Water permeability, l dm⁻² min⁻¹ at 500 mm WG.

[c] Bursting pressure, kg cm⁻².

Table 2.13 Examples of 'Propyltex' polypropylene precision monofilament textiles[a]

Reference no.	PP5100	PP6-3660	PP3000-HD	PP10-2000	PP12-1680	PP18-1000	PP20-840	PP30-590	PP35-500	PP405	PP50-297	PP280	PP79-210	PP100-149	PP140-105	PP74
Aperture (μm)	5100	3360	3000	2000	1680	1000	840	590	500	405	297	280	210	149	105	74
Warp meshes/cm	1.6	2.3	2.5	3.5	4.0	6.7	8.0	10.5	12.0	15.7	19.7	22.7	27.6	39.0	47.4	59.5
Weft mesh/cm	1.6	2.3	2.5	3.5	4.0	6.7	8.0	10.5	12.0	15.7	19.7	22.7	27.6	39.8	47.4	59.5
Thread dia. (μm)																
Warp	1000	1000	1000	800	800	500	400	350	300	200	200	150	150	100	100	85
Weft	1000	1000	1000	800	800	500	400	350	300	200	200	150	150	100	100	85
Thickness of fabric (μm)	1800	1800	1800	1600	1600	920	765	700	610	350	420	275	320	230	230	220
Open area (%)	66.6	59.7	56.2	49.0	45.1	44.9	45.1	38.4	36.0	40.4	34.2	40.4	33.6	33.8	24.8	19.4
Weight (g/m²)	235	340	380	335	380	335	380	240	200	170	100	130	85	100	78	70
Permeability to air[b]	–	–	–	–	> 12 000	9700	8270	8875	8660	7565	7670	8100	6835	7090	5000	5120
Permeability to water[c]	–	–	–	–	–	–	–	–	–	–	–			–	–	–
Bursting pressure[d]	–	–	–	–	> 50.0	40.0	27.0	32.0	31.0	20.0	23.0	17.0	17.5	12.0	15.0	14.0

[a] Sefar.

[b] Air permeability, l/dm²/min @ 20 mm WG.

[c] Water permeability, l/dm²/min @ 500 mm WG.

[d] Bursting pressure, kg/cm².

Table 2.14 Examples of 'Fluortex' fluorocarbon precision monofilament textiles[a]

Reference no.[b]	PEK 2000	PEK 3000	PTFE 850	PEK 590	FEP 590	FEP 500	PEK 500	PEK 420	PEK 100	COP 210	COP 180	COP 150	COP 120	COP 105	COP 70	COP 52
Aperture (µm)	2000	1000	850	590	590	500	500	420	100	210	180	150	120	105	70	52
Warp meshes/cm	3.8	6.7	8.9	11.6	11.5	12.5	13.0	14.9	20.0	32.1	35.7	40.0	50.0	54.0	63.0	85.0
Weft mesh/cm	3.8	6.7	8.9	11.6	11.5	12.5	13.0	14.9	20.0	32.1	35.7	40.0	50.0	54.0	63.0	85.0
Thread dia. (µm):																
Warp	600	500	270	270	280	300	270	250	200	100	100	100	80	80	90	60
Weft	600	500	270	270	280	300	270	250	200	100	100	100	80	80	80	60
Thickness of fabric µm	1130	1000	505	465	555	570	500	450	365	200	200	200	170	175	190	125
Open area (%)	59.3	44.5	57.6	47.0	46.0	41.0	42.5	39.3	36.0	46.0	41.3	36.0	36.0	32.2	19.5	19.5
Weight (g/m²)	575	490	190	240	530	370	270	260	290	86	100	110	115	115	135	96
Permeability to air[c]	-	–	–	–	-	–	-	–	-	8400	7552	6720	5000	5520	1900	3150
Bursting pressure[d]	30.0	26.0	14.0	16.5	6.5	7.0	17.0	18.0	14.5	6.5	5.5	7.5	8.0	8.0	9.0	8.5

[a] Sefar.

[b] Reference Nos. identify the source of the PTFE/PEK = Hostaflon; FEP = Teflon; COP = Aflon. See Table 2.15 for their distinctive properties.

[c] Air permeability, l/dm²/min at 20 mmWG.

[d] Bursting pressure, kg/cm².

Table 2.15 **Properties of alternative PFTE polymers used in SST 'Fluortex' textiles**

Fibre (monofilament)	FEP (Teflon)	PFK (Hostaflon)	LX (ETFE) (Tefzel) (Luxel)	LX (E-CTFE) (Luxilar) (Halar)	COP (Aflon)	PVDF
Properties						
Specific gravity	2.12	1.75–1.77	1.70	1.69	1.73–1.76	1.78
Tensile strength (kg/mm^2) (dry)	11–23	35–60	45–60	45–60	40–47	40–45
Rel. tenacity (wet %)	100	100	100	100	100	100
Elongation at break (%) (dry)	20–70	20–45	25–45	25–45	25–35	30–60
Elongation at break (%) (wet)	20–70	20–45	25–45	25–45	25–35	30–60
Moisture absorption (%) at 65% rel. hum and 20°C (68°F)	0	0	0	0	0	0.04
Melting point (°C)	285	270	270	245	265–270	170–180
Softening point (°C)	275	265	260	235	260	155
Temperature resistance or approx. limiting temp. in dry condition (permanent temperature)	−190°C to +232°C short-termed to 260°C, permanent temperature to 205°C	−200°C to +150°C evt. to +180°C	−200°C to +155°C	−60°C to +150°C	180°C to +150°C	−50°C to +100°C
Resistance to light	Excellent	Excellent	Excellent	Excellent	Excellent	Very good
Abrasion resistance	Average to good	Average to good	Average to good	Average to good	Average to good	Average to good
Resistance and reactions to acids	Very resistant	Very resistant	Very resistant	Very resistant	Very resistant	Very good
Resistance to alkalis and reaction with caustics	Very resistant	Very resistant	Very resistant	Very resistant	Very resistant	Very good
Reaction to organic solvents (as used for instance for dry cleaning)	Insoluble	Insoluble	Insoluble	Insoluble	Insoluble	Partly resistant
Special feature	Anti-adhesive	Anti-adhesive	Anti-adhesive	Anti-adhesive	Anti-adhesive	Anti-adhesive

Table 2.16 Monofilament cloths for liquid filtration[a]

Fibre	Quality code	Weave	Weight (g/m^2)	Permeability to air[b]	Tensile strength[c]	
					Warp	Weft
PA	NX281-01	Satin	280	1900	100	160
PA	NX281-07	Satin	280	500	90	160
PA	NX281-21	Satin	280	400	90	160
PA	NX281-22	Satin	280	1600	90	160
PA	NX371-01	c/twill[d]	375	710	360	130
PA	NX371-07	c/twill	375	400	360	130
PA	NX371-21	c/twill	375	125	360	130
PA	NX381-07	c/twill	380	85	360	130
PE	AM441-01	Satin	440	1650	180	230
PE	AM441-07	Satin	440	400	180	230
PP	PX201-01	Twill	200	3000	280	90
PP	PX201-07	Twill	200	190	260	80
PP	PX291-01	Satin	295	1400	350	140
PP	PX291-07	Satin	295	550	350	140
PP	PX291-21	Satin	295	1650	350	140
PP	PX321-01	Satin	320	950	400	120
PP	PX331-07	Satin	335	120	340	120
PP	PX341-07	Satin	340	24	340	120
PP	PX351-07	c/twill	350	400	340	120
PP	PX351-21	c/twill	350	20	340	120
PP	PX361-07	Twill	365	1260	350	160

[a] Sefar.
[b] Air permeability, $l/dm^2/min$ @ 200 mmWG.
[c] Tensile strength, kgf/5 cm.
[d] c/twill=compound twill.

Table 2.17 P & S 'Filterlink' woven fabrics[a]

Specification weight (g/m^2)	Grade: SE0770 1350	SE780 11340	SE790 1650	SE795 1660	SE870 1120
Filament diameter, μm					
MD (i.e. warp)	0.60	0.70	0.6	0.7	0.58×0.88[b]
Cross (i.e. weft)	0.90	0.90	0.9+F[c]	0.9+F	0.9
Filaments per 10 cm					
MD	160	136	160	136	104
Cross	27	18	27	18	19
Material					
MD	PES	PES	PES	PES	PES
Cross	PES	PES	PES+F	PES+F	PES
Permeability to air[d]	>2350	>2350			

[a] Sefar.
[b] Air permeability, $l/dm^2/min$ @ 200 mmWG.
[c] F=polypropylene filler.
[d] Profiled filament.

As has already been mentioned, an additional filtration parameter exists for multifilament (as well as staple) yarn fabrics, in that there is now a choice of path of the fluid being filtered either between the yarns or through them, a division dependent both upon the tightness of the weave and upon the degree of twist of the yarns. The weight of multifilament fabrics can vary quite widely, from below 100 g/m^2 to more than 1000 g/m^2. Table 2.18 summarizes the characteristics of a typical range of multifilament filter fabrics. Most of those listed are intended for filtering liquids, with grades available in polyamide, polyester and polypropylene, and with the weaves variously plain, twill, or a variant of satin (reverse satin); the grades for gas filtration are all twill weaves, the yarns ranging from glass, to polyester and PTFE. An example of a multifilament plain weave is shown in Figure 2.3, while a twill weave fabric is shown in Figure 2.10.

Fabrics made from fibrillated yarns have only a limited use in filtration, mainly as support fabrics. Two such fabrics are described in Table 2.19. Nevertheless, yarns made from Gore-Tex expanded PTFE are particularly attractive, since they combine the exceptional chemical resistance of conventional PTFE, with significantly better mechanical properties in respect of tensile strength (2 to 3 times greater at all temperatures up to 300°C) and

Table 2.18 Multifilament cloths[a]

Fibre	Quality code	Weave	Weight (g/m^2)	Permeability to air[b]	Tensile strength[c]	
					Warp	Weft
Cloths for filtering liquids						
PE	AM992-81	Twill	1100	30	1100	400
PE	AM992-82	Twill	1100	15	1100	400
PP	PX312-32	Twill	310	95	280	120
PP	PX322-01	Plain	325	10	280	250
PP	PX412-70	Plain	410	3	500	120
PP	PX412-77	Plain	410	<3	450	120
PP	PX582-01	Twill	580	70	700	280
PP	PX592-07	Twill	590	6	700	280
PP	PX662-32	r/satin[d]	660	5	500	520
PP	PX662-33	r/satin	660	<3	500	520
PP	PX682-32	r/satin	680	10	500	520
PP	PX682-33	r/satin	680	<3	500	520
Cloths for filtering gas/dust						
Glass	GL299-00	Twill	290	250	130	150
Glass	GL469-00	Twill	460	235	280	75
Glass	GL749-00	Twill	745	230	400	180
PE	AM179-00	Twill	170	95	220	135
PTFE	TF299-00	Twill	290	140	75	60

[a] Madison Filtration Ltd.

[b] Air permeability, l/dm^2/min @ 20 mmWG.

[c] Tensile strength, daN/5 cm.

[d] r/satin=reversible satin.

abrasion resistance (8 times greater). The expanded PTFE yarns have a very low elongation at break, excellent creep characteristics, extremely low shrinkage characteristics, and better flex life. These yarns are available in 100, 200, 400, 1200, and 2400 denier, with the 400 denier yarn being that most commonly made up into a woven fabric. The extra strength of these materials enables the

Table 2.19 Woven cloths of fibrillated tape yarn for liquid filtration[a]

Fibre	Quality code	Weave	Weight (g/m²)	Permeability to air[b]	Tensile strength	
					Warp	Weft
PP	PX314	Mock leno	310	1575	300	200
PP	PX454	Mock leno	450	395	400	240

[a] Madison Filtration Ltd.

[b] Air permeability, l/dm²/min @ 20 mm WG.

[c] Tensile strength, daN/5 cm (10 Newtons = 1 daN = 0.981 kg. The P & S standard text uses daN).

Table 2.20 Woven cloths with mixed yarn[a]

Fibre	Quality code	Yarn type		Weave	Weight (g/m²)	Permeability to air[b]	Tensile strength[c]	
		Warp	Weft				Warp	Weft
PE	AM673-09	Multi	Staple	r/satin[d]	630	20	600	200
PE	AM673-10	Multi	Stable	r/satin	630	8	600	200
PP	PX235-01	Mono	Multi	Twill	235	800	280	150
PP	PX235-07	Mono	Multi	Twill	235	270	280	150
PP	PX235-21	Mono	Multi	Twill	235	80	280	150
PP	PX305-01	Mono	Multi	Tatin	300	500	350	120
PP	PX305-07	Mono	Multi	Satin	300	24	350	120
PP	PX345-07	Mono	Multi	Satin	340	24	350	180
PP	PX575-01	Mono	Multi	Satin	570	315	450	550
PP	PX575-08	Mono	Multi	Satin	570	11	450	550
PP	PX467-42	Multi	Staple	r/satin	460	95	500	120
PP	PX467-43	Multi	Staple	r/satin	460	10	500	120
PP	PX547-03	Multi	Staple	r/satin	545	11	500	220
PP	PX547-04	Multi	Staple	r/satin	545	<3	500	220
PP	PX587-09	Multi	Staple	r/satin	585	8	500	220
PP	PX587-10	Multi	Staple	r/satin	585	<3	500	220
PP	OX587-11	Multi	Staple	r/satin	585	<2	500	220
PP	PX617-09	Multi	Staple	r/satin	610	13	500	220
PP	PX617-10	Multi	Staple	r/satin	610	<3	500	220
PP	PX817-82	Multi	Staple	Twill	815	40	900	240
PP	PX817-83	Multi	Staple	Twill	815	<3	900	240
PP	PX858-82	Multi	Tape	Twill	850	40	900	540
PP	PX858-83	Multi	Tape	Twill	850	8	900	540
PP	PX858-86	Multi	Tape	Twill	850	40	900	540
PP	PX858-87	Multi	Tape	Twill	850	8	900	540

[a] Madison Filtration Ltd.

[b] Air permeability, l/dm²/min @ WG.

[c] Tensile strength, daN/5 cm.

[d] r/satin = reversible satin.

use of a much lighter woven scrim for non-woven media (for example, 135 g/m^2 instead of 304 g/m^2).

The use of mixed yarns (a different type of yarn for warp and weft) can give considerable benefit to a filter fabric, by comparison with a single yarn material. Surface smoothness, and with it cake discharge, fabric strength, durability and filtration efficiency can all be improved by the use of mixed yarns, as compared with a single yarn. Some examples of mixed yarn woven fabrics are given in Table 2.20, showing a wide range of permeabilities.

The coated fabrics exemplified by Madison's Primapor and Azurtex materials are used for the fine filtration of liquid slurries containing titanium dioxide, china clay and dyestuffs. They are available in maximum widths up to 1.65 m, and in nominal weights between 620 and 750 g/m^2. The average pore sizes are 2.5 and 4 μm for the two grades of Primapor and 6 μm for both grades of Azurtex, while the corresponding values of liquid permeability for Primapor are 40 and 80 l/m^2/min and 110 l/m^2/min for Azurtex (all measured at 20 kPa Hg).

Finally, among the types of woven fabric are those made by multi-layer weaving. A range of these is illustrated in Table 2.21, covering a standard range of vacuum filter belts. Table 2.21 shows mostly polypropylene belts (with nominal pore sizes of 12–160 μm), with two examples in fluorocarbon (20 and 40 μm).

2.3.3 Special-purpose fabrics

There are two types of filter fabric, intended for special-purpose filtration, that have appeared in several new forms since the first edition of this Handbook was written. These cover anti-electrostatic media and combination media.

Table 2.21 Double layer weave fabrics for vacuum filter belts[a]

Belt style[b]	Pore size (μ)	Maximum temperature (°C)	Filtrate permeability			Belt stability	
			Very high	High	Normal	High[c]	Normal
PP-12/MM/DLW/C	12	90			x		x
PP-20/MM/DLW/C[d]	20	90			x		x
PP-21/MM/DLW/C	20	90			x	x	
PP-30/DLW/C	30	90			x		x
PP-41/MM/DLW/C	40	90			x	x	
PP-50/DLW/C[d]	50	90			x		x
PP-81/DLW/C	80	90			x	x	
PP-85/DLW/C	85	90		x			x
PP-120/DLW	120	90	x				x
PP-161/DLW	160	90	x			x	
FK46-20/MM/DLW/C	20	120			x		x
FK6-40/DLW/C	40	120		x			x

[a] Sefar.

[b] PP=polypropylene; FK=fluorocarbon.

[c] Excellent mechanical properties, suitable for filters with press belt device.

[d] Available as permanent antistatic version for application in hazardous locations.

Of growing importance in industrial applications are the combination filters, mainly for air cleaning, that undertake two duties at once: the removal of solid particles (or liquid droplets), and the removal of odours or other gaseous impurities. This can be done by the complete carbonization of the material, to give an activated carbon surface to the entire medium, or the inclusion within the medium of particles of activated carbon. domnick hunter[5] supplies compressed air filters using ACC (activated charcoal cloth), which has been made by the carbonizing of polyester or polypropylene fabrics. Such material usually needs supporting on a lightweight carrier, such as a spun bonded polymer. The lack of robustness is more than made up for by the very high adsorptive capacity and the low pressure drop of these materials.

Such included particles can also be of other chemicals, such as potassium permanganate and catalysts. As particle inclusion is more easily done in non-woven matrices, such uses are discussed in Chapter 3.

The use of materials that are intrinsically charged electrostatically to aid in filtration, mainly of dusts from air, has been known for a long time. Of much more recent development are those materials intended to conduct away any charge that might build up on the medium, and any trapped cake, so minimizing the hazard from the explosion of dry dusts or flammable solvents. Typical of these media are those made by Arville Textiles (and sold as filter media components by the Multiple Fabric Company), which incorporate fine steel or carbon threads in the weave, or use carbon fibres within the yarns.

2.4 Knitted Fabrics

Knitted fabrics are constructed by the interlocking of a series of loops made from one or more yarns, with each row of loops caught into the preceding row. Starting with the frame knitting machine, which first allowed production of a complete row of loops at one time, the modern knitting industry has grown into one with highly sophisticated machinery. Knitted fabrics can be made flat or cylindrical (as well as fully fashioned, for the garment industry).

From the point of view of filtration, knitted fabrics are a lot more open than are woven fabrics. Accordingly they are rarely used as a medium in a single layer, but rather as a packed bed of many layers, in which format they work well as demisters and coalescers.

Knitted fabrics can be made from yarns of quite wide variety, but for industrial use they normally employ single filaments as the yarn. By far the greatest proportion of knitted fabric is made from single wire or single polymeric filament, and, as such, is covered later in this Handbook (in Chapter 5 to some extent, and in Chapter 6 in more detail).

2.5 Selection of Woven Fabrics

The selection of any filter medium is dictated by the wish to achieve the optimum combination that it offers of all of the factors listed in Chapter 1: machine related,

Table 2.22 Relative cost of construction details of woven textiles[a]

	Maximum ←		← Proportion of cost →			→ Minimum
	Fibre[b] Material	Type of fibre	No. of threads	No. of twists	Yarn diameter[c] (mm)	Weave[d]
↑ Cost increases	Fluorocarbon	Monofilament	High	High	High	Satin
	Aramid	Multifilament	Medium	Medium	Medium	Twill
	large difference in cost	Staple	Low	Low	Low	Plain
	Wool					
	Polyamide					
	Acrylic					
	Modacrylic					
	Polyester					
	Cotton					
	Rayon					
	Saran					
	Acetate					
	Polypropylene					
	Vinyon					
	Glass					

[a] Based on comments by Madison Filtration Ltd on Sperry Ehler's original table.

[b] There is a vast difference between the top two and the others. It is only in deciding whether to use flurocarbon or aramid that the relative fibre costs become a consideration. Note also that the order ignores the influence of quality; thus, a low quality wool would appear much lower on the table.

[c] The relative cost order for yarn diameters is correct for monofilaments and multifilaments, but should be reversed for staple yarns.

[d] The choice of weave order has negligible effect upon the total cost.

application related and filtration specific. In addition to all of these, there is the question of cost. Another table originally published by Ehlers(11) sought to provide an overview of the relative impact of its constructional variables on the total cost of a woven fabric. This table was revised by one of the present authors(3), and is reproduced here as Table 2.22, still largely relevant after 20 years.

Ehlers's earlier tables (Tables 2.7–2.9) form a sound basis from which to choose a woven fabric. Perhaps the key features are the regular structure and the relative strength of woven fabrics by comparison, say, with many non-wovens. This is particularly the case where the medium is subject to variable mechanical strains during use – such as in a tower press, or in Heinkel's inverting basket centrifuge. Typical of the special needs of tower presses is the Albany International Primaflo series of belts, made from polyester or polypropylene, with weave patterns specially developed to maximize strength and structural integrity, giving lifetimes approaching 10 000 cycles.

A major set of data on fabric choice is included at the end of Chapter 3, offering application guidance for both woven and non-woven fabrics in a variety of applications.

2.6 References

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CHAPTER 3

Non-woven Fabric Media

Whilst in the total world of textile fabrics, woven materials are dominant, by comparison with other forms of textile, the reverse is true in filtration media fabrics, with non-wovens taking an ever increasing share of the fabric component of the filter media market. One reason for this is the continuing demand for finer filtration, of both liquids and gases, which can be met by very finely spun fibres, assembled into ever more complex forms of non-woven materials.

3.1 Introduction

In the form of woollen felts, non-wovens can claim to be the oldest form of textile fabric, and for many centuries represented the only alternative process to weaving, by the combined action of moisture and heat on carded wool fibres. This simple scenario has been radically changed during the last half-century by the development of a continually expanding variety of manufacturing techniques and novel products, based on a similarly continually expanding array of raw materials.

The first significant step recorded in this development process was the production of a few thousand metres of adhesive-bonded fibre webs in the USA in 1942(1), for which the term 'non-woven fabric' was coined. Subsequent years have seen the invention of various other adhesive techniques, including adhesive dispersions, the wet and dry laying of webs, and the integral bonding of thermoplastic fibres. Alternative processes have included mechanical bonding, based on needling or stitch knitting, with or without the use of binding threads. To these became added the increasingly important ability to laminate two or more fabrics together, or to apply a coating to a non-woven product, so as to form a composite fabric.

As these techniques and processes were evolving during the 1960s, there was a considerable amount of international debate over describing them all as 'non-woven fabrics'. In fact, in his book *Manual of Nonwovens*(1), Professor Krcma devoted more than two pages of text to this topic, in addition to a list of 24 literature citations – one of which has the stark heading: 'Wanted: a new name for nonwovens'[2]. The point of dispute was the linguistic contradiction inherent in this combination of words, which evidently caused grammatical problems in literal translations into some other languages. Despite these semantic niceties, common usage has long since resulted in the acceptance of this terminology.

Krcma's own definition of the term is all-embracing: 'non-woven fabrics are textile fabrics made of a fibrous layer, which may be a carded web, a fibre web, or any system of randomly laid or orientated fibres or threads, possibly combined with textile or non-textile materials such as conventional [woven] fabrics, plastic films, foam layers, metal foils, etc., and forming with them a mechanically bound or chemically bonded textile product.'

That definition includes paper as a non-woven fabric, which is a usage foreign to the filtration application. Paper is, of course, frequently made, or at least dried on a non-woven belt, but it is covered separately in this Handbook (Chapter 4), because the fibres, made from wood cellulose, are much shorter than the natural or synthetic fibres actually used to make non-woven fabrics. Whilst paper is essentially a wet-laid product, the great majority of non-woven fabrics are dry-laid.

A non-woven fabric, then, is one that is made up from an agglomeration of fibres, and sometimes of continuous filaments, which are held together by some form of bonding, to create a more or less flexible sheet of fabric. This will be as wide as the bed upon which the non-woven material is laid down, and as long as the receiving rolls can accept. In their bulk, as-made, format non-wovens are sometimes referred to as 'roll goods' (as are woven fabrics as they leave the loom), as opposed to piece goods, which might refer to the individual pieces of filter media cut from the roll, prior to their being fitted into or onto a filter.

The chemical properties of a non-woven fabric are dictated almost entirely by the nature of the basic fibre – unless there is a binding adhesive of significantly different properties (such as melting or softening temperature). Accordingly, the chemical properties of non-wovens can be obtained from the same tables of such properties that were given at the start of Chapter 2 for woven fabrics.

3.2 Types of Non-woven Fabric

There is a steadily increasing range of non-woven fabrics, as manufacturers develop new processes for their production. Nevertheless, it is possible to define two broad classifications of such materials, into which almost all non-woven fabrics will fall, and which can then be used as headings for subsequent description. These two classes are, to a large extent, divided by the means utilized to hold the loose fibres together:

- felts, which use the basic characteristics of the fibre to provide mechanical integrity, or which use mechanical processing to create a fabric; and
- bonded fabrics, which use some additional adhesive material to hold the fibres together, or, more commonly, rely upon the thermoplastic nature of the polymer to provide adhesion.

This second group is then further divided in two, according to whether the basic formation of the basic fibre is an integral part of the manufacture of the medium (the dry-laid spun media) or not (resin and thermal bonding).

It should be realized that non-woven fabrics are used in many other fields of industry and commerce besides filtration, and that they are therefore a very important part of the industrial scene. Two major (and related) societies, INDA[3] and EDANA[4], exist to support the non-wovens industry, including the organization of conferences devoted to the use of non-wovens in filtration – annually in the USA, and every third year in Europe.

In its brochure for its 'Index '99' exhibition, EDANA stated that: 'Non-wovens represent 90% of all filter media used in dry and liquid filtration.' Even if paper media are included in the total, this is a high figure, but nevertheless it does indicate the importance of non-wovens to the filter media marketplace.

3.3 Felts

Some fibres, wool especially, have the ability to cling together to form a coherent mass. Most others can be made to adhere by suitable processing. The first step in any felt making process is the unloading of the bulk fibre into a carding machine, where the fibres are drawn out into a thin web, which has its fibre content roughly aligned in one direction. Pieces of such web can then be placed one above the other to provide a felt of the required thickness. The successive layers can all be aligned with the fibres all lying in the same direction, or in different directions to give equal directional strengths. When sufficient thickness has been achieved, the felt is compressed and heated, often after dampening, to produce its final structure.

The distinctive characteristic of felt is that it comprises a mass of individual fibres, which are compacted and locked together to form a cohesive structure. Early civilizations learnt how to felt wool by means of heat and moisture, so as to produce cohesion through the localized breakdown of the complex structure of these natural fibres. Although this process is not applicable to the wide variety of modern synthetic fibres and filaments, they can nonetheless be felted, either by bonding with an adhesive (as discussed in Section 3.4), or by a mechanical entanglement process known as needle punching.

3.3.1 Needlefelts

For some, undemanding, applications, a simple felt can provide suitable performance, without any form of strengthening. However, their low tensile strengths, and the ease with which fibres can become detached from the felt and enter a downstream flow, make simple felts unattractive for most filtration purposes, and some mechanical (or chemical) strengthening is required.

Needle punching is by no means a new technique, since it originated in the 1880s with natural fibres, but it is only since about the early 1970s that it has come into prominence because of its applicability to many synthetic fibres. The first step is to assemble several layers of carded fibre into a 'lofty' (i.e. bulky) web or 'batt'; this is then compressed into a denser structure by needle punching with a mass of special barbed needles reciprocating at speeds up to 2000 strokes/ minute, as illustrated in Figure 3.1.

With perhaps 100 or more needle penetrations per square centimetre, the effect is to entangle the fibres and to reduce the thickness of the web substantially, to a degree that is controlled as desired. Punching may be on both sides of the web instead of just the one, as in Figure 3.1; this improves the uniformity of the felt.

Before needling, the web of loose fibres is prepared with great care, using the traditional carding methods of the textile industry: several layers of carded fibre are stacked on top of one another, according to the desired thickness and density of the final needlefelt. Carding aligns the fibres along the length of the machine, so that a stack of layers in parallel produces a felt that is far stronger in the machine direction then transversely. Cross laying of alternate layers can eliminate this directional difference, or even reverse it, depending on the angle between consecutive layers.

Most felts are mechanically strengthened by needling, but an alternative, and more specialized, technique employs a set of high-pressure water jets to fix the fibres in place – a technique known as hydroentanglement.

3.3.1.1 Needlefelt properties

The relatively low tensile strength of a plain felt is significantly improved by needling. Even greater strength can be achieved by forming the needlefelt around an inner scrim, which is a single layer of very open woven mesh, as in Figure 3.2. The scrim layer is placed within the pile of individual webs that make up the felt; some felts are asymmetric in structure, with the scrim located accordingly for optimum abrasion resistance. Formation around a scrim is the more common structure of needlefelts for filtration, although scrimless felts are also sometimes used. A scrimmed needlefelt is essential in the case, say, of filter bags that are cleaned by a reverse jet of air, to expand the bag. The frequent and regular expansions and contractions would be more than a plain needlefelt could tolerate.

The shape of the cross-section of the fibre is a significant factor in determining the strength of a needlefelt. This has accordingly received considerable attention from manufacturers seeking to meet the demanding conditions imposed on their

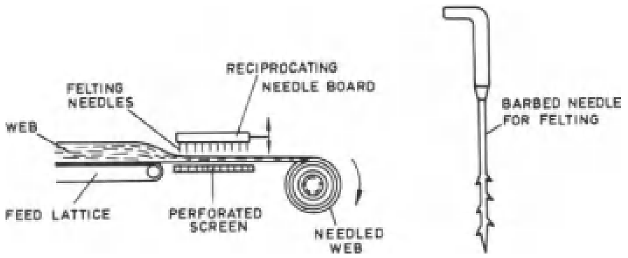


Figure 3.1. Principles of the needle felting process using barbed needles.

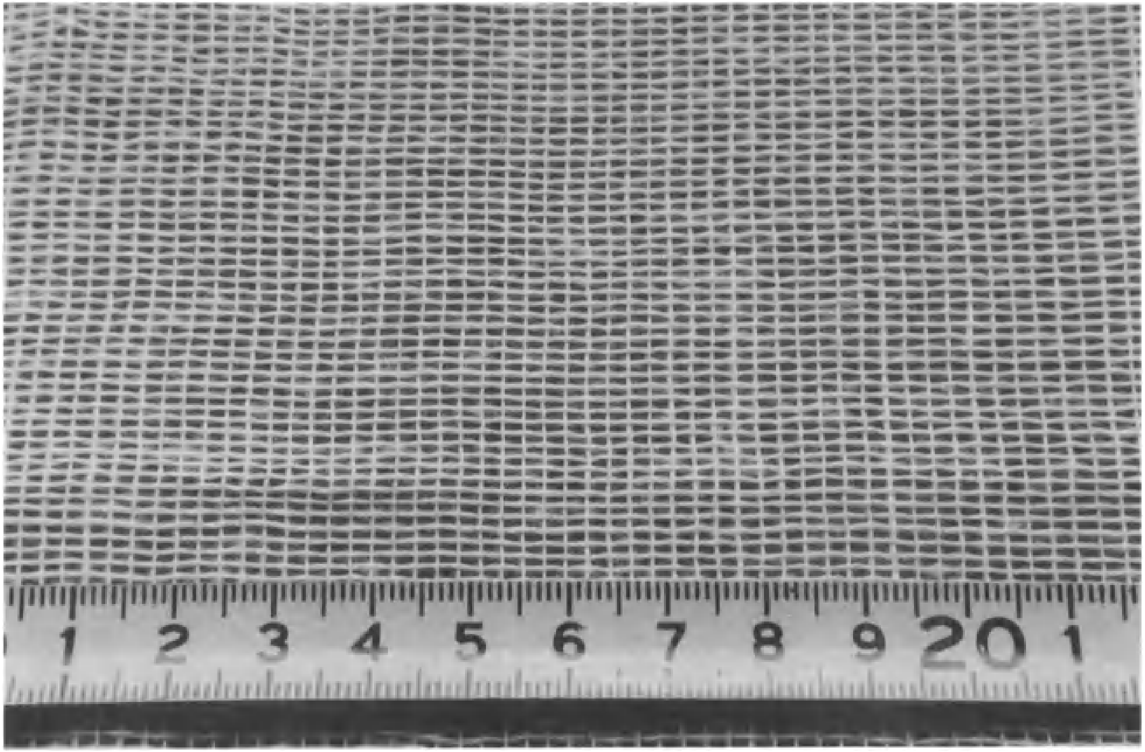


Figure 3.2. A typical scrim around which a felt is formed by needle punching.

products in applications varying from carpets to clothing. with filtration by comparison generally providing a relatively small-scale market. Figure 3.3 shows the highly profiled form of Lenzing's P84 fibres, while various fibre shapes are illustrated in Figure 2.5 of Chapter 2.

The fineness of the fibres in a needlefelt has a significant impact on filtration efficiency, notably in respect of the concentration of particles in the exhaust from bag house fabric filters. A paper by Dilger(5) summarizes the results of a development programme by Du Pont utilizing fine fibres of both Nomex and Teflon. The emission level of a 520 g/m^2 needlefelt of standard 2.2 dtex Nomex fibres was 1.19 g/m^3 higher than that of a 500 g/m^2 felt of 1.1 dtex fibres.

In many ways, needlefelts would appear to be ideal for filtration, combining the possibility of greater flexibility and versatility in construction, including the ability to produce asymmetric forms, by exploiting variations of fibre diameter and shape, plus the final felt density. Thereby it should be possible to achieve a far more uniformly open surface and controlled in-depth structure than with woven fabrics. On both of these counts, however, the reality falls short of the ideal, but still provides a rich source of media of great industrial value, especially in dry filtration for the collection of dusts.

The possibility of optimizing construction of a needlefelt to suit a particular application is, in practice, limited by the practical realities of the textile industry, with its commitments to fields other than filtration. Two factors must be borne in mind: first, felt manufacturers are generally dependent on outside suppliers for the fibres they require, and can only buy grades that the suppliers find it economic to produce on the large scale implicit in their own manufacturing processes; secondly, felting itself is also essentially a large-scale operation, and is therefore inevitably geared to large markets.

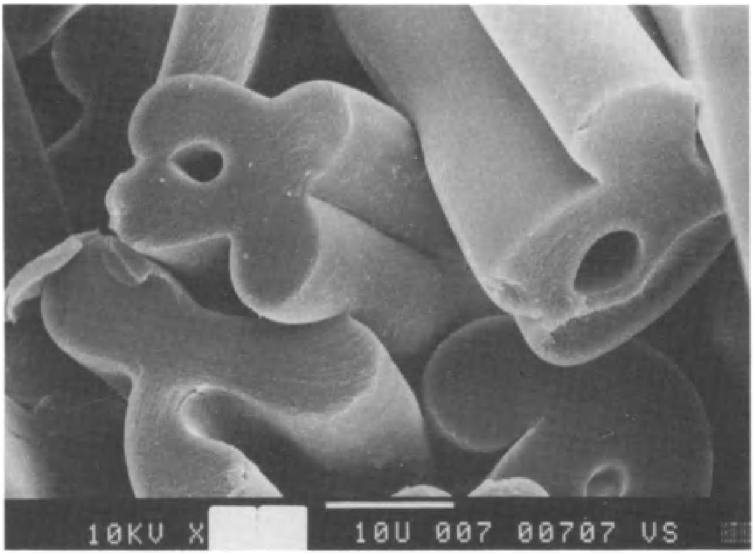


Figure 3.3. Microphotograph showing the cross section of Lenzing's P84 fibres.

As for the uniformity of the surface and control of the in-depth structure of a needlefelt, close inspection under magnification reveals something of the underlying technical difficulties. Figure 3.4 is a microphotograph of a section cut through a felt that has been needle punched on both sides. In Figure 3.4 the points of penetration by the needles are clearly visible, revealing the orientation of fibres imposed at a point of penetration: it also shows the yarns of the scrim along the centre line of the sample. It is very possible that the needle holes may be significantly larger than the pores in the rest of the structure.

For much of the last 30 years, needlefelts have been the dominant material for filter media, especially for gas cleaning. However, they are now steadily being replaced by the thermally bonded spun polymeric media, discussed in Section 3.5, which are capable of much finer degrees of filtration.

Initial enthusiasm for the seemingly endless potential of these then new types of filter media in the early 1970s stimulated Wrotnowski^(6) to propose a theoretical model to relate the pore size of a needlefelt to the diameter of the fibres and the density of the felt. For a time, this relationship was used as a guide to the ranges of needlefelt available – as shown for polyester and polypropylene needlefelts in Table 3.1, but subsequent experience and material development led to its being largely discarded in favour of the empirical summary of the available fabrics, as discussed later.

3.3.1.2 Surface coatings

The finishing processes applied to needlefelts are much the same as for woven fabrics, as discussed in Section 2.3.1.2. These include calendering and singeing, the latter being illustrated in Figure 3.5, as techniques to modify the surface finish, rather than adjusting pore size.

The coating of needlefelt fabric surfaces is a little more complex, and sometimes it is difficult to draw the line between coated fabrics and the bonded media discussed in Section 3.4, or between coated fabrics and the membranes

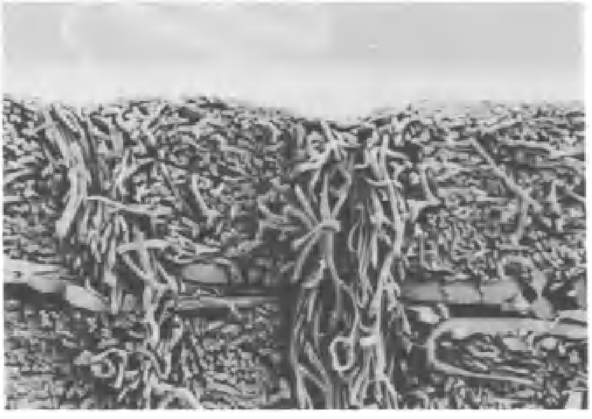


Figure 3.4. Cross section through a needle felt, showing the scrim and also the fibre re-orientation caused by the needling, at ×62 magnification.

made using felts as substrates and discussed in Chapter 8. Coatings can be employed to change the porosity of the surface of the felt, and/or to protect the materials of the fibres from heat or the corrosive effects of gases (or, to a lesser extent, of liquids), or to protect against abrasion. Another major use is to increase the ability of the mesh to release a cake of collected solids, whether this be hygroscopic or oily.

Simple surface coatings include the Ravlex material described in Chapter 2, and illustrated in Figure 3.6, and the Madison 'Primapor' and 'Azurtex' materials also described earlier.

Webron, for example, supplies its Microweb 2000 and Microweb II media as PTFE and acrylic coatings, respectively, on a polyester needlefelt (at 2.1 m wide), with relatively high permeabilities. The company also supplies Supaweb chemical treatments, which can be applied to felts of most synthetic materials, and which are thermally bonded to the basic material. Each treatment conveys a particular additional property upon the felt:

- Supaweb DR improves cake release behaviour;
- Supaweb WR repels water and improves release of hygroscopic dusts;

Table 3.1 Theoretical variation of pore size of needle felt with fibre diameter and felt density

Felt density (g/cm^3)	Polyester			Polypropylene			
	Fibre diameter (μ)			Fibre diameter (μ)			
	12	18	25	15	21	30	48
0.01	41	64	91	42	60	77	134
0.12	36	57	81	37	53	69	118
0.14	33	51	73	33	47	61	106
0.16	30	48	66	30	43	55	96
0.18	27	43	61	28	39	51	88
0.20	25	40	57	25	36	47	81
0.22	24	38	53	24	33	43	75
0.24	23	35	50	22	31	40	69
0.26	21	33	47	21	29	37	65
0.28	20	31	44	19	27	35	61
0.30	19	29	42	18	26	33	57
0.32	18	28	40	17	24	31	54
0·34	17	27	38	16	23	29	51
0.36	16	26	36	15	21	28	48
0.38	16	24	35	14	20	26	46
0.40	15	23	33	13	19	25	43
0.42	14	22	32	13	18	24	41
0.44	14	21	30	12	17	22	39
0.46	13	21	29	12	16	21	37
0.48	13	20	28	11	16	20	35
0.50	12	19	27	11	15	19	33
0.52	12	18	26	10	14	18	32
0.54	11	18	25	10	14	17	30
0.56	11	17	24	9	13	17	29
0.58	10	16	23	9	12	16	28
0.60	10	16	23	8	12	15	26

- Supaweb OR aids release of oily cakes;
- Supaweb CR greatly improves resistance to chemical attack;
- Supaweb FR resists the effects of incandescent particle carry over.

The corresponding treatment processes employed by Fratelli Testori, a long-established maker of filtration fabrics, include:

- Novates, a coating of polyurethane on polyester or acrylic felts, which is hydrophobic and oleophobic; it resembles a membrane, although the finished pore size is only stated as 'below 15 µm';
- Mantes, a chemical treatment of the felt with a resin containing PTFE, for application to acrylics, and high-temperature fibres such as aramid, polyimide and sulfar (PPS), giving good chemical resistance;
- Kleentes, which involves steeping the fabric in a chemical solution containing PTFE and fluoride resins at high concentrations, following which the fabric is dried and heated to fix the fluorides on the fibres; used

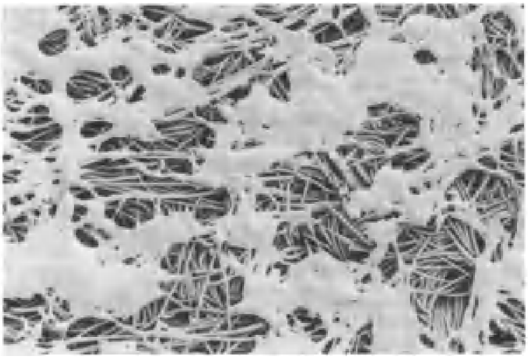


Figure 3.5. The surface of a heavily singed needle felt.

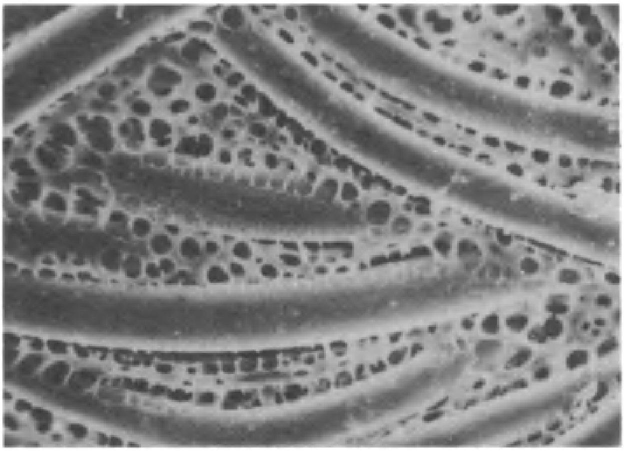


Figure 3.6. 'Ravlex' coating on spunbonded polypropylene needle felt.

on polyester or acrylic fibres to give good cake release and protect from chemical activity;

- Rhytes, which is made in a similar fashion to Kleentes but is applied to higher temperature fibres, to improve the high-temperature performance, and reduce chemical attack.

Madison has also developed an abrasion-resistant coating in its Tuf-tex coatings for polypropylene, nylon and PET substrates (woven as well as non-woven). These are thermosetting resins sprayed or knifed onto the surface, giving not only abrasion resistance, but also improved dimensional stability.

3.3.1.3 *Needlefelt fabrics*

The type and range of needlefelt fabrics available are well illustrated by the data of Table 3.2. This shows the main products of Andrew Textile, a long-established needlefelt maker (and sister comapny of Webron Products), in the company's standard range, for four different fibres: polyester, polypropylene, homopolymer acrylic, and copolymer acrylic. A similar table, Table 3.3, shows the corresponding data for a range of bigher temperature polymers: aramid, PPS, PTFE and polyimide. These materials have porosities between 72 and 87%, and

Table 3.2 Standard needlefelts[a]

Product	Weight (g/m^2)	Thickness[b] (mm)	Density (g/cm^3)	Air permeability[c]	Breaking strength[d]	Elongation[e] (%)	Lineal (%)	Shrinkage[f], C
Polyester								
T350TFS	350	1.35	0.26	350	1000	3	3	170
T400TFS	400	1.40	0.27	260	1100	3	3	170
T450TFS	450	1.45	0.31	220	1200	3	3	170
T500TFS	500	1.75	0.29	190	1200	3	3	170
T550TFS	550	1.80	0.31	165	1300	3	3	170
T640TFS	640	2.15	0.30	140	1300	3	3	170
Polypropylene								
P400PFS	400	2.00	0.20	225	450	4	3	100
P450PFS	450	2.20	0.20	170	500	4	3	100
P500PFS	500	2.30	0.22	150	500	4	3	100
P550PFS	550	2.75	0.20	130	550	4	3	100
Acrylic HP								
H400HSS	400	1.78	0.22	260	500	4	3	150
H500HSS	500	2.15	0.23	200	600	4	3	150
H550HSS	550	2.33	0.24	165	650	4	3	150
Acrylic CP								
C500HSS	500	2.10	0.24	600	600	4	3	140

[a] Andrew Textile Industries Ltd.

[b] Thickness at 2.2 kPa.

[c] Air permeability, $dm^3/dm^2/min$ @ 20 mm WG.

[d] Minimum breaking strength, N/5 cm.

[e] Maximum elongation @ 50N/5 cm.

[f] Maximum lineal shrinkage after 24 h exposure to dry heat.

Table 3.3 High-temperature needlefelts[a]

Product	Weight (g/m^{2})	Thickness[b] (mm)	Density (g/cm^{3})	Air permeability[c]	Breaking strength[d]	Elongation[e] (%)	Lineal (%)	Shrinkage[f], C
Aramid								
X407XSS	400	2.00	0.20	265	500	3	3	240
X489XSS	480	2.30	0.21	200	650	3	3	240
X500XSS	500	2.10	0.24	180	650	3	3	240
X550XSS	550	2.30	0.24	165	700	3	3	240
X559XSS	550	2.40	0.23	175	750	3	3	240
X509XSS	500	2.30	0.22	200	650	3	3	240
PPS								
R552RSH	550	1.85	0.30	225	500	3	2	200
R500RSH	500	1.60	0.31	230	600	3	2	200
PTFE								
F702FFH	700	0.96	0.73	145	500	6	3	250
F750FFH	750	1.00	0.75	115	600	6	3	250
F840FFH	840	1.05	0.80	90	600	6	3	250
G800FFH	800	1.40	0.57	110	650	6	3	250
F700FFH	700	1.05	0.67	135	600	6	3	250
Polyimide								
I550ISS	550	2.65	0.21	170	600	4	3	250

[a] Andrew Textile Industries Ltd.

[b] Thickness at 2.2 kPa.

[c] Air permeability, dm^{3}/dm^{2}/min @ 20 mm WG.

[d] Minimum breaking strength, N/5 cm.

[e] Maximum elongation @ 50N/5 cm.

pore sizes between 35 and 66 μm. The tensile strengths range from 40 to 100 kgf/5 cm strip.

Two significant recent introductions by Andrew Textile concern scrims and microfibres. The use of a scrim in needlefelt has been traditional in Europe, but it has been less common in the USA. Andrew introduced its Fibre-Locked felts to Europe, to overcome the problems of the weakening of a scrim in the needling process. This material has lower tensile strengths than those of scrim supported felts, but the general filtration performance is better.

Consequent upon the availability of finer, so-called 'microdenier' fibres, Andrew has also introduced its Micro-felt, made 100% from fibres of less than 10 μm in effective diameter. This material is able to achieve much finer degrees of filtration, with mean pore sizes of 12 to 25 μm (from fibres of 0.5 to 2.25 denier).

Figure 3.7 shows an interesting variant of the flat sheet form in which needlefelts are generally produced, this being Webron's Circron circular seamless tubes or sleeves. They are produced by continuously winding and needling a web of fibres around a rotating mandrel, so as to apply a number of layers to build up the required final thickness; the tube thus formed is drawn continuously off one end of the mandrel, so that the length is virtually unlimited. Circron tubes of various fibres are available with inside diameters from 68 to 350 mm, wall thicknesses from 8 to 18 mm, and in materials including

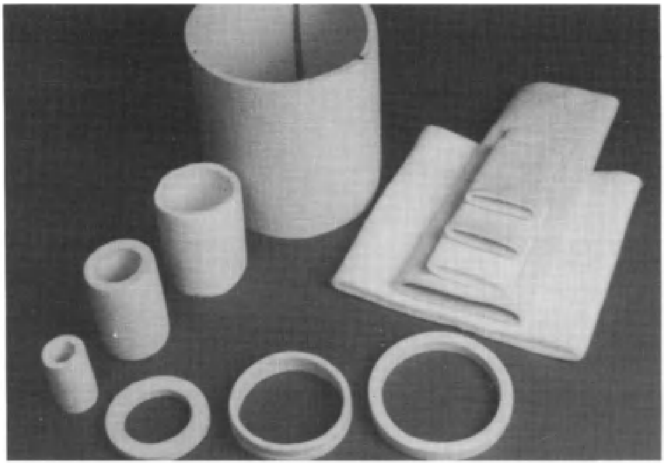


Figure 3.7. 'Circron' seamless needle felt tubes.

polypropylene, polyester, acrylic, aramid and PPS; porosities are 65–90%, with pore sizes up to 400 µm.

3.3.2 Electrostatic effects

The filtration of solids from fluids can create electrostatic effects, or can benefit from the existence of electrostatic charges on the filtration media. Especially in the case of the filtration of dusts, the presence or absence of such charges can make a great difference to the filtration performance.

3.3.2.1 Electrically charged non-wovens

Many particles in fluid suspension carry a small electric charge, and so will be more effectively removed from suspension if the filter medium carries an opposite charge. This effect is utilized in the media known as 'electrets', and the phenomenon of 'zeta potential'. The effects are covered in detail in Chapters 4 and 5.

3.3.2.2 Anti-static media

A well-known problem in applying needlefelts to dust filtration is the hazard that can arise from the build-up of electrostatic charges on the filter surface. To guard against this, the system must be well earthed, which is only possible if the fabric of the filter bags has a sufficiently high electrical conductivity. By contrast with this requirement, the synthetic polymers from which needlefelts are made have a high electrical resistance, and are therefore very susceptible to becoming highly charged with static electricity.

The solution to this difficulty is to increase the conductivity of the fabric, either by chemical treatment, so that the polymeric fibres become coated with metal salts, or by incorporating into its structure a small quantity of other fibres that are themselves highly conductive. It is worth emphasizing the importance of ensuring that, in use, filter bags of anti-static cloth are properly earthed: if they are not earthed, they will actually increase the static hazard since their much higher capacitance will enable correspondingly high static charges to accumulate.

Chemical treatment has the disadvantage that it is not durable, since the coating is likely to abrade and disintegrate in use, especially if filter bags are occasionally laundered. By contrast, the inclusion of conductive fibres provides permanent protection. Examples of conductive fibres are DuPont's Epitropic and Bekaert's Bekinox. The latter are of a special grade of stainless steel that is of extremely high purity, so as to avoid the risk of inclusions within the very fine 6.5, 8, 12 or 22 μm diameter fibres.

Epitropic fibres are primarily polyester, with an outer sheath of polyester isophthalate copolymer, which is impregnated with particles of carbon black, as illustrated in Figure 3.8. The sheath has a melting point 35°C lower than the core; it can be softened by controlled heating so that the carbon particles become embedded in it, to be an integral part of the fibre surface. The electrical conductivity of these fibres is 50 times higher than that of stainless steel; this, combined with their significantly lower density, is claimed to give them a significant cost advantage for lower temperature applications suited to polyester.

An alternative approach is to make the scrim conductive as well as having stainless steel fibres among those of the felt. This feature is exemplified by Andrew Textile's conductive felts, listed in Table 3.4.

3.4 Bonded Media

The fibres in felted media or needlefelts are held together by the natural interlocking of the staple fibre, or by the additional entangling of needling or hydroentanglement, coupled with a small effect of temperature at the points of contact of the fibres. Another group of non-woven materials achieve their

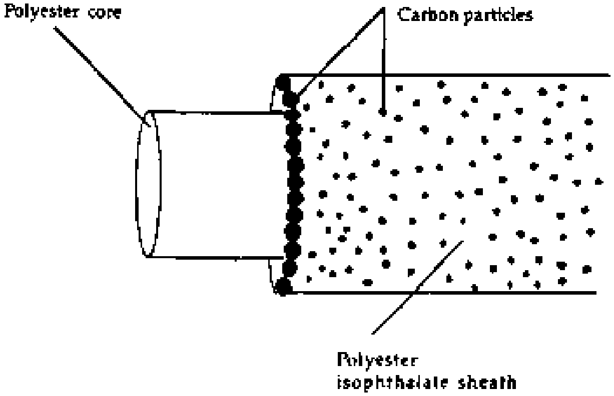


Figure 3.8. The structure of 'Epitropic' fibres.

Table 3.4 Anti-static needlefelts[a]

Product	Weight (g/m²)	Thickness[b] (mm)	Air permeability[c]	Breaking strength[d]	Elongation[e] (%)	Lineal (%)	Shrinkage[f], °C
Conductive							
XS550XKS	550	2.40	150	750	3	3	230
TS500TKS	500	1.55	180	1100	2	3	170
TS550TKS	550	1.70	160	1100	2	3	170
TE500TFS	500	1.65	175	1100	2	3	170
TE640TFS	640	1.90	125	1250	2	3	170
HS500HKS	500	2.30	250	650	5	3	140
PS502PKS	500	2.60	210	1000	2	2	100

[a] Andrew Textile Industries Ltd.

[b] Thickness at 2.2 kPa.

[c] Air permeability, dm³/dm²/min @ 20 mm WG.

[d] Minimum breaking strength, N/5 cm.

[e] Maximum elongation @ 50N/5 cm.

[f] Maximum lineal shrinkage after 24 h exposure to dry heat.

cohesion by a specific bonding process of the fibres in the felt, either by means of the addition of a separate bonding agent, or by localized melting of thermoplastic fibres at the points of contact.

3.4.1 Resin-bonded media

Historically the first of the bonded materials to come into use, the *chemically* or *resin-bonded* materials employ an adhesive resin of some kind, impregnated throughout the bulk of the felt, to provide the required degree of cohesion to the fibres. The web of fibres, staple or artificial, would be formed in exactly the same way as felts, by carding and layering, and then a quantity of resin, usually in liquid form, would be sprayed or otherwise distributed throughout the fibre mat, followed by some kind of curing process, to set the resin to achieve both the required level of permeability and also of material strength.

By far the greater amount of bonded material is made by *dry laying*, but there are some specialized media made by *wet laying*. Wet-laid media are produced by the ancient art of papermaking: short staple fibres, whether natural or synthetic, are dispersed in water to produce a slurry; this slurry is then fed continuously onto a moving screen or array of wires, and the slurry dewaters by gravity drainage, sometimes assisted by pressure or vacuum. The resultant web of uniform, but randomly orientated, fibres is then dried over a series of heated rollers. An adhesive or binding agent can be incorporated in the original slurry, or sprayed on the web after its formation: the drying process will then set the binding agent as required. Almost all wet-laid media are made from wood cellulose or glass fibre, and are used as filter papers or related formats – which are discussed in detail in Chapter 4.

Dry-laid media are so called because the first step in their manufacture is the formation of a web of short fibres, directly from the raw fibre material, by means of the conventional bundle opening and carding methods and machines of the textile industry. Multiple layers or sandwiches of the carded fibres are then laid mechanically, with successive layers having the same or different directions of orientation of the fibres, according to the required strengths of the finished material in its individual directions. The layering may be done by cutting the web into strips as it is formed, and then depositing these strips, one above the other, or by using several carding machines in series, as in Figure 3.9.

Less frequently, the opened fibre is transported and dispersed pneumatically by *air laying*, thereby forming a non-directional web, which is usually bulkier ('loftier') than carded webs.

If the fibres are of suitable material, the web may be heat-sealed by means of hot rolls. If not, then the web may be treated with a binding resin, either by spraying onto one or both sides of the web, or by immersion in a bath of the resin, before it is finally dried and cured.

The web of fibre, mixed with bonding agent, can be laid down on a cylindrical former, to produce a cartridge element, as described in Chapter 9.

3.4.2 Thermally bonded media

If the web of fibre is of a thermoplastic polymer, and is not too thick, then the fibres can be bonded by passing the felt between pairs of heated rolls, which have a dimpled surface, with raised areas opposite one another, to compress the fibres and heat them in localized spots across the width of the roll.

Freudenberg, one of the world's largest makers of non-wovens for filtration, has a set of such 'point-sealed' media, shown in Table 3.5, relating to polypropylene and used for industrial liquid filtration.

3.5 Dry-laid Spun Media

Probably the most exciting developments in non-woven media have come from a series of combined extrusion and layering processes that exploit the

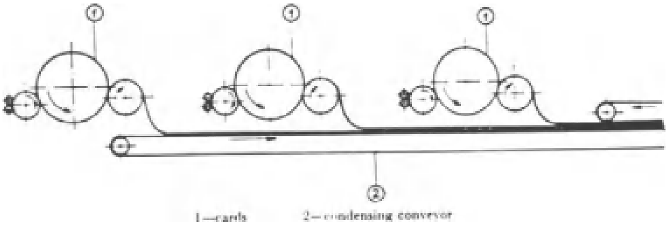


Figure 3.9. Forming a multi-layer web by simultaneously dry laying a sequence of webs from several carding machines in tandem[1].

Table 3.5 Freudenberg point-sealed media[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)
FFK3423	23	0.23	2350*	671	53	150	80
FPK3440	40	0.38	1180	198	106	100	45
FFK3460	60	0.48	855	144	170	90	43
FFK3470	70	0.50	600	101	188	84	40
FFK3480	80	0.56	560	94	210	78	37
FPKH3410	100	0.64	396	67	250	69	27

[a] Freudenberg Viesstoffe KG, Filter Division.

[b] At 100 Pa (* 50 Pa).

[c] $l/m^2/s$ @ 200 mmWG.

[d] N/5 cm in machine direction.

thermoplastic nature of many synthetic polymers. From small beginnings only a relatively short time ago, the dry-laid spun media have now increased to the state where they are of comparable importance in the filter media market place with woven media and needlefelts.

Since the late 1960s, these novel manufacturing processes have developed rapidly, to give the resulting materials this commanding position in the filter media business. The development has been so rapid that a standard set of terms has not yet been agreed on an industry-wide basis – some refer to all such materials as 'spunbonded', others differentiate between spunbonded and 'meltblown', while terms such as 'melt spun' and 'flash spun' are also used.

The earliest such processes were those first called melt spinning, now generally known as spun bonding, and which remain important to the present day. They produced relatively coarse filaments, while the newer developments, such as melt blowing, have enabled the production of much finer fibres.

The key feature of these processes is that a molten polymer is extruded through a series of holes in a spinneret, and the resultant filaments are laid down in various ways on a moving belt running under the spinnerets. The final bonding of the filaments or fibres is achieved by various combinations of heat, pressure and chemical activation, although the thermoplastic nature of the polymer is the prime structural feature. It is this integral production of filament or fibre followed immediately by its laying down as the medium that distinguishes the spun media from the felts – which are made, usually, from bundles of fibre bought in from a separate supplier.

Thus, diverging from the usage of the first edition of this Handbook, where all of these materials were classed under the general heading of spunbonded media, they are here classed as dry-laid spun media. The essential difference between spunbonded and meltblown materials is recognized and described in the following notes.

The differences between the two main classes of dry-laid spun material are significant in terms of filtration behaviour, but both are available with the same range of finishing processes as are used for woven and needlefelt materials: calendering, singeing and coating. The lamination of different materials is also an important feature of dry-laid spun media.

3.5.1 Spunbonded media

In the production of spunbonded media, conventional synthetic fibre technology is used to extrude molten polymer through the orifices of a set of spinning heads or spinnerets, mounted above, and across the width of, a moving screen belt. This produces a multiplicity of continuous filaments, which are first quenched by a cross flow of air, and then drawn downwards by concurrent air streams, through an aspirator jet. The spinnerets oscillate from side to side, and the result is that the filaments, kept apart by electrostatic charges, are randomly laid down on the belt (which has a suction box underneath it).

The fineness of the filaments depends directly upon the size of the capillary nozzles in the spinnerets, and is therefore relatively coarse. Spunbonded media are therefore not capable of very fine degrees of filtration, but are relatively strong in mechanical terms.

The continuous roll of spunbonded material is finally consolidated to the required performance specification, usually by some form of calendering. The majority of spunbonded materials are made from polypropylene and polyester melts.

The name Reemay was originally the registered trademark of Du Pont for the company's spunbonded polyester material. The name lives on, now within the BBA Nonwovens Group, which provides an extensive range of spunbonded media, all produced in the manner described above. The range includes the Reemay polyester media, as well as the polypropylene Tekton media (known as Typar within North and South America), and other polyester media such as Synergex, Typelle and QualiFlo.

Table 3.6 lists the properties of filtration-grade Reemay, made from fine polyester fibres with diameters of 16 or 23 µm; the filaments may be of round or trilobal cross-section, and, as shown in Figure 3.10, they may be straight or crimped. Corresponding grades of Tekton/Typar polypropylene media are summarized in Table 3.7; their thicker 25 and 39 µm fibres, together with a modification to the process to introduce directional orientation of the filaments, provide high material strength.

Another extension of the spunbonding process is to add a needle punching stage. BBA's Typelle has a polyester web formed by spunbonding, which is then partially consolidated in the normal way for spunbonds, prior to being needle punched. Data for Typelle are given in Table 3.8.

3.5.2. Meltblown media

Melt blowing was reported by Meyer(7) as having been pioneered in a programme aimed at developing microfibres capable of collecting radioactive particles in the upper atmosphere. The process was refined and licensed for commercial use by Exxon, and is now one of the most important production routes for filtration media.

Table 3.6 'Reemay' polyester spunbonded media[a]

Style No.	Filament		Weight (g/m)	Thickness (mm)	Grab tensile N (MD×XD[d])	Trap tear N (D×XD[d])	Bursting pressure (kg/cm^2)	Permeability to air[e]	% Filtration efficiency	
	Size[b]	Shape[c]							In air[f]	In water[g]
Straight fibres										
2004	4	T	14	0.13	36×27	11×14	0.62	6830	35	25
2005	4	T	17	0.18	41×32	18×23	0.48	6590	40	28
2055	4	T	19	0.15	50×41	18×18	0.69	5514	73	25
2006	4	T	20	0.18	45×36	18×23	0.76	4880	33	30
2011	4	T	25	0.18	63×50	23×27	0.83	5124	66	30
2014	4	T	34	0.28	86×72	27×32	1.17	4294	66	37
T-667	4	T	34	0.23	99×90	32×32	n/a	3780	80	50
2015	4	T	37	0.25	99×95	45×45	1.58	3540	61	40
2016	4	T	46	0.28	162×122	41×50	2.20	2560	65	40
2024	4	T	71	0.30	275×212	41×50	3.58	1708	92	70
T-679	4	T	81	0.36	277×212	38×47	3.58	n/a	90	80
2033	4	T	100	0.43	459×351	68×77	5.78	1220	96	83
2044	4	T	136	0.56	563×450	63×86	7.36	927	99	88
2250	2.2	R	17	0.13	45×36	14×23	0.48	5670	60	30
2275	2.2	R	25	0.15	68×63	27×32	0.69	4150	83	60
2200	2.2	R	36	0.20	95×86	31×32	1.03	3170	98	48
2214	2.2	R	46	0.25	144×135	42×44	1.93	2560	85	75
T-608	2.2	R	54	0.28	162×153	59×63	n/a	n/a	88	70
T-609	2.2	R	61	0.25	180×167	54×54	n/a	1830	86	81
2295	2.2	R	100	0.48	338×320	101×101	5.23	1220		
Crimped fibres										
2410	4	T	39	0.46	68×51	n/a	0.62	4760	50	15
2415	4	T	45	0.43	106×79	n/a	1.10	3415	63	30
2420	4	T	63	0.46	133×97	n/a	1.24	3170	68	30
2430	4	T	81	0.48	196×152	68×81	1.99	2074	75	35
2440	4	T	98	0.53	251×187	n/a	2.61	1708	88	45
2470	4	T	203	0.76	612×450	167×212	5.64	732	95	91

[a] BBA Nonwovens. [b] Denier values listed. Diameters are 16 and 23 μ. [c] T=trilobal cross section; R=round cross section. [d] MD=machine direction; XD=across machine. [e] Air permeability, l/dm^2 min^{-1} @ 20 mm WG. [f] Based on 8–18 μ particles. [g] Based on 50–60 μ particles.

Table 3.7 'Tekton' polypropylene spunbonded media[a]

Style no.	Filament size[b]	Weight (g/m²)	Thickness (mm)	Grab tensile N (MD×XD)[c]	Trap tear N (MD×XD)	Bursting pressure (kg/cm²)	Permeability to air[d]	% Filtration efficiency	
								In air[e]	In water[f]
Low Denier									
T-367	3	34	0.18	120×67	31×27	1.69	1757	40	15
T-244	4	42	0.21	92×54	54×52	1.91	1757	45	25
T-135	4	54	0.25	122×68	69×41	2.43	1219	60	70
T-1161	4	156	0.41	590×360	158×90	7.29	134	94	79
T-195	6	203	0.53	765×495	270×159	12.17	77	94	90
Standard[g]									
3123	8	42	0.20	162×167	61×41	2.41	1625	56	15
31407	8	47	0.20	167×167	91×91	2.61	3135	41	15
3153	10	52	0.20	212×203	104×104	2.75	2439	51	15
3201L	10	64	0.23	160×153	167×153	3.78	1949	45	30
3251L	10	85	0.25	501×477	185×167	n/a	995	45	20
3301L	10	102	0.30	639×617	198×211	6.13	790	65	16
33403	10/30	115	0.34	585×657	216×225	6.19	n/a	18	15
3351	10	119	0.36	666×644	295×324	n/a	751	65	83
3401L	20/30	136	0.37	648×730	319×351	8.59	461	75	41
3601L	30	203	0.46	1071×1170	428×464	14.64	240	95	60
3801L	30	271	0.53	1490×1557	495×572	19.94	n/a	90	96
LF Series[g]									
T-309	10	68	0.25	329×302	95×109	2.69	2198	70	55
T-311	10	136	0.36	617×657	180×198	6.46	490	70	73
T-313	10	169	0.43	761×792	232×252	8.04	156	76	79
T-315	10	203	0.48	905×927	234×279	9.56	156	80	85
T-317	10	271	0.53	1222×1296	252×342	n/a	125	87	97

[a] BBA Nonwovens. [b] Denier values listed. Diameters mostly 19 μ but 25 and 39 for T series. [c] MD = machine direction; XD = across machine. [d] Air permeability, l/dm²/min at 20 mm WG. [e] Based on 5–10 μ particles. [f] Based on 50–60 μ particles. [g] LF = ultra low flex, designed for efficient cake release.

Table 3.8 'Typelle' needle punched polyester spunbounded media[a]

Style no.	Filament size[b]	Weight (g/m)	Thickness (mm)	Grab tensile (N MD×XD)[c]	Trap tear (N MD×XD[c])	Bursting pressure (kg/cm)^2	Permeability to air[d]	% Filtration efficiency	
								In air[e]	In water[f]
5150	2.2	51	0.38	144×104	63×54	1.17	3264	86	61
5154	4	51	0.36	86×68	32×86	0.89	4426	80	52
5200	2.2	60	0.38	194×144	81×99	1.44	2774	75	70
5204	4	68	0.56	140×108	54×68	1.65	3820	71	78
5300	2.2	102	0.51	185×171	75×78	1.79	1699	99	72
5450	2.2	153	0.79	293×270	113×113	4.13	1142	97	86
5600	2.2	203	1.17	340×311	130×133	6.53	826	94	89
5900	2.2	302	1.78	567×441	140×180	9.21	634	94	94
5120	2.2	338	2.26	635×468	149×207	11.28	451	97	95

[a] BBA Nonwovens.

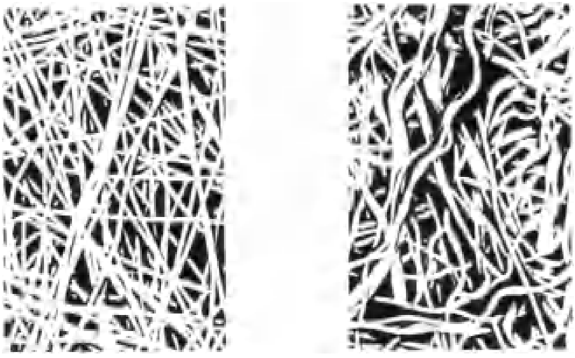
[b] Denier values listed. Diameters 16 μ.

[c] MD=machine direction XD=across machine.

[d] Air permeability. l/dm^2 min^{-1} @20 mmWG.

[e] Based on 8–18 μ particles.

[f] Based on 50–60 μ particles.



Straight Fibers Crimped Fibers

Figure 3.10. Reemay polyester fibres.

Molten polymer is once again extruded at high temperature from spinneret orifices to form continuous filaments. Now, however, these filaments are impacted by high-velocity air streams, which cause the filaments to fibrillate, and to break into fine, moderately short fibres, some 10 to 20 cm in length. These fibres are then collected, in random orientation, on a moving screen belt, with a suction box underneath it. Because the fibres are both finer and shorter, the meltblown media are less strong than, for example, spunbonded material, and so they are most often used in combination with other stronger media (see Section 3.6).

Meltblown fibres have a relatively high surface area per unit weight (1 m^2/g), and a smaller diameter (5–10 μm) than spunbonded materials. They are thus able to filter to a finer degree than spunbonded materials. The most common material used for melt blowing is polypropylene.

3.5.3 Other spun media

The production of materials by extrusion of polymeric filaments has been taken a stage further by Du Pont in its flash spinning process to produce Tyvek high-density polyethylene sheet products. Like the other spinning processes, flash spinning involves extrusion through a spinneret; but whereas pure molten polymer is extruded in the other processes, with flash spinning the extrudate is a partially separated two-phase mixture of pure solvent droplets and a highly saturated polymer/solvent mixture. The decompression across the spinneret capillaries induces flash evaporation and the formation of fibrils; voids are created within the fibrils as ruptures are caused by expanding globules of solvent vapour. The fibril webs are collected on a moving belt, and are then subjected to a combination of heat and pressure to promote self-bonding. This forms sheets of continuous strands of very fine interconnected fibres, with very high specific surface areas (30 m^2/g), and a high bursting strength.

Because Tyvek is an exceptionally tough material, its primary fields of application are in packaging and construction materials, for which purposes the Tyvek name is still used. In its basic form, its permeability is too low for use as filter media, so the process has been extended, to produce filtration grades, now marketed under the name SoloFlo. This development was also reported by Meyer(7–9), a particularly interesting aspect of these reports being the variety of wastewaters successfully processed by the combination of the SoloFlo filter media and the Oberlin automated pressure filter. Pertinent data on the SoloFlo material are given in Table 3.9, together with those for other grades of DuPont media that have some filtration uses (mainly as membrane substrates). The higher permeability for the SoloFlo grade is shown in its lower pressure drop figure.

A material being developed(10) for military use, for the protection of personnel against chemical and biochemical attack, updates a 70-year-old technique called electrospinning, to produce a mat of nanofibres. As well as in the form of a flat sheet, this mat can be laid down upon any surface – from a model of a human body to the core of a filter cartridge – and promises to be a very good filtration medium.

3.5.4 *Extruded meshes*

Other forms of extruded polymer are used in filtration in the form in which they are made. There are several suppliers of extruded plastic mesh materials, all deriving from the original Netlon patents, which could be formed into non-woven media. However, the process is mainly used for single layers of mesh, and accordingly is discussed in detail in Chapter 6.

3.6 Composite Non-wovens

Non-wovens of all types are used frequently as part of a composite material, with the various component layers chosen to give the right combination of filtration properties and material strength characteristics.

Special composites have been developed within the range of spun media. One of these is what is now known as SMS, namely a triple-layered material

Table 3.9 DuPont 'SoloFlo' flash spun media*

Property	SoloFlo	1058D	1059D	1073D
Mean flow pore size (μm) (at psi)	5.2 (1.3)	1.7 (4.0)	2.3 (2.9)	1.8 (3.7)
Bubble point (μm) (at psi)	11.0 (0.6)	4.9 (1.4)	5.4 (1.2)	7.1 (0.9)
Void volume (%)	66.3	56.1	58.7	45.6
Liquid efficiency (%)	99.98	98.41	99.63	99.92
Permeability (psid)	1.3	10.0	4.1	4.3
Basis weight (g/m^2)	42.4	54.3	64.4	74.6
Thickness (mm)	0.13	0.14	0.17	0.19

*E I du Pont de Nemours Inc.

consisting of a central meltblown layer, with spunbonded materials top and bottom. SMS media are typified by BBA's UltraFlo range, which is made in polypropylene, in six grades, ranging from 17 to 88 g/m^2 in weight, 0.1 to 0.48 mm thick, and 1 575 to 255 $l/m^2/s$ permeability.

There are two contrasting styles of laminated structure, depending on whether the filter medium is intended to function by depth filtration or by surface filtration. With depth filtration, the medium should be graded so as to increase in fineness in the direction of flow. The upper, coarser layers will act as a pre-filter, in which the larger particles are retained, with the smaller particles then being trapped subsequently in the finer layers. This will maximize the dirt-holding capacity per unit area of medium, and hence its life before it is discarded.

Typical of this type of laminated medium is BBA's range of spunbonded composite material called Synergex, formed from several layers of polyester filaments. Some typical data are given in Table 3.10. There are two versions, depending on whether the calendering rolls are smooth, so as to generate 'flat bonded' material, or embossed, so as to generate 'pattern bonded' products.

By definition, surface filtration ideally involves the collection of all particles on the surface, or upstream face, of the medium, with none passing into its depth; thereby the efficiency of the medium is totally dependent on the pores in this surface being sufficiently small for the required purpose. Surface filtration has, of

Table 3.10 'Synergex' composite spunbonded media[a]

Style no.	Filament size[b]	Weight (g/m)	Thickness (mm)	Grab tensile N (MD×XD[c])	Bursting pressure (kg/cm^2)	Permeability to air[d]	% Filtration efficiency	
							In air[e]	In water[f]
Flat bonded								
6110	2.2	34	0.13	104×72	1.65	2630	70	50
6115	2.2	51	0.18	104×131	2.27	1536	75	80
6120	2.2	68	0.20	234×189	3.23	1094	80	85
6125	2.2	85	0.25	320×234	4.95	826	90	85
6130	2.2	102	0.30	342×297	5.02	710	91	90
6140	2.2	136	0.36	500×383	7.01	365	98	97
Pattern bonded								
6215	2.2	51	0.25	162×126	2.48	1584	89	80
6220	2.2	68	0.33	216×171	3.71	1296	95	70
6230	2.2	102	0.41	392×288	5.91	874	100	93
6240	2.2	136	0.46	536×401	8.18	442	99	99
6250	2.2	169	0.64	666×486	9.56	442	99	96
6260	2.2	203	0.74	770×567	11.76	413	99	97

[a] BBA Nonwovens.

[b] Denier values listed. Diameters 16 μ.

[c] MD=machine direction XD=across machine.

[d] Air permeability, $l/dm^2/min^{-1}$ @ 20 mm WG.

[e] Based on 8–18 μ particles.

[f] Based on 50–60 μ particles.

course, been practised for as long as filtration has been in use, and suitable media can be found to provide efficient separation by this means, according to the nature of the particles to be removed.

However, the modern emphasis on extremely high-efficiency removal of very fine particles has led to the demand for very finely porous surface layers, and this demand has been met by the lamination of a membrane on to a suitably robust substrate. Non-woven materials have proved to be very suitable as substrates, especially for the support of PTFE membranes. Depending upon the intended application, substrates range from lightweight spunbonded polypropylene or polyester, to substantial fabrics such as thick needlefelts. These materials, which are effectively membranes as far as filtration is concerned, are more fully discussed in Chapter 8.

In the same way that woven media can be made with combined filtration and chemical treatment behaviour, combination media exist in the non-woven field as well. Typical of these are BBA's Qualiflo media, made from polyester fibres, which are resin bonded. Qualiflo are thick media, internally graded to provide efficient filtration (99% against 2–3 μm particles) and high dust-holding capacity (658 g/m^2). In addition, they can be custom engineered to incorporate a wide range of powders for specific applications; for example, grade EH-AC-980 incorporates activated carbon granules to provide odour control as well as filtration. The recent purchase by BBA of AQF Technologies has added extra capability in combination media.

3.7 Selecting Non-woven Media

A wealth of information exists to guide the prospective user of a fabric, woven or non-woven, as a filtration medium. Most suppliers of filter media issue such guidance, but completely independent advice is not so easily come by. The notes here are intended to give as balanced a view as possible. (Since much of the data is fibre material dependent, the following notes relate as much to woven media as to non-woven.)

The three main parameters in the choice of a medium are: filtration performance, mechanical performance and cost. As far as cost is concerned, the rough figures of Table 1.5 can be used to compare woven and non-woven fabrics. There it can be seen that, on a unit filter area basis, needlefelts and woven fabrics are about the same price, but thermally bonded materials are significantly lower in cost.

In terms of application, and in the broadest possible terms, woven media are used for liquid filtration, and non-woven media for gas filtration – but there are almost as many exceptions to this general rule as there are agreements. It is perhaps more correct to say that non-wovens have successfully displaced wovens from a large number of gas cleaning applications, but have been less successful in displacement in liquid filtration (although the membrane has taken a large share of the market here). One reason for this is that all the mechanically complicated filter equipment (such a belt or a tower press) are used for liquid filtration, and these need the strength in their belts that only woven fabrics can provide.

3.7.1 *Non-woven media applications*

An early classification of non-woven media by Sandstedt(11) listed a number of applications for dry-laid, wet-laid and spunbonded materials. This was updated for the first edition of the Handbook, and is included here, largely unchanged, as Table 3.11, because it is still largely relevant. The updating included expansion to cover meltblown and needlefelt media. Table 3.11 shows which medium is suitable for which of a number of industrial, commercial and domestic applications. What has changed, of course, is the overall importance of the spun media, at the expense of other dry- and wet-laid materials.

3.7.2 *Woven fabrics and needlefelts*

The following tables are intended only as a preliminary selection guide. They are based primarily on the experience and product range of P & S Filtration, now part of Madison Filter Group. The tables consider only woven fabrics and needlefelts, with one pair of tables summarizing information in respect of liquid filters, and a second pair similarly devoted to dust filters, but, in the latter case, supplemented by a table relating the recommended fabric weight to the vigour of the cleaning method.

3.7.2.1 Dust filters

A total of 16 different groups of fabrics are identified in Table 3.12, each one being allocated a number, and described briefly in terms of its type. Table 3.13 is

Table 3.11 Overview of markets for basic types of non-woven media[a]

Market segment	Type of non-woven media				
	Needle felt	Bonded media			
		Dry laid	Wet laid	Spun media	
				Spunbonded	Melt blown
HVAC air filter		x		x	x
Fabric dust filters	x				
Tea bags			x		
Coffee bags		x			x
Machine tool coolant			x	x	
Milk		x			x
Vacuum cleaner bags	x		x		x
Edible oil			x		x
Face masks	x	x			
Food and beverage			x	x	
Cartridges			x	x	
RO/UF			x	x	x

[a] Original table by Sandstedt(9) updated with assistance from Lutz Bergmann, Filter Media Consulting Inc.

based on specific industries, with subdivision in terms of the operating temperature of named categories of process; in cross-linking these to suitable groups of fabric, a distinction is made according to the filter cleaning option. It must be remembered that these tables do not take account of the availability of spun media nor of membrane media, both of which are increasingly being used for dust cleaning.

Understandably, heavier needlefelt fabrics are advisable for use with the more intensive methods of cleaning. Table 3.14 distinguishes among five categories of cleaning mode, ranging from infrequent shaking, up to pulse jet cleaning at a pressure of 7 bar.

The type of filter, and especially the mode of cleaning, broadly determine the type of fabric that is appropriate. Bergmann(12) comments that US practice is generally to use needlefelts for pulse jet filters requiring outside cleaning, but woven fabrics for the inside cleaning of shaker and reverse air filters.

The chemical and physical properties of the fabric are also of crucial importance, as described in Chapter 2. Table 2.6 is an important summary of media materials for higher temperature dust filtration applications.

3.7.2.2 Liquid filters

A total of 18 groups of fabric are identified in Table 3.15, slightly more than in the corresponding table for dust filters (and with a noticeable preponderance of woven fabrics). A much greater expansion occurs in considering the media applications in Table 3.16, to allow the inclusion of a variety of vacuum and pressure filters, as well as a substantial number of relevant process variables.

Table 3.12 Types of cloths for dust filters[a]

Filter cloth group/cloth type		Air permeability		
		Weight (g/m^2)	m^3/m^2/min at 12.7 mm WG	l/dm^2/min at 20 WG
1	Woven staple polyester	305–480	9–30	140–475
2	Woven multifil polyester	185	6	95
3	Woven multifil warp, staple weft polyester	405	19	300
4	Woven multifil glass	295–460	10–18	155–285
5	Woven staple acrylic copolymer	460	6.5	105
6	Woven staple acrylic homopolymer	375	8	125
7	Woven multifil warp, staple weft polyaramid	340	16	250
8	Woven staple polyaramid	300	6	95
9	Woven multifil PTFE	290	9	140
10	Needlefelt with base fabric, Polyester	340–640	7.5–17	120–270
11	Needlefelt with base fabric, Acrylic copolymer	405–460	10–33	155–270
12	Needlefelt with base fabric, Acrylic homopolymer	600–650	7–12	110–190
13	Needlefelt with base fabric, Polyaramid	340–500	12–25	190–395
14	Needlefelt with base fabric, Glass	950	10.5	165
15	Needlefelt with base fabric, PTFE	730–840	6–9	95–140
16	Needlefelt with base fabric, Polyphenylenesulphide	500	10–15	155–235

[a] Madison Filter.

Table 3.13 Dust filter applications*

Industry	Process	Process Operating Temperature (°C)	Moisture or acidic conditions	Filter cloth group	
				Reverse air/shake cleaned filters	Pulse cleaned filters
Cement	Raw meal crushing, drying	Up to 130°C	Moisture possible	1, 3, 6, 10	10, 11, 12
	Kiln gases and clinker handling	Up to 200°C	Moisture possible	4	14
	Packing transport	Ambient	No	1, 3, 10	10
Iron and steel	Furnace fume	Up to 110°C	No	1, 2, 3, 10	10
	Alumina handling	Ambient	No	1, 3	10
Aluminium	Carbon anode preparation	Up to 200°C	No	7, 8	13
	Potline fume	Up to 120°C	No	1	10
Carbon black	Carbon black	Up to 200°C	Moisture possible	1, 4	13, 14
Non-ferrous smelting zinc, lead, tin	Collection of fume	Up to 190°C	Acidic conditions possible	1, 3, 5, 6, 7, 8, 9	10, 11, 12, 16
Gypsum	Kettles	Up to 150°C	Moisture	5, 6, 11	
Perlite	Perlite production	Up to 170°C	Moisture	4, 7, 8, 10	10, 13
Plastics PVC, A.B.S., polyethylene, polypropylene	Recover	Ambient	No	3	10
Quarry and asphalt	Crusing, grinding, drying aggregate	Up to 120°C	Moisture possible	1, 6	10, 11, 12
	Asbestos milling and drying	Up to 120°C	Moisture	1, 3	10
	Asphalt production	Up to 200°C	Moisture possible	6, 7, 8	12, 13
Coal fired boilers	Fly ash collection	Up to 220°C	Acid possible	4, 6	12, 14, 15, 16
General dust handling including flour, cereal, provender	Dust handling	Ambient	No	1, 3	10

*Madison Filter.

3.7.3 Spunbonded media

Table 3.17 summarizes application data supplied for some of BBA Nonwovens' materials: the spunbonded Reemay and Tekton, the needled spunbonded Typelle, and the laminated Synergex.

Table 3.14 Needle felts to suit cleaning mode of fabric filters[a]

Cleaning mode	Basis weight (g/m^2)	Permeability to air (l/dm^2/min^{-1} @ 20 mm WG)
Infrequent mechanical shaking	235–270	390–660
Periodic shaking	270–370	390–660
Shaking plus reverse air cleaning	370–500	245–390
Low pressure reverse air cleaning	340–475	245–390
Pulse jet cleaning at up to 7 bar	500–680	50–170

[a] Filter Media Consulting Inc.

Table 3.15 Cloth types for liquid filters[a]

Filter cloth group	Cloth type	Weight (g/m^2)	Air permeability (m^3/m^2/min at 12.7 mm WG)	Max continuous operating temperature (°C)
1	Woven monofilament polyester	350–550	30–150	120
2	Woven multifilament polyester	150–650	1–5	120
3	Woven staple polyester	450–700	1–5	120
4	Needled polyester	640	2	120
5	Woven monofilament polyamide	250–400	25–60	100–110
6	Woven multifilament polyamide	100–250	1–5	110
7	Woven staple polyamide	400–800	1–5	110
8	Needled polyamide	600–1000	2–6	110
9	Woven monofilament polypropylene	200–350	40–120	95
10	Woven multifilament polypropylene	350–700	0.5–5	95
11	Woven staple polypropylene	200–650	1–20	95
12	Woven multifilament warp Staple weft polypropylene	450–600	1–8	95
13	Needled polypropylene	400–600	1–5	95
14	Woven monofilament polypropylene	200–330	30–80	85
15	Woven monofilament Polyvinylidine chloride (Saran)	500–600	Over 200	85
16	Woven staple modacrylic	430	Negligible	85
17	Woven cotton/nylon combination	800	0.5	100
18	Woven cotton	500–650	0.5–2.0	100

[a] Madison Filtration Ltd.

Table 3.16 Liquid filter cloth applications[a]

Industry	Process	Filtration equipment	pH	Process operating temperature (°C)	Particle type	Particle size	Filter cloth group	Filter media features
Sugar	1st and 2nd carbonation	Filter leaf					7, 11	High throughout and resistance to blinding
		Candle filter					11	
	Mud desweetening	Rotary vacuum drum	6–10	95	Amorphous	Medium	7, 11	Good mechanical resistance and cake discharge
		Filter press					6, 7, 11	Good mechanical resistance, dimensional stability and seal
		Automatic pressure filter					12	Good dimensional stability, tracking and high strength
	Juice filtration	Filter press					7, 11, 18	Good mechanical resistance, dimensional stability and seal
	Cane sugar refining	Filter leaf					2, 7, 11	High throughput and resistance to blinding
Phosphoric acid	Removal of calcium sulphate	Horizontal rotating pan filter	Up to 6	100	Crystalline	Coarse	1, 9	Resists abrasion and blinding by crystal formation. Good dimensional stability
		Travelling band filter					1	Dimensional stability to ensure good tracking

Table 3.16 *(continued)*

Industry	Process	Filtration equipment	pH	Process operating temperature (°C)	Particle type	Particle size	Filter cloth group	Filter media features
Alumina	Red mud overflow	Filter leaf	13		Amorphous	Fine	9, 10, 11	Resistance to red mud blinding. High throughput
	Ref mud underflow	Rotary vacuum drum				Medium	5, 9, 14	Resistance to blinding and good cake discharge
	Hydrate product and Seed	Rotary vacuum disc			Crystalline	Coarse	5, 9, 14	Resists stretch and abrasion. High throughput and good cake discharge
Edible oils and fats	Expelled oil	Filter press		120	Amorphous	Coarse	3, 7	Good mechanical resistance and retention
	Bleaching						2, 3, 7	Resistance to heat
	Hardening						7, 17	Excellent retention of catalyst
	Winterizing						7, 17	Resistance to blinding from fats. High throughput
Ceramics and china clay	Clay slip dewatering	Filter press	7	40	Crystalline	Coarse	6, 7, 10, 12, 13	Good mechanical resistance and seal. Consistent cake density
	China clay						6, 10, 12	Fine particle retention. Resistance to pin holding
Sewage and effluent	Municipal	Filter press	5–10	30	Amorphous	Fibrous	1, 5, 7, 11, 14, 15	Good resistance to blinding and mechanical damage. Good cake discharge
		Travelling band filter					1	High stability for good tracking. Strong belt joining high mechanical resistance

Table 3.16 *(continued)*

Industry	Process	Filtration equipment	pH	Process operating temperature (°C)	Particle type	Particle size	Filter cloth group	Filter media features
	Industrial	Filter press				Variable	1, 5, 7, 12	Good cake discharge, fine particle retention and high throughout
Dyestuff, pigments and intermediates		Filter press	1–13	90	Crystalline	Fine	2, 10, 11, 12, 13	Fine particle retention and suitable for cake washing
		Automatic pressure filter					10	Dimensional stability to ensure good tracking
		Vacuum filter					2, 3, 9, 11, 12	Good resistance to chemical conditions and blinding
Viscose	Gel filtration	Filter press	12	20	Amorphous	Gelatinous	8	Optimum gel retention. High throughput. Ideal for off-machine and back washing
Starch products	Starches, glucose and gluten dewatering	Filter press	5–8	30	Amorphous	Coarse	7	Good resistance to blinding, ease of washing
							2, 6	Good throughput
Coal	Coal dewatering	Rotary vacuum belt	5–8	20	Crystalline	Coarse		
		Rotary vacuum belt					1	Dimensional stability to ensure good tracking
		Rotary vacuum disc					5, 9	Abrasion resistant and good cake discharge
	Clay tailings				Amorphous		1, 5, 14	Dimensional stability for large presses. Good cake discharge. Resists blinding

Table 3.16 (*continued*)

Industry	Process	Filtration equipment	pH	Process operating temperature (°C)	Particle type	Particle size	Filter cloth group	Filter media features
Metal concentrates	Non-ferrous concentrates	Rotary vacuum disc	5–8	25	Variable	Coarse	7, 13	Good resistance to blinding, high throughput and low moisture content
	Iron ore		5–8	40		Coarse	5, 14	Good resistance to blinding, high throughput and low moisture content
Brewing	Mash	Sparging press	5–8	80	Amorphous	Coarse	9	Maintains high throughput
	Yeast	Filter press		20		Fine	3, 12	Fine particle retention at high throughput
	Roughing	Filter press		20		Fine	8	Maintains high throughput, regenerable
Non ferrous metal refining		Filter press					3, 12, 13	Fine particle retention and resistance to blinding
	Hydrometallurgy	Rotary vacuum drum	1–14	100	Variable	Variable	1, 2, 5, 9, 13	Good blinding resistance, mechanical resistance and cake discharge
		Filter leaf					2, 11	High throughput with good filtrate clarity
	Electrometallurgy	Diaphragm					2, 10, 16	Controlled permeability and low voltage drop
Titanium dioxide	Clarification	Filter leaf	3–11	25	Crystalline	Fine	2, 9	Good resistance to blinding. High throughput
	Removal of iron and treatment	Vacuum leaf	5				3, 11, 18	Good cake pickup. Resistance to blinding and good retention efficiency

Table 3.16 *(continued)*

Industry	Process	Filtration equipment	pH	Process operating temperature (°C)	Particle type	Particle size	Filter cloth group	Filter media features
	Washing and dewatering	Rotary vacuum drum					2, 3, 4, 11	Low moisture content consistent with throughput. Good cake discharge
Cement dewatering	Raw meal dewatering prior to kiln	Filter press	5–8	25	Variable	Coarse	1, 5	Good dimensional stability, mechanical resistance and discharge. High throughput

[a] Madison Filter.

Table 3.17 Application for BBA Nonwovens spunbonded media

	Food and beverage	Swimming pool	Machine coolant	Industrial cartridge	Air filters	Membrane substrate
Reemay						
2004					x	
2005					x	
2055						
2006	x		x			x
2011	x		x		x	x
2014	x		x		x	x
T-667						
2015			x		x	x
2016	x		x		x	x
2024	x		x			x
T-679						
2033	x	x	x	x		
2040	x	x	x	x		
2250	x		x		x	x
2275	x		x		x	x
2200	x		x			x
2214	x		x			x
T-608						
T-609						
2295	x	x		x		x
2410						
2415						
2420						
2430						
2440						
2470	x	x		x		
Tekton						
T-867						
T-244	x			x	x	x
T-135	x			x	x	x
T-161	x			x		x
T-198	x			x		x
3121						x
3141						x
3151	x			x	x	x
3201	x			x	x	x
3251						
3301						
3341						
3351						
3401						
3601						
3801						
T-509	x				x	
T-511	x					
T-513	x					
T-515	x					
T-517	x					

Table 3.17 *(continued)*

	Food and beverage	Swimming pool	Machine coolant	Industrial cartridge	Air filters	Membrane substrate
Typelle						
5150					x	
5154					x	
5200					x	
5204					x	
5300					x	
5450						
5600					x	
5900					x	
5120						
Synergex						
6110	x		x		x	x
6115	x		x		x	x
6120	x		x			x
6125						
6130			x			
6140			x			
6215					x	
6220						
6230						
6240	x					
6250	x					
6260	x					

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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

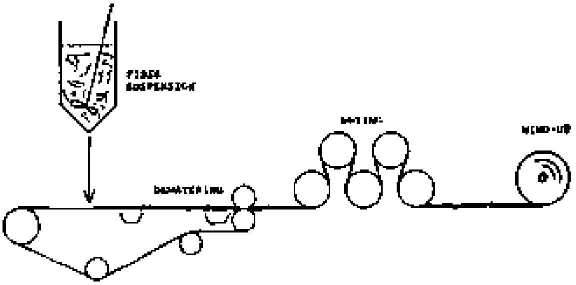

Figure 4.1. The basic wet-laid paper making process.

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.

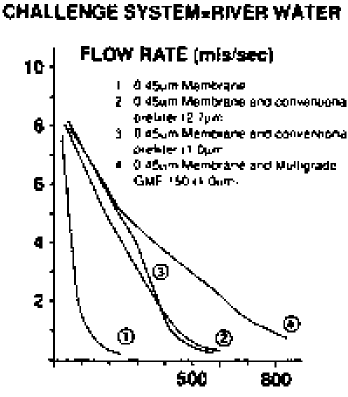

Figure 4.2. Effect of Whatman multi-layer prefilter (curve 4) on membrane life.

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.

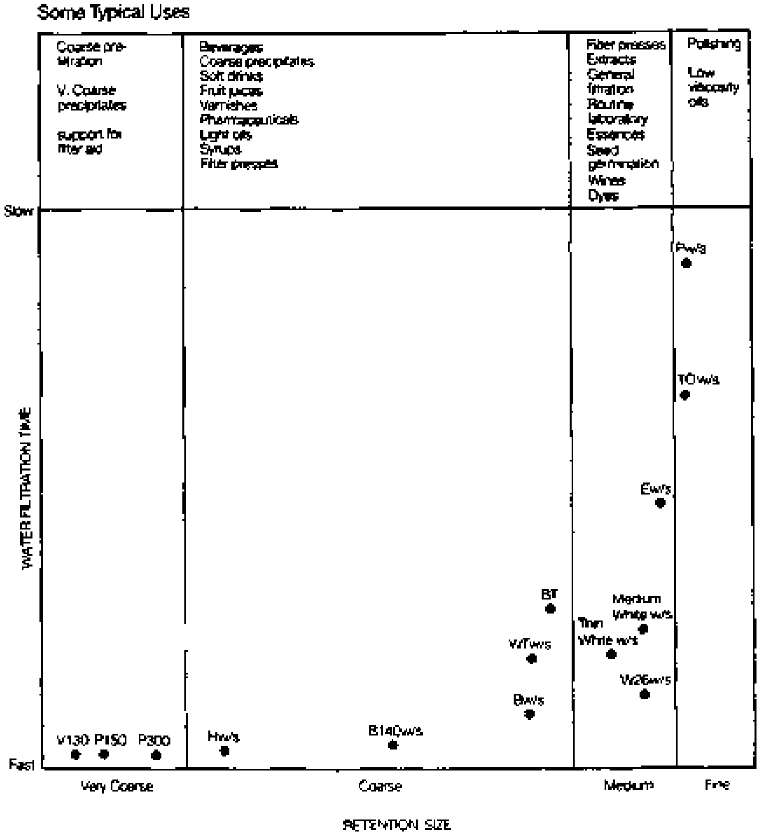

Figure 4.3. Overview of characteristics and applications of Hollingsworth and Vose Company Ltd industrial general purpose cellulose filter papers.

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/m²)	Nominal volatile content (%)	Nominal resin content (%)	Air resistance[c]		Pore[d] pressure (kPa)	Paper thickness (mm)	Retention[e] size (μm)	Corrugation depth (mm)	Typical application
				Δp30 (Pa)	Δp10 (Pa)					
EA11/133	130	9	23	70	–	0.18	0.50	46	0.22	Air/lube oil
G540/202	158	7	26	88	–	0.37	0.60	39	0.30	Air/lube oil
PR05/254	174	10	30	93	–	0.98	0.66	57	0.17	Hydraulic oil
F54E/155	114	6	26	106	–	1.05	0.66	33	–	Flame ret. air
F54E/122	127	8	18	100	–	1.05	0.41	53	–	Air/lube oil
G53E/151	144	9	22	108	–	1.02	0.52	55	0.24	Spark erosion
RF1/185	168	6	26	120	–	1.06	0.76	52	–	Flame ret. air
RF1/131	165	9	22	124	–	1.07	0.42	32	0.20	Air/lube oil
H52C/129	155	8	28	120	–	2.06	0.70	52	–	Flame ret. air
E444/245	141	7	21	140	–	1.12	0.45	29	0.50	Fuel oil
EA146/122	136	9	18	200	–	1.18	0.60	25	–	Heavy duty air
RF3/128	157	8	17	215	–	1.23	0.56	24	0.21	Spark erosion
FF3/254	187	10	30	210	–	1.21	0.60	24	0.18	Hydraulic oil
W994/234	200	7	22	–	150	1.31	0.40	23	0.52	High temp. oil
EA138/226	122	7	20	–	155	1.66	0.40	11	0.25	Heavy duty air
2009/255	138	7	18	–	162	1.72	0.45	10	0.53	Heavy duty air
RF4/143	186	9	15	–	254	1.40	0.58	14	0.20	Hydraulic/fuel
EA152/119	134	9	15	–	310	2.05	0.51	8	–	Hydraulic/fuel
FF5/143	188	9	15	–	510	2.52	0.57	6	0.15	Hydraulic/fuel
M93/205	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] Δp10 = air pressure @ 10 m/min Δp30 = air pressure @ 30 m/min.

[d] Pore pressure = bubble point pressure.

[e] Retention = approximate 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

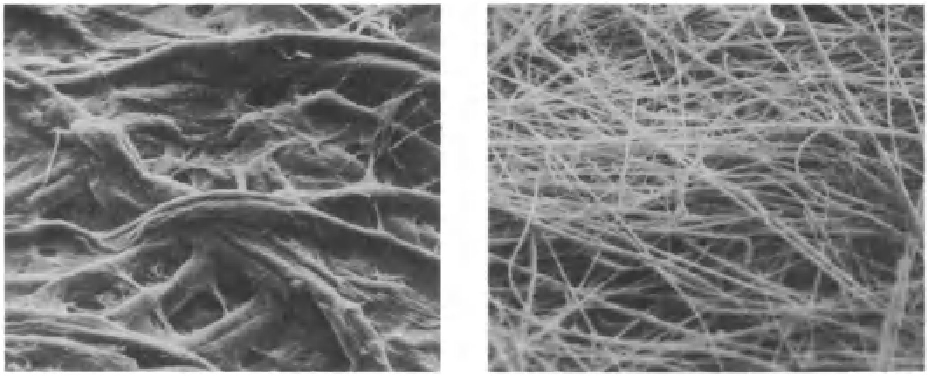

Figure 4.4. (a) Cellulose fibres in Whatman 42 filter paper at ×500 magnification; (b) glass microfibres in Whatman GF/D filter paper at ×500 magnification.

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 35 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 I.

[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[31] 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

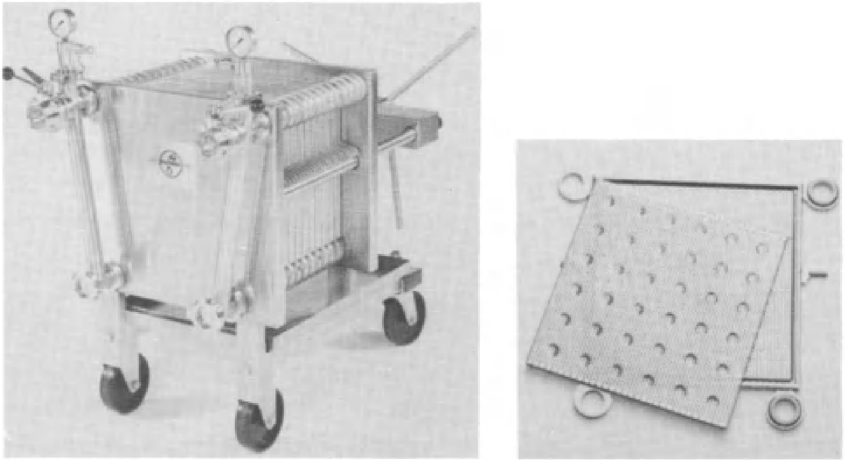

Figure 4.5. The sheet filter is like a conventional filter press but (a) of lighter construction with high quality finish, and (b) the plates easily dismantled for thorough cleaning.

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].

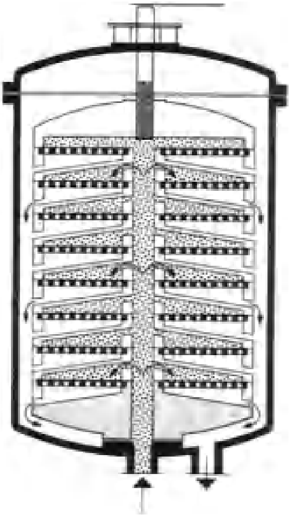

Figure 4.6. Seitz 'Radium' type A horizontal plate filter.

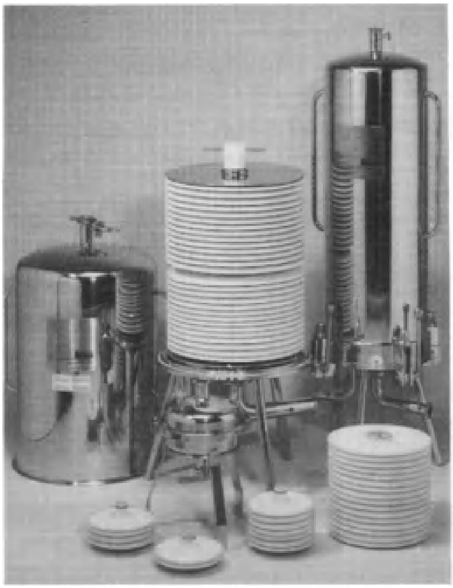

Figure 4.7. Zeta Plus filter cartridges.

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/m^2)	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 (l/min/m^2 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/m^2)	1125	1250	1450	1450	1450	1425
Permeability (darcies)	1.250	0.488	0.310	0.232	0.144	0.065
Water flowrate (l/min/m^2 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/cm³)	Max ash content (%)	Bursting strength[b] (10² kPa)	Permeability[c] (L/min m²)	Test for bacteria retention capability (E. coli in 0.9% NaCl solution) (CFU/cm²)	Cations soluble in 0.05 N H_2SO_4 solution (mg m^{-2})[e] (not applicable for the low-ion grades)			
								Ca^{2+}	Mg^{2+}	$Fe^{2+/3+}$	Al^{3+}
SEITZ-EKS	1 750	3.5	0.56	60	≥2.0	30	10^{7}	<2000	<500	<15	<400
SEITZ-EK 1	1 700	3.5	0.55	54	≥2.0	40	10^{6}	<1500	<500	<15	<400
SEITZ-EK	1 700	3.5	0.55	50	≥2.0	70	10^{5}	<1500	<400	<15	<400
SEITZ-KS 50	1 800	3.7	0.55	50	≥2.0	90	0.5×10^{5}	<1500	<400	<15	<300
SEITZ-KS 80	1 400	3.5	0.55	50	≥2.0	110	10^{4}	<1500	<400	<15	<300
SEITZ-K 100	1 400	3.5	0.55	50	≥2.0	150	–	<1500	<400	<15	<300
SEITZ-K 150	1 100	3.9	0.53	48	≥2.0	190	–	<1500	<400	<15	<300
SEITZ-K 200	1 300	3.9	0.53	48	≥2.0	220	–	<1500	<400	<15	<300
SEITZ-K 250	1 400	4.0	0.52	48	≥2.0	520	–	<1000	<300	<15	<300
SEITZ-K 300	1 250	4.2	0.50	48	≥2.0	800	–	<1000	<300	<15	<250
SEITZ-K 700	1 150	4.1	0.50	48	≥2.0	950	–	<1000	<300	<15	<300
SEITZ-K 800	1 250	4.1	0.30	48	≥2.0	1 300	–	<1000	<300	<15	<300
SEITZ-K 900	1 250	4.3	0.29	48	≥2.0	1 700	–	<1000	<300	<15	<300
SEITZ-T 120	850	2.9	0.29	45	≥2.0	240	–	<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 950	800	2.7	0.30	42	≥2.0	950	–	<750	<200	<50	<150
SEITZ-T 950 ka[d]	800	2.4	0.29	42	≥2.0	1 700	–	<750	<200	<50	<150
SEITZ-T 1000	950	1.6	0.26	55	≥2.0	3 500	–	<750	<200	<50	<100
SEITZ-T 1500	800	1.7	0.22	35	≥2.0	7 500	–	<750	<200	<50	<100
SEITZ-T 2100	700	1.1	0.21	17	≥2.0	10 200	–	<750	<200	<50	<100
SEITZ-T 2600	700	1.4	0.24	1	≥2.0	10 200	–	<750	<200	<50	<100
SEITZ-T 5500	850	4.6	0.16	17	≥2.0	15 000	–	<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	10^8	< 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 Δp = 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 stabilisation.

[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.

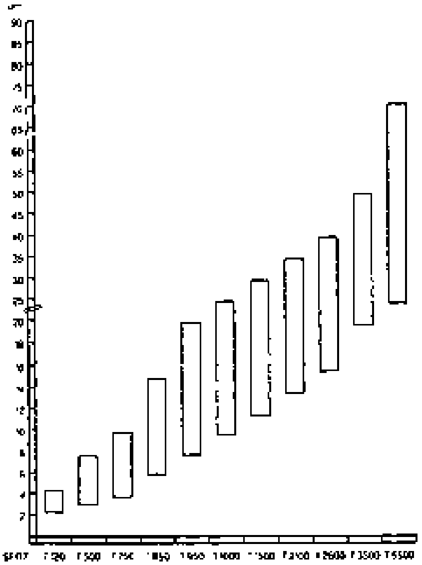

Figure 4.8. Nominal particle retention characteristics of Seitz T-series filter sheets for general industrial duties.

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

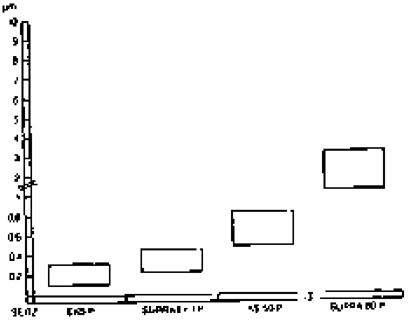

Figure 4.9. Nominal particle retention characteristics of Seitz P-series filter sheets for pharmaceutical duties.

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-SUPRA EK 1P	60	0.06	3	282	282
	600	<0.06	>4	3.11×10^3	3.11×10^3
	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: $\frac{\text{EU ml}^{-1}\text{ unfiltrate}}{\text{EU ml}^{-1}\text{ filtrate}}$

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

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 = $\frac{\text{No. of organisms unfiltrate}}{\text{No. of organisms filtrate}}$ 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.

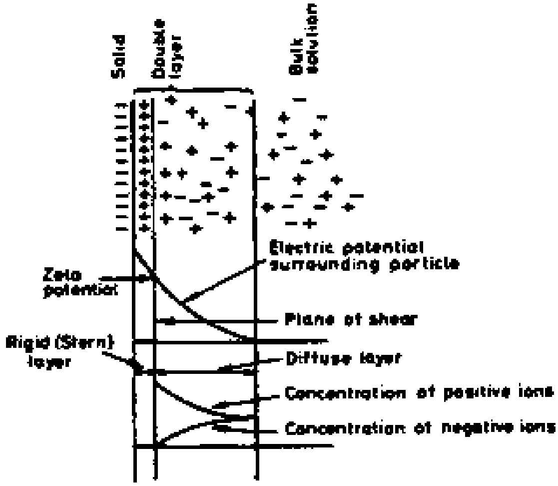

Figure 4.10. The electrical double layer model showing charges assembled around a negatively charged solid surface submerged in water.

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,

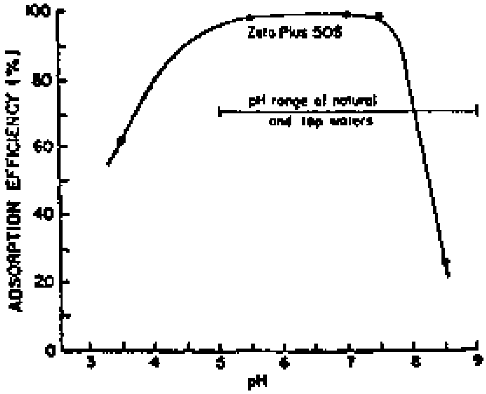

Figure 4.11. Influence of pH on the absorption efficiency of Zeta Plus 50S.

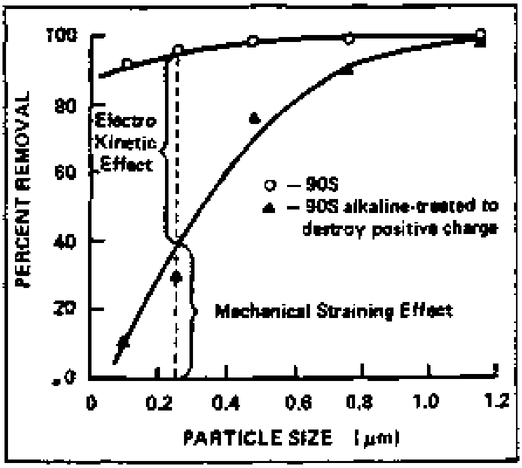

Figure 4.12. Demonstration of electrokinetic contribution to the filtration efficiency of Zeta Plus.

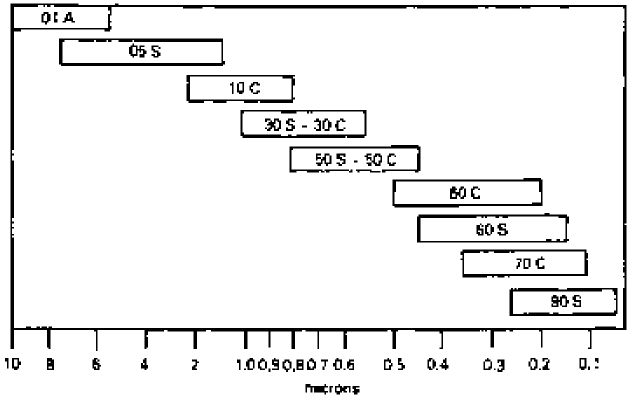

Figure 4.13. Nominal particle retention characteristics of Zeta Plus media.

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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CHAPTER 5

Air and Gas Filter Media

There have already been occasions in parts of this Handbook where it has proved difficult to draw hard and fast boundaries between categories of filter media. This chapter is an especially difficult one to classify, partly because it concerns filter elements or complete filters as well as media, and partly because it deals with media covered by other chapters in the special applications featured in this one. The most important feature of this chapter is that it deals with filter media applications, rather than media types.

Thus, the range of ventilation filters, employed for cleaning or protecting living and working spaces, uses many of the media discussed in Chapter 3, as does the section on dust removal in industrial processes, here also including woven media.

The two special cases of compressed air and hot gas filtration could have been included in other sections of this chapter, but are separated because of their importance.

5.1 Introduction

This chapter is basically concerned with three distinct classes of filter: those for ventilation systems, dust collection and demisting. Ventilation filters are intended to deal with low concentrations of contaminants in air, and are usually expected to remove these contaminants to extremely low outlet concentrations. They function primarily by depth filtration mechanisms, and are therefore mostly difficult or impossible to clean, so that when fully loaded with contaminant they are discarded.

By contrast, those filters used in industrial dust collection are expected to handle much higher inlet dust concentrations. They function primarily by surface filtration, so that they can be cleaned automatically at frequent intervals. They function on a cyclic basis that enables them to remain in operation for very long periods before replacement is necessary.

Demisters differ from the other two classes by virtue of the fact that they deal with liquid droplets in suspension in a gas, rather than solid particles. The droplets are removed in special depth filtration media, in which they are trapped and then coalesce.

Recent years have seen a great increase in demand for clean air in all applications, and this further justifies the keeping of these topics in a separate chapter in the Handbook.

5.2 Living and Working Space Filters

A significant part of the filter media market is concerned with cleaning normal atmospheric air, either as part of the air conditioning of living and office spaces, or more especially in the cleaning of air before it is drawn into working areas that may be sensitive to dust, such as clean rooms for semiconductor manufacture. A smaller component is that which protects the ambient air from harmful gases or particles that might be released within working spaces.

Also concerned in cleaning atmospheric air are those filters used to clean the air intakes of engines, whether internal combustion engines for automobiles or gas turbines for power generation, and the filters used to keep vehicle cabins free of atmospheric pollutants. Another air cleaning duty is in the respirator worn by people subjected to dusty atmospheres, and the final coverage here is of the filter media used in domestic and industrial vacuum cleaners.

5.2.1 Classification of air filters

Air filters are classified on the basis of their filtration efficiency measured under defined standard conditions in relation to a defined test dust or aerosol. The situation is complicated by the number of different classification systems, test procedures and aerosols used for tests, which have evolved in various countries (as is discussed in Chapter 11).

To some extent, this already complex situation has been compounded during recent years as the increasingly stringent standards of cleanliness demanded, for example in the microchip industry, have stimulated the development of more sensitive testing methods. Simultaneously, there have been strong moves towards establishing international standards, notably within Europe under the leadership of CEN (Comité Européen de Normalisation) and Eurovent.

This international cooperation is evident from Table 5.1, adapted from Morris[1]. The parallel Eurovent and CEN classifications distinguish among a total of 17 classes of air filter: the first nine are for coarse and fine dusts, while the five HEPA (High Efficiency Particulate Air) and three ULPA (Ultra Low Penetration Air) filters are for submicrometre particles. As indicated, these classifications draw together standards not only from Europe but also from the USA (ASHRAE being the American Society of Heating, Refrigeration and Airconditioning Engineers).

An alternative classification has been developed as part of an American project, jointly sponsored by ASHRAE and the US Environmental Protection Agency. The project was aimed at developing a new standard to replace ASHRAE

52-76, a revised version of which was approved as an American national standard in 1992 as ANSI/ASHRAE 52.1-1992. The new standard, ASHRAE 52.2-1999, includes the classification system reproduced as Table 5.2[12]. The appropriate test method (using a KCl aerosol) establishes minimum efficiency curves for filters in bands over the size range 0.3–10 μm. A shorthand version of the filter's efficiency performance is the minimum efficiency reporting value (MERV), which is based on the lowest removal efficiencies for different particles in the test. The average removal efficiencies over the three size bands (0.3–1.0 μm, 1–3 μm and 3–10 μm) are calculated, and designated E_1, E_2, and E_3 respectively. From Table 5.2, the filter is then assigned an MERV value.

The efficiency ratings cited in Tables 5.1 and 5.2 relate specifically to the actual filters, such as those in Figure 5.1, which are the critical working components in an effective filtration system. However, the efficiency that they achieve in practice depends on the combined effect of the filter medium (including any pin holes in it due to manufacturing faults), and any fluid flow that bypasses the filter medium through leaks between the edge of the medium and the casing into which it is sealed.

Therefore, unless all such leaks are eliminated, which is generally unrealistic both technically and economically, the efficiency of an actual filter will inevitably tend to be less than the specified rating of the filter medium that it incorporates. The avoidance of leaks, or at least the minimizing of them, is consequently of crucial importance to the filter manufacturer, especially when the products are intended for the top-grade ULPA ratings (Eurovent 16 and 17).

Table 5.1 Eurovent and CEN classifications of ventilation air filter

Type	Eurovent class	CEN EN779 class	Efficiency (%)	Measured by:	Standards
Coarse dust filter	EU1	G1	<65	Synthetic dust weight arrestance	ASHRAE 52-76
	EU2	G2	65<80		
	EU3	G3	80<90		Eurovent 4/5
	EU4	G4	>90		
Fine dust filter	EU5	F5	40<60	Atmospheric dust spot efficiency	BS 6540
	EU6	F6	60<80		
	EU7	F7	80<90		DIN 24 185
	EU8	F8	90<95		
	EU9	F9	>95		EN 779
High efficient particulate air filter (HEPA)	EU10	H10	85	Sodium chloride or liquid aerosol	BS 3928
	EU11	H11	95		Eurovent 4/5
	EU12	H12	99.5		DIN 24 184
	EU13	H13	99.95		(DIN 24 183)
	EU14	H14	99.995		
Ultra low penetration air filter (ULPA)	EU15	U15	99.9995	Liquid aerosol	DIN 24 184
	EU16	U16	99.99995		(DIN 24 183)
	EU17	U17	99.999995		

The rigorous manufacturing and monitoring techniques that have been developed include automatic scanning of filters with CNC (Condensation Nuclei Counting) testing, using an oil-based aerosol.

One of the complications of these various standard test procedures is the diversity of particulate materials specified for them. They range from atmospheric dust to synthetic dusts, and from aerosols of oil to aqueous solutions that rapidly evaporate to leave a residue of fine crystals, with inevitable significant differences in the shape and size distribution of the resultant particles. The characteristics of the more common test materials are summarized in Table 5.3.

Wepfer[3] points out that, rather than a filter being characterized in terms of its efficiency against a particle of some specific size, it is more relevant to the user to know its efficiency for the Most Penetrating Particle Size (i.e. its MPPS efficiency), since it is this which ultimately determines the level of contamination in a clean room. The significance of this is brought out by Figure 5.1, which illustrates how the amount of contaminant penetrating may depend on the filtration velocity, the filter medium and the particle size; this arises from the nature of the depth filtration mechanisms by which HEPA and ULPA filters function. A test method and appropriate standard based on the MPPS has been developed by CEN as EN1822.

As Wepfer warns, filter efficiency is sometimes wrongly considered to be a physical constant, thus ignoring the variations of the wet-laid papermaking process with its own probability distribution. Figure 5.2 shows an example of such efficiency variations of a widely used ULPA medium from a leading manufacturer. A medium with a typical efficiency of 99.9999% (50% probability value) may therefore also have an efficiency of 99.9995% with a probability of 1%. That would

Table 5.2 MERV ratings from ASHRAE 52.2

Group number	MERV rating	Average efficiency in size range (%)		
		0.3–1.0 µm	1–3 µm	3–10 µm
1	1	–	–	$E_3<20$
	2	–	–	$E_3<20$
	3	–	–	$E_3<20$
	4	–	–	$E_3<20$
2	5	–	–	$20\le E_3<35$
	6	–	–	$35\le E_3<50$
	7	–	–	$50\le E_3<70$
	8	–	–	$70\le E_3$
3	9	–	$E_2<50$	$85\le E_3$
	10	–	$50\le E_2<65$	$85\le E_3$
	11	–	$65\le E_2<80$	$85\le E_3$
	12	–	$80\le E_2$	$90\le E_3$
4	13	$E_1<75$	$90\le E_2$	$90\le E_3$
	14	$75\le E_1<85$	$90\le E_2$	$90\le E_3$
	15	$85\le E_1<95$	$90\le E_2$	$90\le E_3$
	16	$95\le E_1$	$95\le E_2$	$95\le E_3$

give five times more penetration and five times more particles in the clean room. Thus, if the manufacturer of ULPA filters has to guarantee a maximum penetration (or minimum efficiency), the average value of penetration of this production lot could typically be about five times smaller than the guaranteed maximum.

5.2.2 Types of ventilation filter

Ventilation filters, such as those that are used to control the cleanliness of the air supply in office buildings or clean rooms, usually comprise a rectangular frame containing a sheet, pad or other array of filter medium. In the simplest form, the filter medium is flat as in Figure 5.3(a). The active surface area can be greatly increased by pleating the sheet as in Figure 5.3(b), especially if the pleats are

Table 5.3 Some dusts and aerosols for testing air filters

Designation	Material	Particle size (%wt.)	Range (μm)
Dusts[a]			
Air cleaner test dusts (Arizona road dust)	Quartz mineral		
AC coarse[b]			0–200
		10–14	0–5
		9–15	5–10
		11–18	10–20
		20–26	20–40
		27–33	40–80
		6–12	80–200
AC fine[b]			0–80
		37–41	0–5
		15–21	5–10
		13–19	10–20
		15–21	20–40
		6–12	40–80
ASHRAE 52/76	Molacco black	23	
	SAE J 726 fine	72	0–80
	Cotton linters	5	
BS2831 No. 3	Fused alumina		8–32
BS2831 No. 2	Fused alumina		0–10
Aerosols			
BS2831 No. 1	Methylene blue (solid[c])		0.6 (median)
BS3928 NaCl	Sodium chloride (solid[c])		0.6 (median)
DOP (USA)	Dioctylphthalate (liquid)		0.3 (median)
Uranine (France)	Sodium salt of fluorescein (solid[c])		0.12 (median)

[a] Dusts to these and many other specifications are manufactured by Particle Technology Limited.

[b] Formerly products of AC Spark Plus Division of General Motors marketed by A.C. Delco. Equivalent dusts are included in the nine grades of a new ISO specification due to be approved early in 1997.

[c] Generated as a dilute solution in water. Evaporation leaves solid particles for filtration.

deep as in Figure 5.3(c); with very deep pleats, the sheet effectively becomes a series of linked pockets as in Figure 5.3(d). There is also a very different format providing a sheet of filter medium, the roll filter, which enables the renewal of the active sheet by incorporating automatic indexing of a roll of medium, triggered by a pressure drop monitor.

Where a sheet or pad is used in a simple frame, then this can be of any suitable medium, from the simplest felt to a multi-layered construction, such as an active layer of synthetic medium or glass microfibres sandwiched between protective outer coverings of open spunbonded fabric.

The nature and diameter of the fibres in the active layer, and in some instances of their density of packing, determine the filtration efficiency and other performance characteristics of the filter. By judicious selection and control of these parameters, ventilation filters are produced in a wide variety of grades, ranging from coarse filters down to the finest with an efficiency greater than 99.999999% against 0.12 μm particles.

Most manufacturers of air filter media supply their media in these various ventilation filter formats. Thus, Freudenberg, one of the leading suppliers of nonwovens, under its Viledon brand name, has a product portfolio that includes:

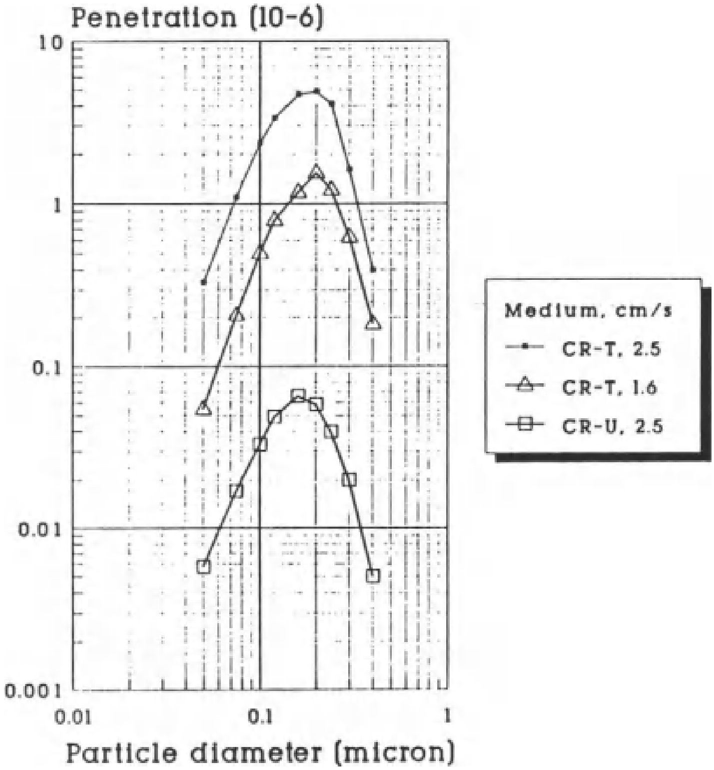


Figure 5.1. Medium penetration versus particle size depends on face velocity and nature of the medium. Tests on Luwa Ultrafilter CR with DEHS aerosol and CNC detection.

- a range of roll goods intended for cutting into specific shapes by the filter maker – these cover EU2 to EU5 (in particular to make simple sheet filters, although the range includes the R/260 material for roll filters);
- a large range of compact pocket filters (as in Figure 5.3(d)), which cover EU3 to EU9, and which are made from needlefelts and spunbonded materials, mostly with a multilayer structure;
- a range of MaxiPleat deep pleated filters, made from bonded glass fibres, for finer filtration, covering EU6 to EU11; and
- a range of specially pleated glass paper filters for HEPA and ULPA usage, covering EU10 to EU17.

5.2.3 Media for ventilation filters

As shown in Figure 5.3, ventilation filters are made either as sheets or pads of fibrous media, as flat arrays of corrugated (pleated) paper-like media, or as sets of filter pockets mounted in the same type of frame – so that any can be fitted into the same housings in the partition wall of a living or work room, or in an air

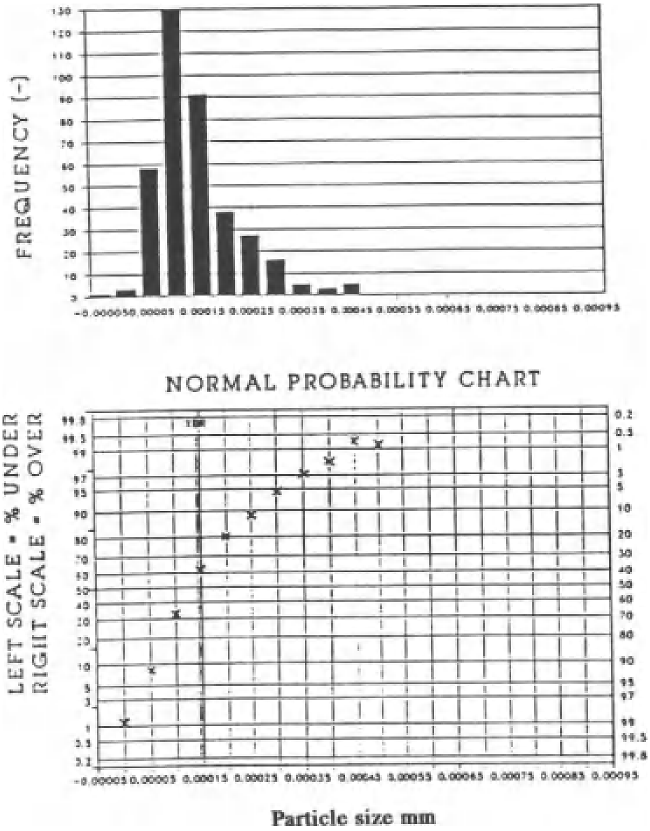


Figure 5.2. Statistical analysis of penetration of 370 production lots of ULPA filters. Penetration measured with laser particle counter at 0.12 μm.

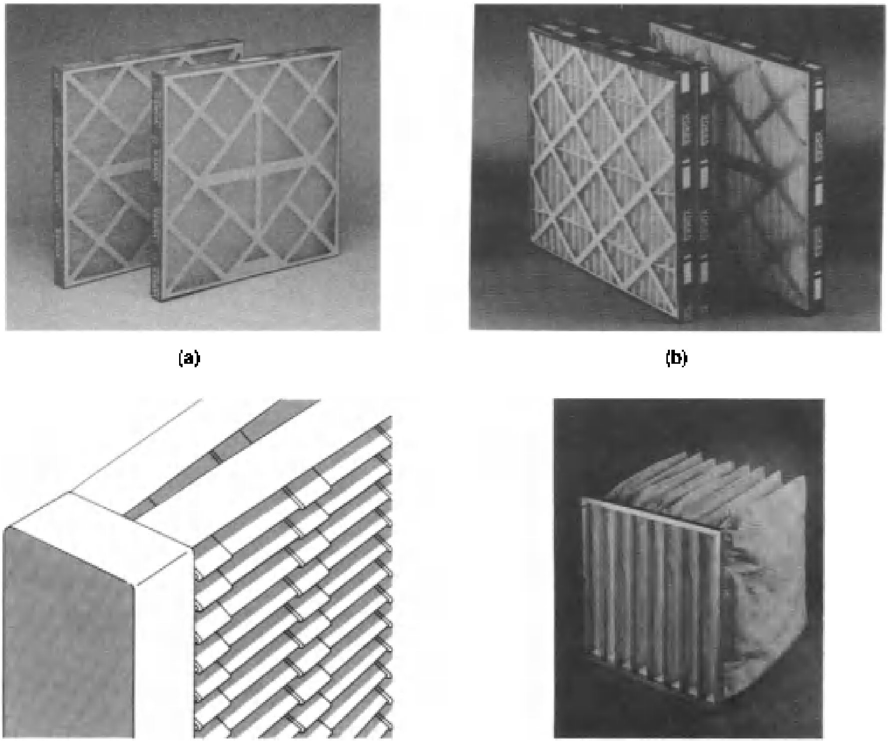
conditioning unit. Although, in principle, any kind of medium could be used for ventilation purposes, the following notes indicate the main media used. These notes supplement the comments on these media made elsewhere in the Handbook.

For a considerable period of time, ventilation filters largely employed simple or needled felts, or pleated papers. Nowadays, the demand for high levels of purity in the filtered air has led to the use of the more recently developed glass and polymeric media.

5.2.3.1 Glass fibre pads

Glass fibres provide a uniquely versatile source of filter media since, in addition to being very inert, they can be produced in controlled degrees of fineness down to exceptionally small diameters. This latter characteristic is of particular importance because the interception/diffusion mechanisms involved in air filtration result in the need for increasingly fine fibres as the size of particles to be captured is reduced.

The various processes for manufacturing glass fibres are briefly summarized in Chapter 4. One of these is the 'rotary' process used by Johns Manville to



(a) (b)

(c) (d)

Figure 5.3. (a) Simple flat panels; (b) shallow pleated panels; (c) deep pleats (for HEPA filters); (d) multipocket bag filters.

manufacture the relatively short and coarse fibres of their Micro-Aire products, of which the six basic grades are identified in Table 5.4. They are available in roll form (in widths up to 2.3 m and lengths up to 150 m), ready for in-plant cutting and sewing to fabricate into filters; they are colour coded for convenience, and can be supplied either with or without a choice of backing materials to provide extra strength. These media contain about 12 or 14% of phenolic resin as a binder; this gives the structure some resilience, so that it compresses when vacuum-packed for shipping, but recovers its full thickness as soon as a pack is opened.

The Micro-Aire range embraces ASHRAE efficiencies from 30 to 95%, nominally covering Eurovent classes up to EU9; in practice, Johns Manville is commercially focused on classes EU5 to EU9, with the coarse dust sector served by lower-cost materials. Examples of single- and dual-layer media are illustrated in Figure 5.4; typical performance curves are reproduced in Figure 5.5.

An alternative low-cost form of glass medium, illustrated in Figure 5.6, comprises continuous monofilament glass fibre of relatively coarse diameter (10–12 μm) bonded with a thermosetting resin. Thicknesses available range from 12 to 100 mm, the corresponding flow resistance and filtration efficiency characteristics of which are indicated in Table 5.5; the efficiency range extends up to Eurovent class EU4. The material is available in widths up to 2 m and roll lengths up to 100 m, and can be supplied with scrim backing.

5.2.3.2 *Glass microfibre papers*

Papers made from glass microfibres, as shown in Figure 5.7, with diameters as small as 0.3 μm or less, form the heart of the HEPA and ULPA filters that correspond to Eurovent classes from EU10 to EU17.

A major source of these papers is the 100 Series Micro-Strand Micro-Fibers produced by Johns Manville's pot and marble process as described in Chapter 4. There are 10 grades of these fibres, their corresponding spread of diameters being given in Table 4.7, while Table 4.6 identifies their chemical composition.

Examples of papers based on these fibres are the four classes of Lydair products summarized in Table 5.6, with typical data for the media in each class given in Tables 5.7–5.10. All of these media are available either plain or laminated to various scrims on one or both sides; the laminate options and identification system are listed in Table 5.11.

5.2.3.3 *Spunbonded polymers*

Confusion can arise (as further discussed in Chapter 3) from the term 'spunbonded media', since it is quite widely used both to embrace the three different categories of polymeric media made from extruded filaments (with fibres of distinctly different fineness), and also, much more often now, to identify one specific category. These media are taking an ever-increasing proportion of the general ventilation media market.

The one specific category, also once known as melt spun, is widely used to make relatively coarse continuous fibres, with diameters in the range 15–40 μm. Development of the original spinning process resulted in the finer (5–10 μm) fibres

Table 5.4 'Micro-Aire' glass fibre media[a]

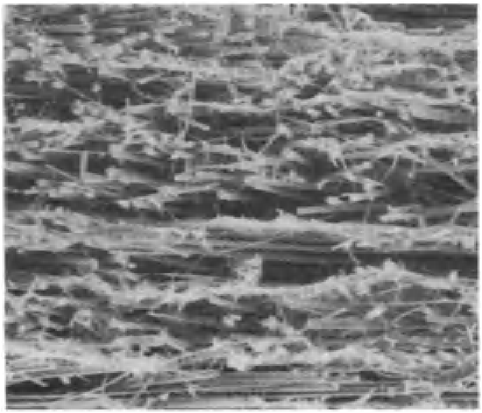
Grade	Colour	Thickness (mm)	Backing[b]	Weight (gm/m^2)	Permeability[c] (mm of water)	Filtration efficiency (%)		Flammability[e] class
						Flat sheet[d]	Ashrae 52.1	
AFS-3	Yellow	6.9	None	65	8.8	68–78	90–95	1
		6.9	B2	73	8.8	68–78	90–95	2
		6.9	BIGS	139	8.8	68–78	90–95	1
		6.9	BINW	105	8.8	68–78	90–95	1
AFS-4	Pink	6.9	None	54	4.4	48–58	80–85	1
		6.9	B2	66	4.4	48–58	80–85	2
		6.9	BIGS	131	4.4	48–58	80–85	1
		6.9	BINW	98	4.4	48–58	80–85	1
AF-11	Orange	6.4	None	61	1.6	18–28	55–65	1
		6.4	B2	75	1.9	18–28	55–65	2
		6.4	BIGS	141	1.6	18–28	55–65	1
		6.4	BINW	108	1.9	18–28	55–65	1
AF-18	Yellow/tan	6.4	None	97	1.6	10–20	50–55	1
		6.4	B2	111	1.9	10–20	55–65	2
		6.4	BIGS	176	1.6	10–20	55–65	1
		6.4	BINW	143	2.1	10–20	55–65	1
AMF-30	Yellow/tan	4.1	B2	62	0.8	5–15	30–40	2
		4.1	BIGS	128	0.8	5–15	30–40	1
		4.1	BINW	95	1.0	5–15	30–40	1
G.P.	Yellow/tan	6.4	None	76	0.9	8–18	40–50	1
		6.4	B2	90	1.3	8–18	40–50	2
		6.4	BIGS	156	0.9	8–18	40–50	1
		6.4	BINW	123	1.5	8–18	40–50	1

[a] Johns Manville Inc. [b] Backings: BIGS, woven glass scrim; recommended maximum air temperature is 167°C; BINW, non-woven mat; recommended maximum air temperature is 121°C; B2, non-woven polyester or nylon; maximum air temperature is 121°C. [c] Nominal pressure drop at an air velocity of 7.6 m/min through a flat sheet. [d] For 0.3–0.5 µm particles at an air velocity of 7.6 m/min through a flat sheet. [e] Underwriters Laboratories Class 1 or 2 for specific flame and smoke requirements.

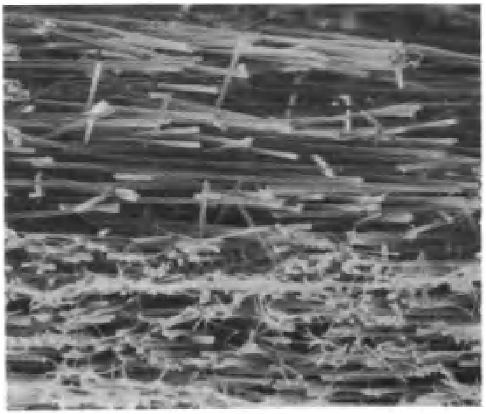
of melt blown media: yet further development has led to Du Pont's even finer flash spun fibres. More information on this set of media types is given in Chapter 3.

Because of the relative coarseness of their continuous fibres, the main role in air filtration for spunbonded media, such as BBA's Reemay, is as protective or support layers in combination with finer media of higher efficiency, and they would normally be used as pleated sheets. They also serve as prefilters in which to trap larger particles, and in composite media such as BBA's Qualiflo, to achieve efficiencies equivalent to EU9 and higher. For further information on these media, see Chapter 3.

The company Irema Ireland has developed a patented version of melt spinning that enables it to produce a wide range of fibre sizes, from 40 μm down to microfibres of the order of 0.5 μm. Irema attributes its success to the flexibility of the very small scale of the original production facilities, which were focused exclusively on the specialist needs of surgical masks. Subsequently the range of 100% polypropylene binderless Micro 2000 Plus media was developed for air



(a)



(b)

Figure 5.4. ASHRAE grade glass filter media: (a) single layer, (b) dual layer. (Photograph: Lydall, Inc)

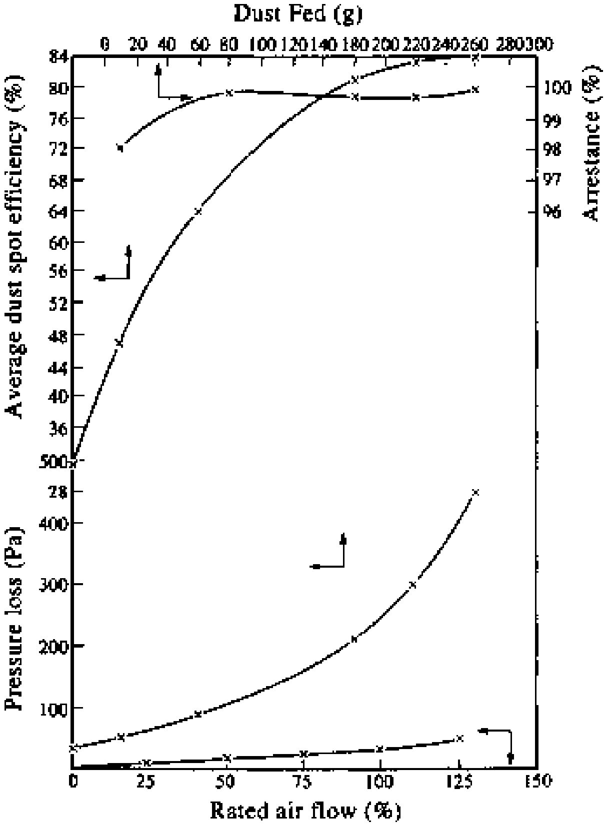


Figure 5.5. Typical ASHRAE test curves.

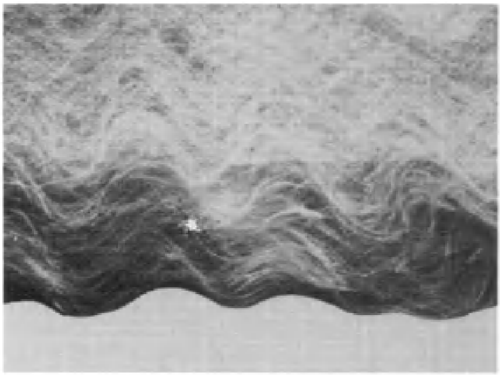


Figure 5.6. Continuous monofibre glass filter medium. (Photograph: Lancaster Glass Fibre Ltd)

filtration. These lofted uncalendered media are in the form of 5–10 mm sandwiches, comprising 60/65 g/m^2 of graded fibres enclosed between cover and backing scrim. They may be used as flat sheets or deep pleated arrays. The characteristics of standard products are given in Table 5.12; filtration efficiencies extend from Eurovent class EU5 to EU9.

5.2.3.4 Meltblown media

The sophisticated techniques of melt blowing permit the production of graded fine short fibres with diameters in the size range 5–10 μm. These form the basis of filters for finer dusts, corresponding to Eurovent classes EU5 to EU8 and beyond; but note that initial efficiencies tend to be inflated by unstable static charges induced by the manufacturing process. Examples of these are the range of polypropylene media with colour-coded scrim backing summarized in Table 5.13.

Other polymers are also available in meltblown form: Hollingsworth and Vose, for example, supplies polyester, nylon and polyphenylene sulphone as meltblown webs, in both simple and composite forms.

Table 5.5 Resin bonded continuous monofilament glass filter media[a]

Thickness (mm)	Clean resistance to air flow (mm WG)			Average efficiency[b] (%)	Arrestance load[b] (g/m^2)
	1.0 m/s	1.5 m/s	2.0 m/s		
12	–	–	4.50	75	650
25	–	–	5.00	80	750
50	0.80	1.50	5.00	86	850
75	1.60	3.00	6.00	90	1050
100	2.60	4.00	6.50	92	1200

[a] Lancaster Glass Fibre Limited.

[b] Test velocity 2 m/s.

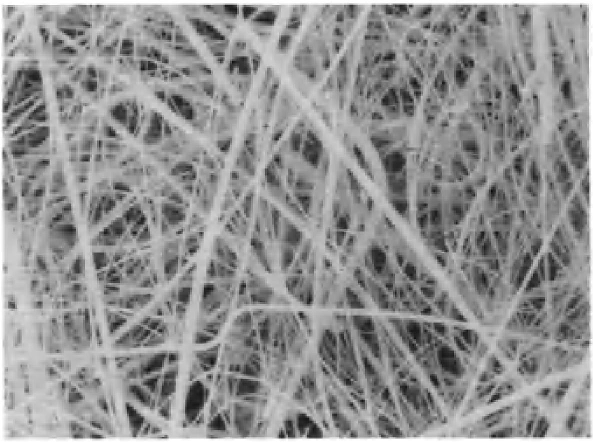


Figure 5.7. Magnified view of microfibre glass paper. (Photograph: Whatman International Ltd)

5.2.3.5 Plastic foam

Reticulated polyurethane foams are available in a range of pore size grades and sheet thicknesses, which can achieve Eurovent ratings from EU1 to EU3. For example, Figure 5.8 shows an efficiency of almost 90% for a 10 mm thick sheet of the finest grade (80 ppi, pores per linear inch). An advantage of plastic foam is that it can be readily washed and reused repeatedly. (More information on plastic foams as filter media is given in Chapter 7.)

5.2.3.6 Expanded metal mesh

Expanded metal mesh may be used dry as a grease trap or demister. It may also be used when wetted with a replaceable oil or adhesive for particular collection, with efficiencies corresponding to Eurovent ratings of EU1 or EU2, as illustrated by the typical performance data given in Table 5.14. In any of these roles, it has the advantage of being readily washed and reused repeatedly. (More detail on expanded metal mesh as a filter medium is given in Chapter 6.)

5.2.4 Electrostatically charged media

It is well known that the efficiency of a filter can be enhanced significantly by an electrostatic charge on the fibres of the medium. The earliest practical example of this was the resin/wool mixture used by Hansen[4] as the basis of the military gas mask patented by him in 1931. An account of this, and of some of the secrecy that understandably surrounded it, was given by Feltham[5], who commented on the notable absence from the patent of any reference to electrical action on which its function depends.

Table 5.6 Summary of 'Lydair' glass filter media[a]

Class	Number of standard grades	Filtration efficiency range (%)		Typical applications
		ASHRAE	DOP[b]	
1000	13	30–95	15–65	Heating and ventilating, inlets to compressors and turbines, paint spray booths
2000	4	–	86–98.5	Prefilter for HEPA, hospital air, computer disc drive, chemical and pharmaceutical processing
3000	6	–	99.91–99.99	HEPA for clean rooms for hospitals, microelectronics industry, processing industries, aerospace, film manufacturing
5000	7	–	99.999 up	ULPA for clean rooms for pharmaceutical processing, microelectronics industry, genetic research, mainframe computers

[a] Lydall, Inc.

[b] 0.3 µm DOP particles @ 3.2 m/min for Classes 1000, 2000 and 3000.
0.12 µm DOP particles @ 1.07 m/min for Class 5000.

Table 5.7 Class 1000 'Lydair' glass paper media[a]

Grade number	1224	1224B	1235[b]	1229	1229A	1229B	1272[b]	1381	1232	1232a	1251[b]	1254	1254A
DOP penetration[c] (%) 0.3 μm particle @ 3.2 m/min	35	35	35	50	50	50	50	75	85	85	85	–	–
DOP efficiency[c] (%) 0.3 μm particle @ 3.2 m/min	65	65	65	50	50	50	50	25	15	15	15	–	–
ASHRAE efficiency (%)	90–95	90–95	90–95	80–90	80–90	80–90	80–90	60–70	55–60	55–60	55–60	40–45	30–40
Air permeability (l/s @ 12.5 mm WG)	13	13	13	20	20	20	20	43	60	69	64	116	162
Pressure drop with air @ 3.2 m/min (mm WG)	5.0	5.0	5.0	3.5	3.5	3.5	3.5	1.5	0.8	0.8	0.8	–	–
Basis weight (g/m^2)	73	81	76	73	68	81	76	73	70	63	76	63	49
Thickness (mm)	0.38	0.43	0.38	0.38	0.36	0.43	0.38	0.38	0.36	0.33	0.38	0.33	0.25
Tensile strength (kgf/cm)													
MD (machine direction)	1.35	1.42	1.35	1.35	1.27	1.42	1.35	1.35	1.27	1.23	1.35	0.96	0.77
CD (cross direction)	0.77	0.84	0.77	0.77	0.77	0.84	0.77	0.77	0.77	0.69	0.77	0.69	0.65
Water repellancy (mm)	381	381	254	381	381	381	254	254	254	254	127	–	–
Yield (m^2/kg)	13.7	12.6	13.1	13.7	15.0	12.6	13.1	13.7	14.7	16.2	13.1	16.21	21.0

[a] Lydall, Inc.

[b] Denotes dual layer for higher dust holding capacity and longer life.

[c] % penetration = 100 − % efficiency.

Table 5.8 Class 2000 'Lydair' glass paper media[a]

Grade number	2233	2221	2220	2400
DOP penetration[b] (%) 0.3 μm particle @ 3.2 m/min	1.5	4.0	7.0	14.0
DOP efficiency[b] (%) 0.3 μm particle @ 3.2 m/min	98.5	96.0	93.0	86.0
Pressure drop with air @ 3.2 m/min (mm WG)	17	15	12	9
Basis weight (g/m^2)	73	83	73	73
Thickness (mm)	0.38	0.38	0.38	0.38
Tensile strength (kgf/cm)				
MD (machine direction)	1.15	1.15	1.15	1.15
CD (cross direction)	0.69	0.69	0.69	0.69
Water repellancy (mm)	254	635	254	254
Combustibles (%)	5	5	5	5
Yield (m^2/kg)	13.7	13.7	13.7	13.7

[a] Lydall, Inc.

[b] % penetration = 100 % efficiency.

Table 5.9 Class 3000 'Lydair' glass paper media[a]

Grade number	3215	3428	3255[b]	3255-N	3514	3248
DOP penetration[c] (%) 0.3 μm particle @ 3.2 m/min	0.015	0.015	0.015	0.015	0.030	0.060
DOP efficiency[c] (%) 0.3 μm particle @ 3.2 m/min	99.985	99.985	99.985	99.985	99.97	99.94
Pressure drop with air @ 3.2 m/min (mm WG)	36	31	36	36	32	30
Basis weight (g/m^2)	73	73	86	86	49	73
Thickness (mm)	0.38	0.38	0.46	0.46	0.25	0.38
Tensile strength (kgf/cm)						
MD (machine direction)	1.35	1.04	1.47	1.47	0.96	1.15
CD (cross direction)	0.69	0.61	0.96	0.96	0.54	0.69
Water repellancy (mm)	381	254	762	762	254	254
Combustibles (%)	5	5	5	10	5	5
Yield (m^2/kg)	13.7	13.7	11.6	11.6	20.5	13.7

[a] Lydall, Inc.

[b] Denotes dual layer for higher dust holding capacity and longer life.

[c] % penetration = 100 − % efficiency.

The key to the Hansen filter is the friction generated during carding of a mixture of wool and particles of amber (fossilized resin). This induces a positive charge on the wool and a negative one on the resin; moreover, the charge is stable because of the very low conductivity of resin, even though wool is a comparatively good conductor. British military respirators were based on this technology through the 1940s and into the 1950s, with some use also of asbestos fibres, until the development of glass microfibres provided an alternative. Even today, Hansen-type material (without asbestos) still finds limited use in some industrial face masks.

Table 5.10 **Class 500 'Lydair' glass paper media[a]**

Grade number	5721	5588	5373	5471	5252	5470	5375
DOP penetration[b] (%) 0.12 μm particle @ 1.07 m/min	0.000001	0.00001	0.0001	0.0001	<0.001	<0.001	<0.001
DOP efficiency[b] (%) 0.12 μm particle @ 1.07 m/min	99.999999	99.99999	99.9999	99.9999	>99.999	>99.999	99.999
Pressure drop with air @ 3.2 m/min (mm WG)	80	63	63	50	50	42	42
Basis weight (g/m²)	78	78	73	73	73	73	73
Thickness (mm)	0.41	0.41	0.38	0.38	0.38	0.38	0.38
Tensile strength (kgf/cm)							
MD (machine direction)	1.35	1.35	1.35	1.04	1.35	1.04	1.35
CD (cross direction)	0.77	0.77	0.69	0.61	0.69	0.61	0.69
Water repellancy (mm)	254	254	508	254	508	254	381
Combustibles (%)	5	5	5	5	5	5	5
Yield (m²/kg)	12.8	12.8	13.7	13.7	13.7	13.7	13.7

[a] Lydall, Inc.

[b] % penetration = 100 − % efficiency.

Table 5.11 **Laminated options for 'Lydair' glass filter media[a]**

Scrim material	Basis weight (g/m²)	Letter code[b]
Reemay	18	A
Woven glass cloth	98	B
Hollitex (calendered Reemay)	16	C
Cerex	28	D
Reemay	32	E
Cerex	32	F
No scrim	–	O

[a] Lydall, Inc.

[b] Example: 1224 A/A specifies – standard grade 1224.
– wire side scrim 18 g/m² Reemay.
– felt side scrim 18 g/m² Reemay.

Because of the high resistivity of synthetic polymers, and because of the nature of the spinning process, fibres as produced tend initially to have a static charge that enhances the initial filtration efficiency; for example, Irema Ireland specifically refers to this feature in respect of its Micro 2000 Plus media in Table 5.12. However, this 'natural static' is generally not stable and soon decays.

5.2.4.1 Corona charged media

A stable static charge can be applied to polymer fibres by a corona discharge. This develops rapidly into a dipole configuration, with each fibre comprising a multitude of frozen-in electric polarization cells or 'electrets', analogous to a series of magnets, so that particles are attracted to the fibres. As shown

Table 5.12 'Micro 2000 Plus' continous fibre synthetic media[a]

Reference no.	Weight (gm/m^2)	Grade/class		Initial NaCl 0.4 µm (%)	Clean pressure drop (Pa)	Dust holding[b] capacity (gm/m^2)	Face velocity (m/s)
		ASHRAE efficiency (%)	Eurovent				
50.1F.19E.a	120	45	EU5	25	25 maximum	60	0.15
60.1A.19E.a	120	60/65	EU6	35	25 maximum	50	0.15
80.1C.19E.a	110	80/85	EU7	65	55 maximum	55	0.15
90.1D.18E.a	120	90/95	EU8	80	35 maximum	45	0.15
95.1F.19E.a	120	95	EU9	85	85 maximum	40	0.15

[a] Irema Ireland.

[b] Dust holding capacity of flat sheet to pressure drop of 250 Pa

Table 5.13 'Poly-Aire' melt blown polypropylene filter media[a]

Grade number	PF-95	PF-85	PF-65	PF-45
Colour	Yellow	Magenta	Orange	White
Maximum thickness (mm)	6.5	6.5	6.5	6.5
Basis weight (g/m^2)	160–194	135–188	118–160	80–135
Air permeability[b] (mm WG)	3.8–6.4	2.5–5.1	0.7–2.3	0.2–1.0
Initial flat sheet particle efficiency[c] (%)	60–70	50–60	15–25	6–14
Average ASHRAE efficiency[d] (%)	90–95	80–85	60–65	40–45
Eurovent class[e]	EU8	EU7	EU6	EU5
Dust capacity (g/m^2)	55–65	79–95	120–150	170–215
Flammability class[f]	2	2	2	2

[a] Johns Manville Inc.

[b] Nominal pressure drop measured at an air velocity of 12.7 cm/s through a flat sheet.

[c] Measured at an air velocity of 12.7 cm/s through a flat sheet with 0.3–0.5 µm particles.

[d] Applicable to finished air cleaning devices, based on ASHRAE-52.1. Efficiency depends on the filter design and construction.

[e] Filter media alone will meet Class 2 rating when tested in accordance with UL-900 'Standard for air filter units'.

[f] Available in 710 mm wide rolls; lengths 68 m for PF-95, 76 m for other grades.

schematically in Figure 5.9 and described by Van Turnhout and Albers[6], negatively or positively charged particles are directly attracted by a coulombic force, while uncharged particles may be polarized into dipoles prior to attraction.

The magnitude of enhancement achievable depends on the nature and the geometry of the fibres. Thus, the charge density achievable with 3M's Filtrete Type S media, comprising round 5–10 μm diameter meltblown fibres of low-density polypropylene, is twice that for polycarbonate fibres (8 as compared with 4 nC/cm²); but it is an order of magnitude smaller than the 75 nC/cm² surface charge of 3M's split-film high-density polypropylene Filtrete Type G, which comprises coarse fibres of relatively large rectangular cross section (10 μm × 60 μm). This results in significant differences in the electromagnetic field

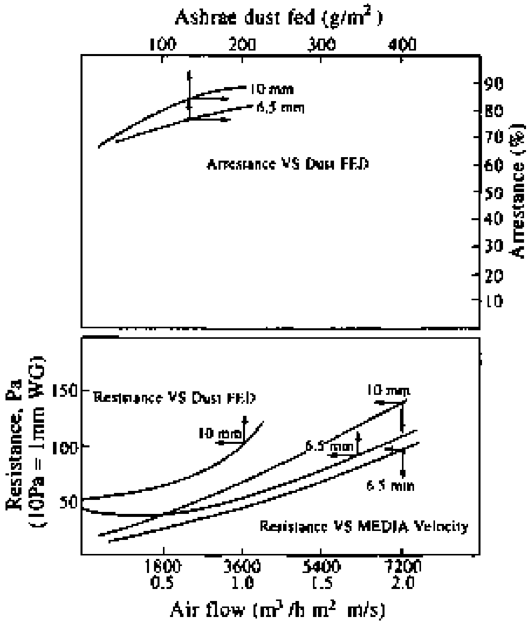


Figure 5.8. Filtration performance of 80 ppi 'Poret' reticulated foam based on ASHRAE 52-68 procedure at a face velocity of 0.8 m/s.

Table 5.14 Typical results of tests[a] of expanded metal air filter[b]

Filter type	Type E		Type SP		Type SS	
Thickness (mm)	25	50	25	50	25	50
Air velocity (m/s)	2	2	2	2	2	2
Clean resistance (Pa)	37	39	54	78	34	39
Final resistance (Pa)	287	289	304	328	284	289
Average synthetic dust arrestance (%)	72	74	78	85	66	77

[a] BS 6540 Part I: Section 3.

[b] The Expanded Metal Company Limited.

surrounding the two types of fibre, with the stronger distorted field of the split fibres of Type G being more able to polarize uncharged particles.

Whilst there are grades manufactured frequently tailored to order, there are three standard grades of the Filtrete Type S media, all of which combine 40 g/m^2 of meltblown fibres with a 30 g/m^2 polypropylene fleece substrate. Their initial atmospheric dust spot efficiencies based on ASHRAE 52.1 are: 84% for SBMF-40V, and 89% for SBMF-40PF and SBMF-40VF, corresponding to Eurovent class EU7. Relationships between particle diameter and efficiency, face velocity and efficiency, and face velocity and pressure drop are given in Figures 5.10–5.12.

The Filtrete Type G media are produced not by any form of spinning but by needling the flat fibres generated by a film stretching process as outlined in Chapter 3. Stretching a film of polypropylene causes the molecules to realign in the direction of the force; the film thereby becomes strong in this direction and weak across it, and can then be split into fibres. These fibres are subjected to the needling process used for manufacturing needlefelts, as described in Chapter 3;

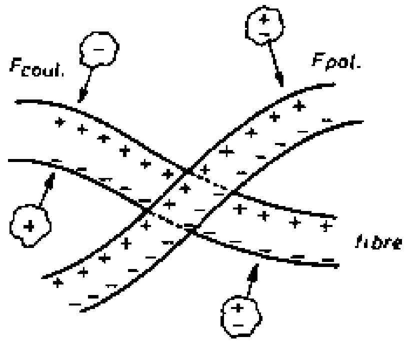


Figure 5.9. Schematic illustration of two modes of attraction of particles to charged fibres. The two charged particles on the left are attached by a Coulombic force. Those on the right are converted into dipoles and attracted by a polarization force.

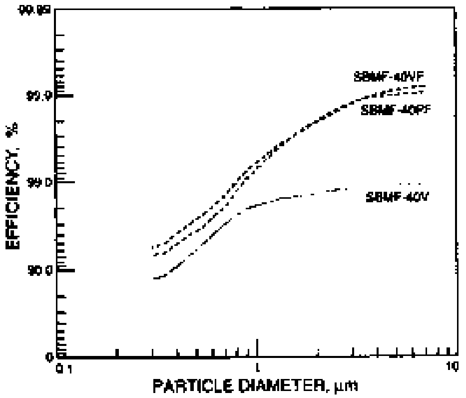


Figure 5.10. Efficiency versus particle size (@ 40 ft/m) for Filtrete Type S. (Illustration: 3M Filtration Products)

sometimes this involves combining the fibres with an open woven scrim located either in the centre of the layer of fibres (denoted by GS) or beneath it (GSB).

These media are produced in a range of basis weights extending from 30 to 300 g/m^2 (indicated by a corresponding suffix, such as GS-100). ASHRAE initial dust spot ratings for a representative number are listed in Table 5.15, corresponding to Eurovent classes between EU5 and EU9. Relationships between particle diameter and efficiency, face velocity and efficiency, and face velocity and pressure drop are given in Figures 5.13–5.15. The impact of the basis weight of the media (g/m^2) on filtration efficiency and on pressure drop is indicated in Figures 5.16 and 5.17.

Comparison of the face velocity versus pressure drop diagrams for Type S and Type G Filtrete shows that the latter has a major advantage in this respect, as a consequence of the high charge density permitting a very open structure, whilst still achieving high filtration efficiencies.

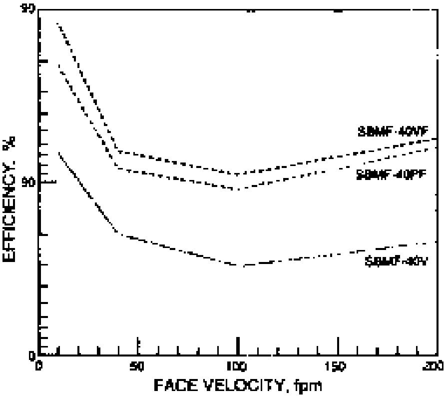


Figure 5.11. Efficiency versus face velocity for Filtrete Type S. (Illustration: 3M Filtration Products)

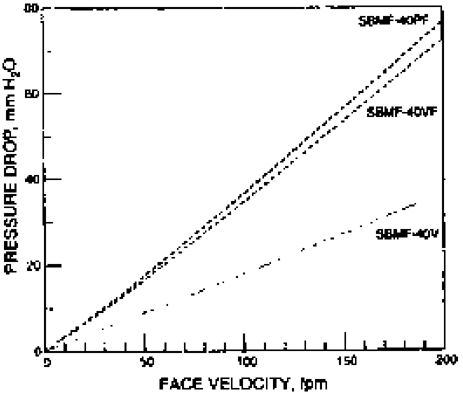


Figure 5.12. Pressure drop versus face velocity for Filtrete Type S. (Illustration: 3M Filtration Products)

Extended tests are reported to demonstrate the high charge stability of Filtrete in respect of time (a decrease of no more than 1.2% over a shelf-life of 4 years), temperature (lengthy stability at up to 80°C, safe for short periods at up to 100°C), and humidity (a very long service life at tropical conditions of 100% humidity at 45°C).

5.2.4.2 Triboelectric media

Electrostatic charges can also be generated by triboelectric means when fibres of different polymers are rubbed together, one becoming positively charged and the other negatively; Table 5.16 lists textile materials in a triboelectric series, where one higher in the series will become positively charged if rubbed with any of those below(7).

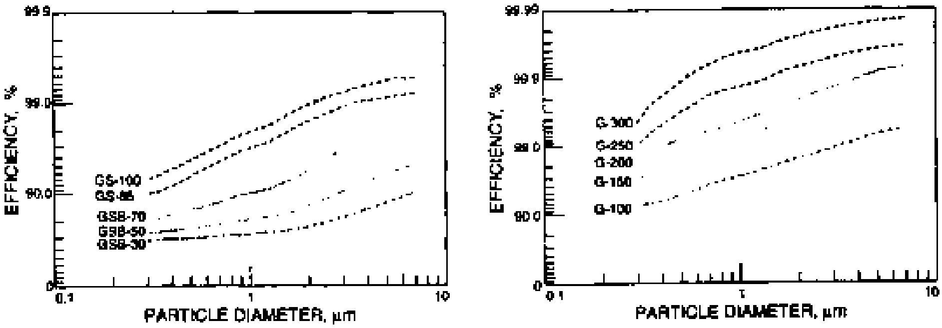
Table 5.15 'Filtrete' Type G media[a]

Grade	Basis weight (g/m^2)	Scrim location		Filtration efficiency	
		Centre	Backing	ASHRAE[b]	Eurovent class[c]
GSB-30	30	No	Yes	52	–
GSB-50	50	No	Yes	64	–
GSB-70	70	No	Yes	74	–
GS-85	85	Yes	No	78	–
GS-100	100	Yes	No	80	–
G-100	100	Yes	No	80	–
G-150	150	No	No	92	6
G-200	200	No	No	95	7
G-250	250	No	No	96	8
G-300	300	No	No	99	9

[a] 3M Filtration Products.

[b] 'Initial atmospheric dust spot' according to ASHRAE 52.1-1992.

[c] Eurovent ratings are only given where full tests have been completed @ 0.20 m/s.



5.13. Efficiency versus particle size (@ 0.2 m/s) for Filtrete Type G. (Illustration: 3M Filtration Products)

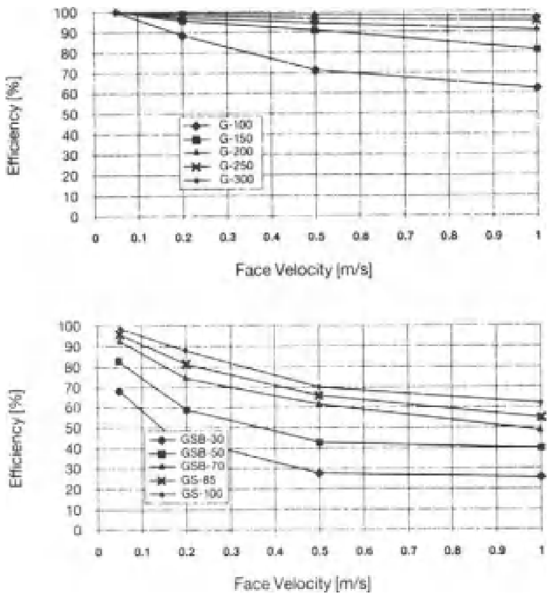


Figure 5.14. Efficiency versus face velocity for Filtrete Type G. (Illustration: 3M Filtration Products)

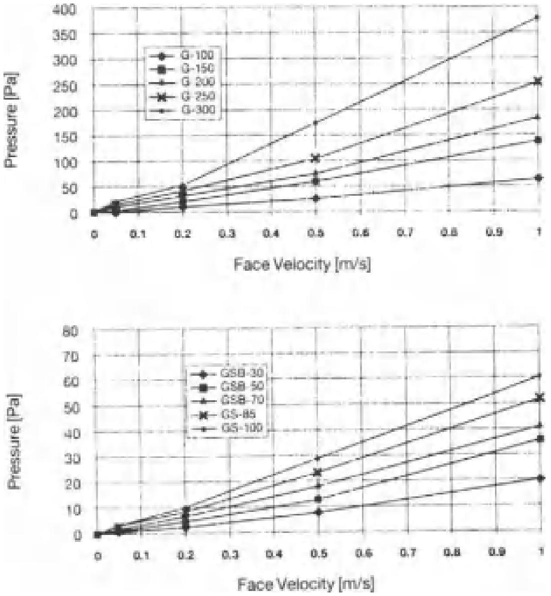


Figure 5.15. Pressure drop versus face velocity for Filtrete Type G. (Illustration: 3M Filtration Products)

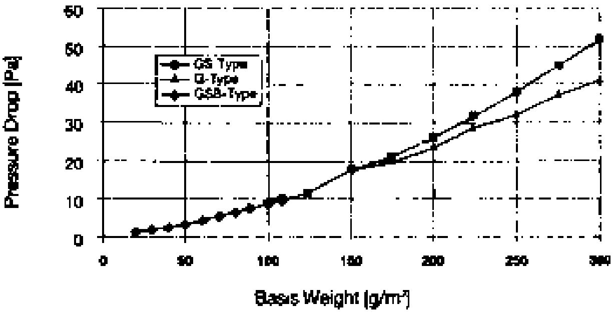


Figure 5.16. Pressure drop versus basis weight for Filtrete Type G. (Illustration: 3M Filtration Products)

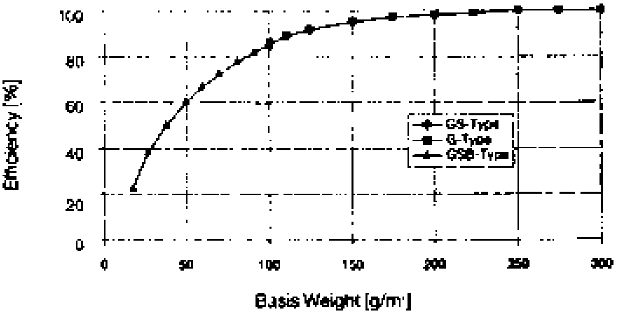


Figure 5.17. Efficiency versus basis weight for Filtrete Type G. (Illustration: 3M filtration Products)

Table 5.16 Triboelectric series of textile materials

Positive

Wool
Nylon 66
Nylon 6
Silk
Regenerated cellulose
Cotton
Polyvinyl alcohol
Chlorinated wool
Cellulose triacetate
Calcium alginate
Acrylic
Cellulose diacetate
Polytetrafluorothylene
Polyethylene
Polypropylene
Poly(ethylene terephthalate)
Poly(butylene terephthalate)
Modacrylic
Chlorofibre

Negative

Media designed to carry triboelectric charges need careful selection of their component fibres to achieve efficient charge creation and retention. The needs for a good electrostatically charged medium are that it should:

- have as high an amount of charge as possible;
- have as high an electrostatic field intensity as possible; and
- hold its charge for a long time, preferably for the life of the filter.

The main triboelectric fibre couple for some time was polypropylene and modacrylic, and this is still exemplified by Hollingsworth and Vose's Technostat media (formally Hepworth)(8).

A newer fibre grouping is polypropylene with polymetaphenylene isophthalamide, supplied as Tribo media by Texel(9), with claims for superior performance. These fibre mixtures are well suited to needle punching technology, and there is evidence that they have much better charge characteristics than corona charged material(10).

5.2.5 Combination filters

The filters and their associated media discussed so far in this chapter have all been concerned with the removal of dusts, i.e. solid granules, from suspension in atmospheric air. It may also be necessary, however, in an air conditioning operation, to remove gaseous impurities, in particular odorous chemicals. This can be done at the same time as the removal of dust if the filter medium contains (or is made up of) an adsorptive substance such as activated carbon.

It is, of course, perfectly possible to have activated carbon 'filters', whose sole purpose is to remove gaseous impurities, and which provide no filtration of particles at all (or not intentionally). However, most activated carbon filters for contaminated air are made in much the same way as dust filters, and the combined duty is now a common feature of air conditioning. Thus, Freudenberg supplies its Viledon DuoPleat Filter in a range of standard AC frame sizes, as a rigid deep pleated design, capable of EU7-rated filtration. The medium is a combination of activated carbon and a triple-layered synthetic fibre non-woven, with microfibres forming the central layer(11). (The similar Viledon CarboPleat Filter is for odour removal only.) BBA's Qualiflo media (see Chapter 3, Section 3.6) can include activated carbon particles in the matrix of a resin-bonded polyester fibre material, also to provide odour removal combined with fine dust filtration.

It is normally intended that very fine ('absolute') air cleaning filters should remove bacteria and viruses by direct filtration, so that air can be sterilized by such action. However, there is now a growing range of combination media where the fibres have been treated in some way with a range of anti-bacterial coatings, to provide an alternative (or supplementary) means of pathogen removal. These treatments may work by physical action (damaging the impinging cells) or chemical destruction on the pathogen particles, and may be 'permanent' or have a definite active life, after which the filter is discarded or retreated.

Another combination activity is the combination of filtration with some kind of chemical activity, such as the catalytic destruction of gaseous impurities, like dioxins and furans. Thus, W L Gore has its Remedia D/F catalyst filter system(12), which is intended to remove dioxins from an exhaust gas stream to well below acceptable discharge values, by contact with catalyst particles held in a fibre matrix, and, at the same time, remove fine solid particles, on which dioxin may also have become adsorbed.

5.3 Other Atmospheric Air Filtration

The previous section was concerned with the conditioning of air in large spaces, but there are several other applications of filters to ambient air, which impose special requirements upon their associated media. These include the air intake filters on engines of all types (mobile or stationary), the respirators or filters used to protect individual people or the occupants of vehicles from the impurities in the atmosphere, and finally the filters used to prevent the emission of collected dust from suction (vacuum) cleaners back into the living space.

5.3.1 Engine air filters

The air drawn in to engines of all kinds for the purpose of combustion needs to be cleaned of dust particles, which might otherwise damage the moving parts of the engine – the pistons and cylinders, or turbine blades. As engines improve in design and performance, so the need for ever-cleaner air has driven the demand for increasing efficiencies in the intake air filters.

The filter used in mobile internal combustion engines has changed little over the years, apart from increased use of pleated media. However the material of the filter medium improved markedly with the arrival of synthetic needlefelts and the spun polymeric media, which are steadily taking market share from the older paper media, although the latter still holds the major share (estimated at 79% of the market in 2000(13) for both treated and untreated paper).

The automobile engine filter is well known to most vehicle owners, as a shallow, drum-shaped item containing a ring of radially pleated medium, which has to be changed at regular intervals. The turbine air intake filter, on the other hand, may be a huge array of panel filters, made from the same kinds of media as are used in air conditioning systems. Pocket and deep pleat filters are frequently used for this application.

5.3.2 Respirators

Individual respirators (or face masks) are essential safety equipment in many dust-generating industrial applications, and are increasingly being worn by people walking or cycling in congested town centres. They are simple structures –

a device to hold a small piece of filter medium, which can comfortably be held firmly against the mouth and nose, and the medium itself.

The chief characteristics of the medium for respirators are efficient removal of solid particles and lowest possible resistance to flow, so as to restrict the breathing process as little as possible. Bearing in mind the current concern over the emission of PM2.5 (2.5 μm) dust particles by vehicle diesel engines, it can be seen that the respirator has quite a task to keep soot particles out of the lungs.

Typical of the media used in respirators are the needlefelts described in Table 5.17: relatively thick sheets of needlefelts, made mainly from a mixture of polypropylene and polyacrylonitryl fibres. These have low breathing resistances, allowing the making of a small mask, and avoiding the fitting of a bypass valve used when breathing resistance rises too high.

5.3.3 Cabin air filtration

The cabins of vehicles used for personal and public transport are as much in need of clean air as are living and working spaces, although manufacturers were a lot slower to realize and supply this need. People are tending to spend longer times in vehicles of all kinds, and there is currently wide acceptance of the need to provide clean air, especially inside automobiles driving in polluted areas, and in aircraft to reduce the transfer of illnesses.

Road vehicles are increasingly being fitted with cabin filters, mainly in the form of pads of needlefelts or spun polymers, cut to fit the channels available in the confined spaces of the vehicle's ventilation system. These need to be efficient enough to keep out the exhaust fumes and pollen that can be so much a nuisance within the vehicle.

Packed aircraft, often travelling long distances, form a good breeding ground for bacteria and viruses, and the air circulation systems of aircraft are increasingly being required to filter out submicrometre particles, to ensure that their passengers reach their destinations without acquiring diseases en route.

Table 5.17 Viledon needlefelts for respirators[a]

Type	Basis weight[b]	Thickness (mm)	Fibre types[c]	NaCl penetration[d]	Flow resist[e]
2396	160	2.5	PP + PAN	6	8
2397	250	3.0	PP + PAN	2.5	14
2398	350	3.5	PP + PAN	1	25
2402	210	2.4	PES + PP + PAN	0.9	15

[a] Freudenberg Vliesstoffe KG.

[b] In g/m^2.

[c] PP, polypropylene; PAN, polyacrylonitryl; PES, polyethersulphone.

[d] Maximum penetration (%) at 8 cm/s.

[e] Maximum flow resistance (Pa) at 8 cm/s.

ASHRAE is working on a new standard (161) to cover air quality in commercial aircraft.

5.3.4 Vacuum cleaner filters

The domestic or commercial vacuum cleaner is a significant user of filter media, mainly in the dust collecting bag, but for other purposes as well. Even the newer cyclonic designs still need final exit filters to stop the emission of fine particles back into living or working spaces. There are three stages of filtration in the standard vacuum cleaner:

- the main dust collecting bag;
- the motor protection filter; and
- the final exhaust filter.

The bag, in a sense, acts as a prefilter, collecting only coarse dust. It is normally made from cellulose paper, although non-woven media are used where wet cleaning is undertaken. The medium needs to be mechanically strong, and have a good dust retention capability for coarse dusts.

There is then a filter to protect the cleaner's electric motor, both from the fine dust that gets through the bag, and from a coarse dust invasion should the bag fail or be incorrectly installed. The medium needs to be able to collect fine particles, and will often be a two-layer material, made from non-wovens, and often including electret media.

The final exhaust filter has to retain very fine dusts, especially including pollen grains, bacteria and other micro-organisms. It must supply this high collection efficiency without affecting the cleaner's suction performance. This medium is now made from microfibre non-wovens, very probably with an electret component. For this function, Freudenberg supplies a three-layer medium, the central one being an electret, made from polycarbonate fibres, sandwiched between two supporting layers of polypropylene. Some typical examples of this medium are given in Table 5.18.

Table 5.18 Viledon exhaust filter media for vacuum cleaners[a]

Property	LRS 302	LRS 304	LRS 305	LRS 306	LRS 310	LRS 311
Basis weight (g/m^2)	170	177	180	174	170	120
M/f weight[b] (g/m^2)	40	14	20	14	7	20
M/f diameter[c] (µm)	4–6	7–10	7–10	7–10	7–10	7–10
NaCl penetration[d] (%)	0.5	10	6	10	28	6
Pressure drop[d] (Pa)	100	23	30	23	11	30

[a] Freudenberg Vliesstoffe KG.

[b] Basis weight of central microfibre layer.

[c] Microfibre diameter range.

[d] Maximum level at 8 cm/s.

5.4 Industrial Dust Removal Filters

Whilst the air and gas cleaning filters described so far have some quite severe constraints in terms of fine particle removal, the filters used in industrial processes have a rather different problem to face – that of relatively high quantities of dust in the inlet gas, often so much as to need arrangements to remove the collected dust at regular intervals. There are two main types to consider, those mainly concerned with exhaust streams from large processes, and those installed around the workshop for local gas cleaning duties.

5.4.1 Process exhaust filters

The filters installed on process exhaust streams – boiler, furnace and incinerator exhausts, and the outlet flows from metallurgical and chemical processes – are normally expected to handle dust loadings an order of magnitude greater than filters used in ventilation applications. (Very large dust loadings would normally be passed through a cyclone first, before the exhaust filters.)

Such flows, as well as being quite heavily dust laden will usually be large in volumetric terms, and quite often very hot. The particular situation of excessively hot gases is covered in the next section, while the present one covers temperatures at or not far above ambient.

The filters used here are usually built to accommodate a large number of filter elements – bags, pockets or cartridges – and much of the discussion relates to the nature of these elements, which is further expanded in Chapter 9.

5.4.1.1 Fabric filters

The term 'fabric filters' conventionally embraces the various forms of bag house and bag filters that are formed by a housing containing a multiplicity of vertical tubular (bag) or rectangular (pocket) cloth-covered elements, as shown in Figures 5.18 and 5.19. Filtration may deposit dust either on the inside or outside surface of each bag, depending on the direction of flow. Operation is cyclical, with filtration intermittently interrupted to permit cleaning by a variety of techniques, including mechanical shaking and reverse flow of the gas.

The type of filter, and especially the mode of cleaning, broadly determines the type of fabric that is appropriate to it. Bergman(14) comments that American practice is generally to use needlefelts for pulse jet filters requiring cake removal from the outside, but woven fabrics for the inside cleaning of shaker and reverse air filters.

With the increasing application of cartridge filters for dust collection, it is logical to classify some of these as fabric filters. Generally these are of conventional tubular pleated form, mostly based on spunbonded nonwoven media, but some (e.g. Figure 5.20) utilize membrane laminates. By contrast, a novel form of pocket filter introduced by Donaldson DCE is made from disposable pleated flat cartridges or modules of spunbonded polyester (Figure 5.21), each providing a filtration area of 4 m^2.

5.4.1.2 Rigidized media

The term 'rigidized media' was devised by Smith[15] to identify a category of dust filters that has evolved from the conventional pocket fabric filter illustrated in Figure 5.19. The name is apposite since it highlights their key distinguishing feature, namely that the traditional flexible fabric has either been made rigid or has been replaced by rigid material. This rigidity makes possible two major constructional modifications, as illustrated in Figure 5.22: the filtration surface is ribbed, thereby increasing the filtration area per unit volume; and the resultant filter medium is self-supporting, without need of internal separators between the two faces of an element. The resultant filter element is, in effect, a flat disposable cartridge.

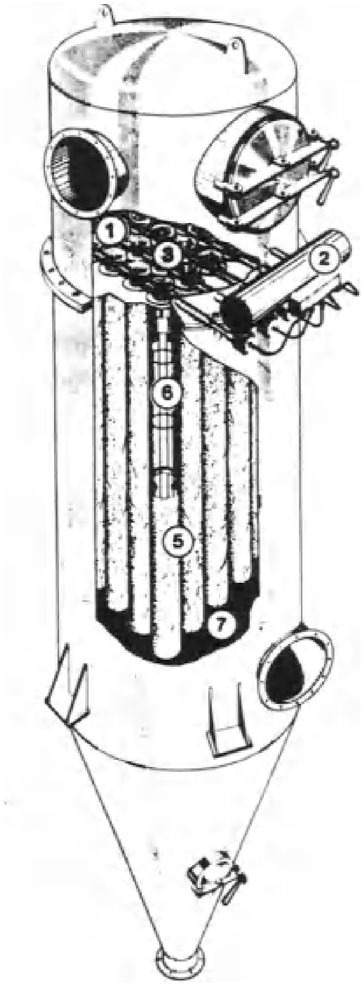


Figure 5.18. A tubular bag fabric filter with pulse jet cleaning: 1. clean gas duct; 2. compressed air; 3. nozzle; 4. baffle plate; 5. filter bag; 6. support cage; 7. dirty gas chamber. (Illustration: Intensiv Filter GmbH)

The pioneers in this technique were the German company Herding GmbH Filtertechnik, whose technology under licence is the basis of Donaldson DCE's range of Sintermatic filters. The filter medium is made from polyethylene granules that are firmly fused or sintered in a ribbed aluminium mould, the active surface then being subjected to a PTFE-epoxy treatment to form a microporous coating, which both improves filtration efficiency and aids cake discharge.

The commercial success of these filter elements stimulated efforts to develop alternative versions that would avoid the relative complexity and high capital cost associated with the sintering process. One option is to rigidize filter cloth by impregnating it with epoxy resin and heat-curing it: despite difficulty in achieving even distribution and concentration of the resin, this has been shown to work reasonably well with both woven and needlefelt fabrics.

As described by Smith, a more elegant method to rigidize filter cloth is to construct it from a fibre, the properties of which enable it to be heat set without the use of a resin. Whilst the theoretical possibility of this had long been recognized, there are practical difficulties in controlling both shrinkage and the embrittlement that occur with many synthetic polymers when they are heated

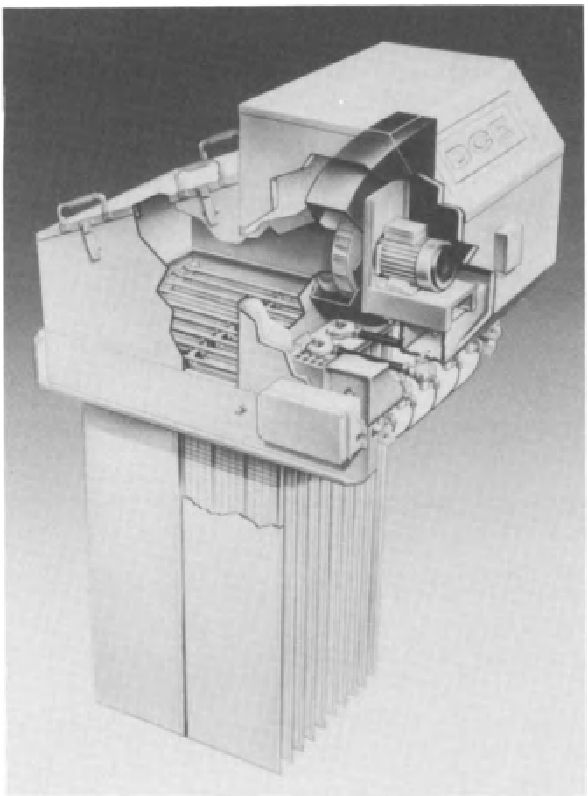


Figure 5.19. A pocket bag filter. (Illustration: DCE Ltd)

above their transition temperature. These problems have been overcome by a patented process that employs special tooling, with the advantage that the shrinkage tends to reduce the pore size of the fabric and so to improve the smoothness of its surface.

By comparison with conventional needlefelt fabric filter bags, those of rigidized media elements potentially offer advantages, but also have some limitations. The key points identified by Smith are summarized in Table 5.19, while Table 5.20 provides typical comparative data; both the resin- and heat-rigidized elements are based on needlefelts.

5.4.2 Workshop filters

Many industrial processes, especially in the mechanical engineering and metal products processing sectors, produce dusts in very localized zones, such that efficient system operation requires local filtration activity, to prevent dusts from spreading too far from their point of origin, or to pick up any dusts that settle in

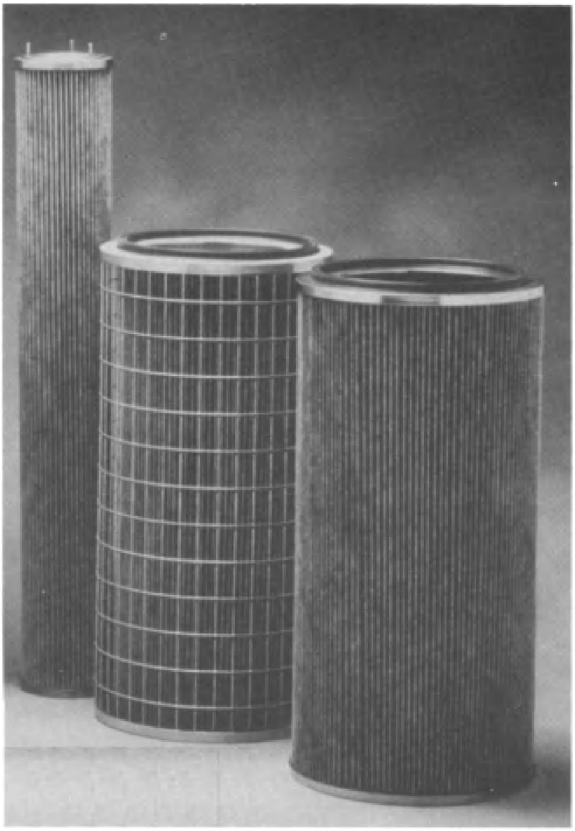


Figure 5.20. Antistatic grade membrane cartridges. (Photograph: W L Gore Associates Ltd)

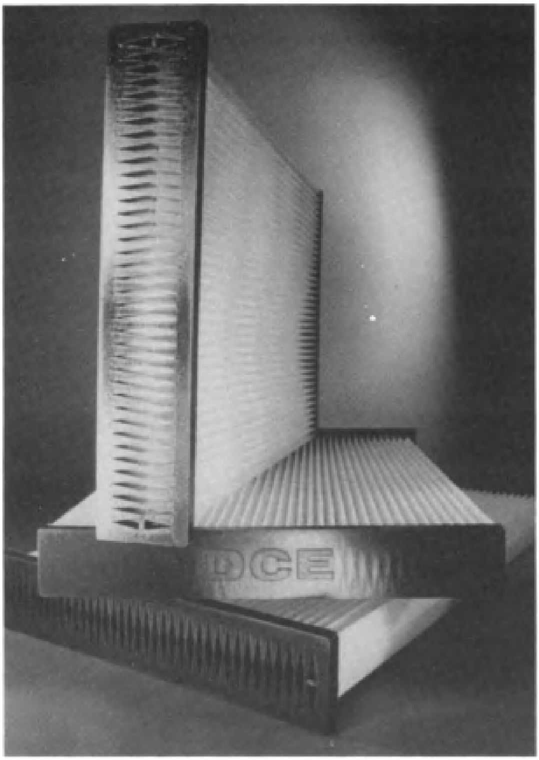


Figure 5.21. Replaceable pleated elements for a DCE 'Unicell' filter.

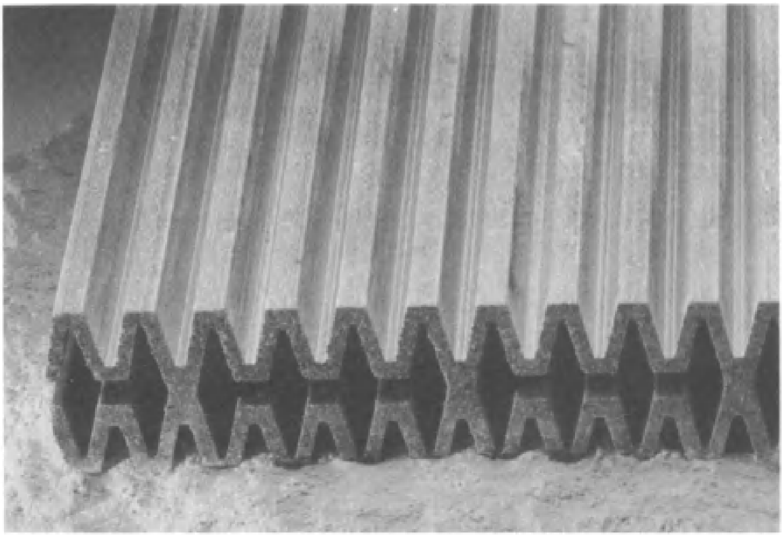


Figure 5.22. A section through a 'Sintermatic' rigidized media filter element. (Photograph: DCE Ltd)

the immediate vicinity of the dust producing unit. Quite often, the dusts are worth recovering, so that the filters involved will be required to release their collected solids efficiently.

Local collection of spilled dust is the province of the industrial suction cleaner, with filtration needs very similar to those discussed in Section 5.3.4. Hoods may be placed over machinery and an air flow sucked from around it, through a filter system, probably similar to the ventilation filters discussed earlier. This is especially true for systems such as a paint booth, where an air flow is necessary to carry fumes away from any workers, and needing to be filtered before it can be released (or further processed).

There are some localized processes, such as an air circulation through a dryer, where the operating temperature is significantly above ambient, but not as high as to be the subject of the next section. For these duties, manufacturers can supply glass fibre filters, such as Freudenberg's Viledon LH series of filterpacks, which are able to accept gases at up to 300°C.

Table 5.19 Rigidized media filters versus fabric filters

Advantages of rigidized media elements	
Very compact:	filtration area in a given volume is 50–200% greater
High efficiency:	concentration of outlet emission is greatly reduced, especially for sintered media
Self-supporting:	no inserts needed to prevent collapse of bags under suction
Long bag life:	3 year warranty is standard for some rigidized filters
Limitations of rigidized media elements	
Pressure loss:	higher resistance to flow, especially for sintered media
Cleaning:	shaker/vibration mechanisms not suitable; pulse-jet cleaning is good for free flowing dusts but incomplete with tenacious dust
Blinding:	may occur with very fine dusts
Quality control:	must be higher than for conventional bags
Replacement cost:	the higher cost may be offset by longer life

Table 5.20 Comparative data for fabric rigidized media filter elements

	Standard bags	Sintered elements	Resin rigidized elements	Heat rigidized elements
Effective area per bag (m^2)	1.5	3.3	2.3	2.3
Typical clean air pressure drop at 1.5 m/min (mm WG)	10	70	20	15
Typical dust pressure drop at 10 g/Nm^3 and 1.5 m/min (mm WG)	100	170	120	100
Typical outlet emission (mg/Nm^3)	10	<1	2	2
Comparative cost per m^2 (media only)	1	4	3	2.5
Comparative cost including housing (typical only)	1	1.2	1	0.9

5.5 Hot Gas Filtration

The processing of hot exhaust gases from a wide variety of industrial processes. including power stations, imposes a difficult problem upon the system designer. If the process is to be efficiently run, then as much heat energy as possible should be recovered from the exhaust gas. Heat recovery usually means passage of the exhaust gas through some kind of heat exchanger – and most heat exchanger designs are easily plugged with solids if the exhaust is dusty – which most are. Hence, it is necessary to filter the exhaust gases free of such solids – and most filter media are unsuitable for temperatures much in excess of 100°C, let alone the 500°C or more of most process exhausts(16).

This quandary has led to one of the fastest growing parts of the filter media business – the provision of media capable of withstanding hot exhaust gas temperatures. These temperatures are such that no organic material is likely to be suitable, and recourse has to be made to inorganic media. Ceramic materials have become the obvious choice for this role, and much skill is now expended by the makers of such media in making them of adequate strength and filtration efficiency. Two major developments for future benefit – solid waste incineration and coal-fired energy generation – will rely on efficient hot gas filtration.

5.5.1 High-density, 'hard' ceramic media

This category, which is considered at length in Chapter 7, embraces the porous ceramic tubes and sheets that have long been used for a variety of industrial applications, including filtration, where they are particularly useful for hot gas clean-up operations. Typically made from granules of refractory materials such as aluminosilicates, silicon carbide and silicon nitrate, their void fraction is of the order of 40%, with pore sizes ranging from several hundred micrometres down to about 10 µm. A significant step in recent years is the development of laminated forms that incorporate ceramic membranes.

5.5.2 Low-density, 'soft' ceramic media

In contrast to the high-density ceramics, the modern low-density media are made from chopped ceramic fibres and have void fractions of about 90%. They are the basis of the filter candles that have been developed specifically for the rigorous needs of high-temperature dust filtration associated with processes such as coal combustion and gasification, incineration, and catalyst recovery. However, their use is by no means restricted to such arduous conditions: at the beginnings of the 1990s a report stated that around 30% of Cerafil plants were operating below 200°C, with another 30% in the 200–300°C range, and only 5% above 500°C.

Numerous advantages are claimed for these filter candles, as compared with traditional hard ceramics, including greater resistance to thermal and physical shock, lower pressure drop, less weight and lower cost.

5.5.3 Other rigid porous media

Sintered metal and porous plastic materials are suitable for use in dust filtration. Both, but especially sintered metal, permit fabrication to form self-supporting elements of diverse shapes. Sintered metals are suitable for hot gas treatment, while there are some plastic media capable of operating at 150°C and higher – but not at most exhaust gas temperatures. These media are discussed in more detail in Chapter 7.

5.6 Filtration of Compressed Air and Other Gases

The compressed air or other gas leaving a compressor will contain all of the impurities that were present in the inlet gas, plus oil picked up from the lubricant in the compressor (assuming that it is oil lubricated). A range of filters and other process units will usually be required as ancillaries to a standard compressor system. The number of filtration stages and the types of filter media appropriate to these stages depend both on the source of the gas (and hence the nature and amounts of contaminant) and on the degree of purity necessary for a specific application. To illustrate this, the following overview considers first a basic general-purpose compressed air system, and then the additional series of purification stages appropriate to achieve the very high purity essential for the most critical of the medical gas systems used by hospitals. (This treatment is an edited version of that included in the first edition of this Handbook, which was prepared with the assistance of domnick hunter ltd.)

5.6.1 Basic general-purpose compressed air system

The source of compressed air is the ambient air around the compressor, which could be quite dirty. Contamination may arise from the atmosphere or from the compressor itself (or, of course, from the compressed air distribution system). Typical levels of contaminants to be expected are summarized in Table 5.21. Minimizing their presence in the compressed air is achieved by the combined

Table 5.21 Level of contaminants to be expected in compressed air

Contaminant	Source	Typical concentration
Dirt particles	Atmosphere	Up to $140 \times 10^6/m^3$
Carbon	Burnt oil	Up to 10 mg/m^3
Water	Atmosphere	Up to 11 g/m^3
Rust	Pipework	Up to 4 mg/m^3
Oil	Compressor lubricant	5–50 mg/m^3
Oil/water emulsion	Mixture of oil and water	Up to 11 g/m^3
Vapour	Gaseous oil	0.05–0.5 mg/m^3
Micro-organisms	Atmosphere	Up to $3850/m^3$
Unburnt hydrocarbons	Atmosphere	Up to 0.5 mg/m^3

effects of an air intake filter that also protects the compressor from the ingress of damaging solid particles and an outlet air/oil separator. (Contamination that is picked up in the distribution pipework has to be dealt with by an additional point-of-use filter.)

5.6.1.1 Air intake filter

The air intake filter on a compressor normally consists of a mechanical separation stage combined with a pleated cylindrical fibrous paper filter with a high surface area. The filter medium is usually unsupported resin-impregnated cellulose paper of industrial grade (similar to that often used in automotive applications); polyurethane resin forms an integral end seal preventing bypassing of the medium, while the side seam can be mechanical, thermally formed or resin sealed. Typically the medium has a basis weight of 145 g/m^2, a thickness of 0.6–0.8 mm, and a minimum particle retention size of 5–10 μm.

5.6.1.2 Air/oil separator

The air/oil separator is basically a coalescing filter. It follows the compression, and comprises primary and secondary stages, with the objective of reclaiming the lubricating oil prior to the air being discharged at the required pressure. The primary stage utilizes gravity settling assisted by a reduction in gas velocity; downstream from it, the typical oil loading is 5–50 g/m^3 of polydispersed aerosols.

The second stage is normally a multi-layer cartridge, the media used depending on whether the flow through it is out-to-in or in-to-out. With the latter, the first, prefiltration layer can be a choice of several high particulate loading fibrous fabrics, such as a 0.3–0.7 mm thick, 100 g/m^2 viscose rayon bonded with regenerated cellulose. There is then an overlapping support layer, typically a 1 mm thick, 120 g/m^2 50% mixture of polyester/nylon bonded with synthetic rubber; the function of this is to contain the multiple layers of high-efficiency media wherein the fine oil mist droplets coalesce into much larger droplets.

These high-efficiency layers are of borosilicate glass fibres of various characteristics. They include a thin felt of coarser fibres bonded with phenolic resin and also microfibres bonded with an acrylic binder; integral support layers of spunbonded nylon provide intimate support for the fragile glass media to help the separator survive the rigours of frequent changes in pressure and the resultant cyclic loading of the media. Following the coalescing action of the glass fibre media, the large oil droplets are prevented from re-entrainment by a barrier comprising a 3–5 mm thick, 250 g/m^2 nylon or polyester non-woven acrylic bonded fabric; this ensures rapid drainage of the coalesced liquid to the base of the separator, for subsequent pressurized expulsion back to the air intake.

The whole coalescer assembly is resin bonded and mechanically locked into end caps of suitable location design, thus forming a highly efficient separator capable of removing particles down to 0.3 μm at over 99.995% efficiency. Oil carryover from a compressor is usually less than 5 mg/m^3 of air; this allows for long service periods for the compressor.

5.6.2 Purification stages for medically pure air

Each of the sequence of purification stages summarized in Figure 5.23 is discussed in sequence in the following discussion.

5.6.2.1 First stage: coalescing prefilter

This may be a combination of a cyclonic device with coarse coalescing media. and/or a pre-coalescer designed for high liquid and particulate loading. Non-woven synthetic fabrics coalesce relatively large droplets of oil and water: polypropylene, glazed on both sides for integral strength, is typically used, followed by anti-re-entrainment barriers similar to those used in the air/oil separator described above, which together give a high particulate loading device of long life.

5.6.2.2 Second stage: high-efficiency coalescing filters

Various grades of borosilicate glass microfibre media form the main component of this multi-layer filter. In order, the layers are: first a perforated stainless steel supporting cylinder, then graded nylon and polypropylene spunbonded sheets and then 0.5–1.5 mm thick, 100 g/m^2 microfibre media:

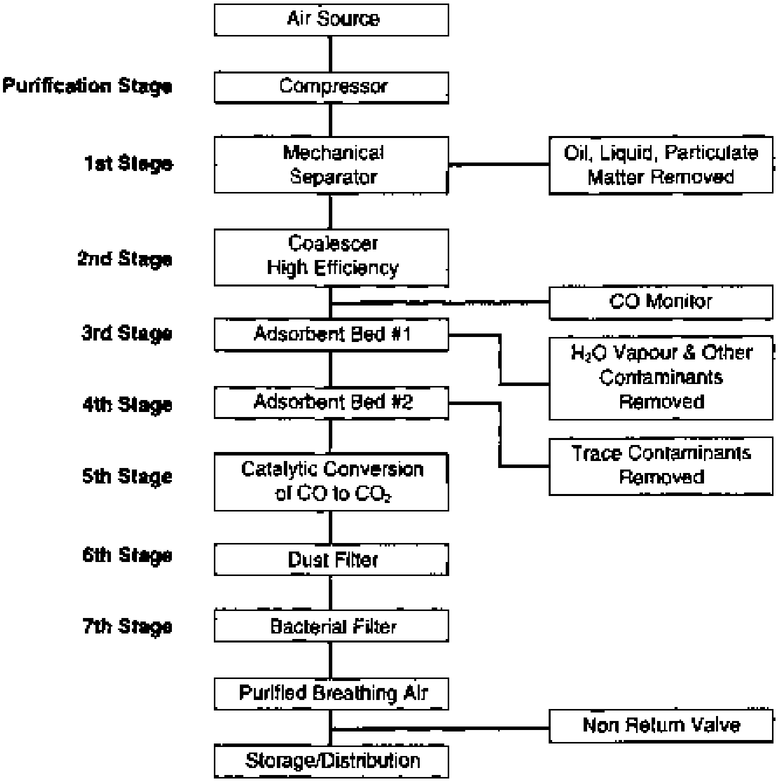


Figure 5.23. The sequence of separation stages to purify compressed air or gas for use in critical medical applications. (Illustration: domnick hunter ltd)

occasionally, a prefilter layer of phenolic bonded glass fibre is also included to collect particulates. The final layer is an anti-re-entrainment barrier to prevent coalesced liquid from being dispersed again into the air stream; this is generally reticulated polymeric foam with high drainage capacity, but for higher temperatures 2–4 mm thick, 400 g/m^2 spunbonded polyester media may be used. The oil carryover achieved is down to 0.01 mg/m^3 of air, with particulate retention of 0.01 µm.

5.6.2.3 *Third stage: adsorbent bed air dryer*

A desiccant dryer must be used if a low dewpoint (down to −70°C) is required. This is a bed of granular adsorbent material such as activated alumina or synthetic zeolites; when loaded with moisture, the bed may be regenerated by various means, including the use of heat or pressure swing desorption. Stainless steel screens are typically used to support and retain the granules; integral polyester spunbonded pads prevent most particles generated by attrition from migrating downstream.

5.6.2.4 *Fourth stage: adsorbent bed for removing hydrocarbon vapours*

This closely resembles a desiccant dryer but utilizes activated carbon as the adsorbent bed. Activated carbons may be manufactured from a wide range of materials, including wood, coal, and nut shell. For the removal of hydrocarbon vapours from compressed air streams, carbons based on coconut shell are often preferred. This bed is not regenerated *in situ* but is periodically replaced.

5.6.2.5 *Fifth stage: catalytic bed for conversion of toxic gases*

Normally this comprises a bed of granular oxides of copper and manganese that, by catalytic action and chemisorption, oxidize inorganic gases such as carbon monoxide to carbon dioxide and water. Because the levels of carbon monoxide present in compressed air are generally relatively low (15 ppm), the oxidation products do not usually form a problem. Dust retention pads need to be of high temperature resistance; bonded glass fibres are suitable for this use.

5.6.2.6 *Sixth stage: dust filter*

Despite their individual retaining filters, some dust fines will escape from the three preceding beds. Such fines are typically below 5 µm in size, so a high-efficiency dust removal medium is required at this point. Generally this will comprise 1.5 mm thick, 150 g/m^2 pads of an intermediate grade of borosilicate glass fibres. As in other filters using this type of media, a bonded synthetic support is necessary to prevent flexing and possible fracture of the glass fibres due to cyclic differential pressure loading. With flow out-to-in, a perforated steel core supports a thermally sealed polyester scrim; this inner scrim acts as a prefilter and also supports the glass fibres, outside of which there is a retaining screen.

5.6.2.7 *Seventh stage: bacterial filter*

The function of this final filter is to cold-sterilize the clean compressed air by the removal of any remaining viable organisms that are trapped and held within the filter matrix. In the presence of a carrier such as water, bacteria and viruses could eventually compromise the integrity of the filter; it is therefore essential that these filters remain dry, although they will also be subjected to a steam or chemical sterilization process to clean them. The filter media must consequently withstand sterilization, and must not add to the potential to support the growth of organisms. Favoured materials for this filter are highly efficient borosilicate glass microfibres or PTFE absolute membranes, supported by 100% glass fibre woven fabric or polysulphone/polypropylene spunbonded textiles; the media must not shed and must remain integral throughout repeated sterilization cycles. Stainless steel support cylinders and end caps are essential, whereas the membrane products tend to favour heat-treated moulded polypropylene support cages. The achievement of logarithmic reduction values greater than 9 (i.e. 9 orders of magnitude) for virus levels down to 0.04 μm (T4 Phage) must be demonstrated and verified.

5.7 Demisters

A demister comprises a thick pad of filaments that provide a high surface area, so that the liquid droplets of the mist may be captured by the individual filaments. The mechanisms of capture include direct interception (where the space between adjacent fibres is less than the diameter of a larger droplet), inertial impaction (due to the momentum of a larger droplet), and Brownian movement (bringing fine droplets sufficiently close to fine fibres). Since, especially with very small droplets, the minimum size of droplet captured is closely related to the fineness of the filaments, two basic forms of demister have evolved, one for coarse mists (droplets greater than 5 μm) and the other for fine mists (droplets less than 2 μm).

5.7.1 Coarse mists

Coarse mists comprise droplets ranging upwards from about 5 μm in diameter. Such droplets can readily be caught by comparatively heavy gauge (e.g. 100–300 μm) filaments of either metal or plastic, in the form of flat or (less often) tubular knitted mesh pads; these are illustrated in Figure 5.24 and are described in more detail in Chapter 6. The liquid thus collected within the pad drains from it continuously under gravity.

Table 5.22 summarizes the specifications of some of the most commonly used demister pads of one leading manufacturer.

Another manufacturer, KnitMesh, reports that normally a 10–15 cm thick demister pad will remove 99% of all droplets of 5 μm or greater, and over 99.5% of those above 10 μm, whilst still being very effective down to 2 μm.

For maximum efficiency, the superficial face velocity should be between certain limits; if it is too low, insufficient impingement will occur, whereas too high a velocity will result in re-entrainment. Accordingly, it is recommended that the working velocity should be between 75 and 30% of the maximum allowable velocity as given by the relationship:

$$V_m = K[(D-d)/d]^{0.5}$$

where V_m = maximum allowable velocity (m/s),

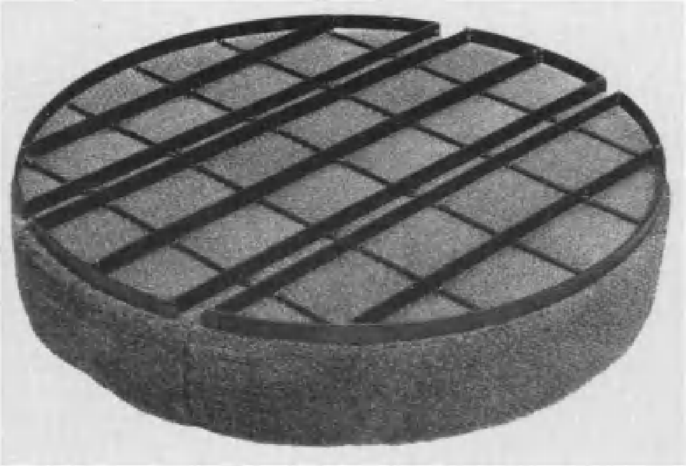


Figure 5.24. Knitted wire mesh demister pad. (Photograph: Begg Cousland Ltd)

Table 5.22 Specifications of most commonly used 'Becoil' demister pads*

Material	Mesh style	Wire diameter (mm)	Density (kg/m^3)	% Free volume	Surface area (m^2/m^3)
Stainless steel	H	0.28	192	97.5	360
	H	0.265	168	97.9	320
	SH	0.28	136	98.0	256
	SH	0.265	120	98.5	228
	L	0.28	112	98.5	210
	L	0.265	101	98.7	192
	UL	0.28	80	99.0	151
	UL	0.265	70	99.1	133
	H237	0.1524	135	98.3	430
	UL238	0.1524	54	99.3	194
	H1241	0.112	430	94.6	1936
Polypropylene	L	0.25	21	97.7	369
	UL	0.25	15	98.3	264
	H	0.50	69	92.4	606
	SH	0.50	50	94.5	439
Halar	H	0.50	127	92.4	606
	SH	0.27/0.5	59	96.5	390

*Begg Cousland Ltd.

d = density of gas/air,
D = density of liquid,
K = a constant, usually 0.107, but see Table 5.23.

Typical relationships between superficial gas velocity, droplet size and separating efficiency, and between superficial face velocity, water loading and pressure drop, are given in Figures 5.25 and 5.26. These are based on extensive tests with air and entrained water (at atmospheric pressure and 20°C) with standard general purpose KnitMesh.

Table 5.23 ***K* values recommended by Knitmesh Ltd**

Duty	*K* value
Clean conditions	0.107
Vacuum operation	0.061–0.085
High efficiency: clean conditions	0.107
Plastic demisters: highly corrosive conditions	0.064
High pressure: >20 bar	0.085

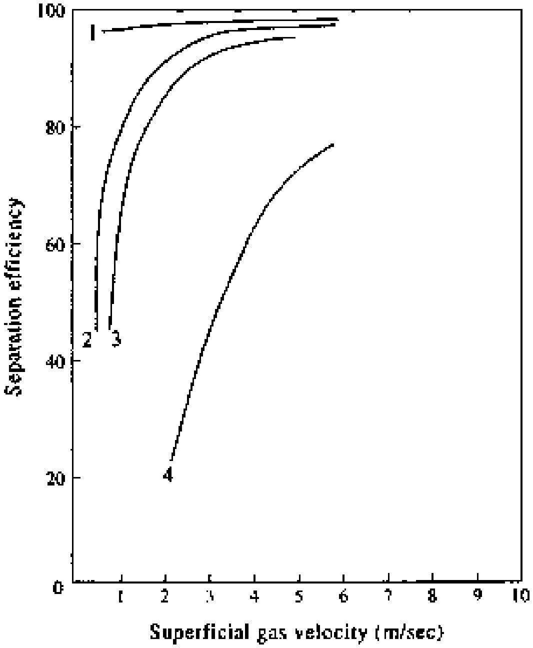


Figure 5.25. Effect of face velocity and droplet size on the efficiency of KnitMesh Type 9030 SL/SS demister. Air/water @ 20°C. Droplet sizes: curve 1–10 μm; curve 2–5 μm; curve 3–4 μm; curve 4–2 μm.

5.7.2 Hybrid mists

Hybrid droplets in the size range 2–5 µm can be agglomerated into greater than 5 µm droplets by prefiltration through a coalescer pad. the resultant larger droplets then being trapped by a conventional coarse demister. For example, Begg Cousland Ltd use this two-stage technique by combining their Becoil demister and Becone coalescer in series. to achieve an overall 100% removal of droplets greater than 5 µm and 98% removal of those greater than 2 µm. the corresponding overall pressure drop being approximately 120 mm WG.

The Becone coalescer pad is itself a modified form of the demister pad illustrated in Figure 5.23, being fabricated from a composite fabric that consists partly of monofilaments and partly of a staple fibre yarn. The very fine staple fibres, having a correspondingly higher filtration efficiency, serve as sites for collection of fine droplets; these coalesce into larger droplets that are then re-entrained into the discharging gas. The pressure drop across a coalescer pad is typically some three times that across a demister.

5.7.3 Fine mists

Candle-type demisters comprising annular pads of very fine fibres were developed simultaneously by Fairs(17) of ICI in the UK and by Brink(18) of Monsanto in the USA in the late 1950s. Separate accounts of both are included in the 1964 book edited by Nonhebel(19,20).

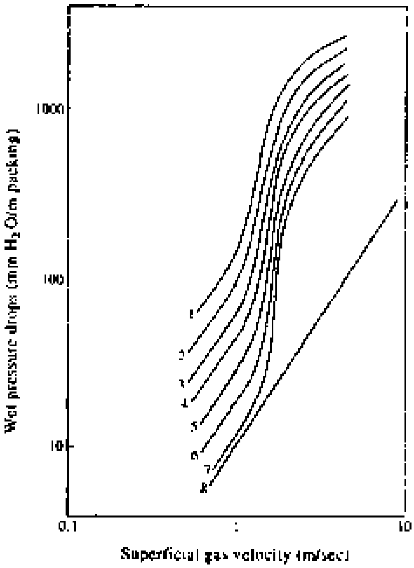


Figure 5.26. Effect of face velocity and water loading on the pressure drop of KnitMesh Type 9030 SL/SS demister. Air/water @ 20°C. Water loading curves: 1. 40 m^3/m^2 h; 2. 35 m^3/m^2 h; 3. 30 m^3/m^2 h; 4. 25 m^3/m^2 h; 5. 20 m^3/m^2 h; 6. 15 m^3/m^2 h; 7. 10 m^3/m^2 h; 8. dry pad.

While the general forms of these demisters are understandably very similar, comprising a multiplicity of long vertical candles (Figure 5.27) suspended in a suitable housing, there was a point of crucial difference in respect of the fibres: Fairs insisted on the importance of the fibres being hydrophobic, whereas Brink regarded this as an unnecessary limitation.

The Fairs thesis was based on the observations that hitherto the filtration efficiency of candle demisters was significantly less than that theoretically predicted, and that they tended to become waterlogged with collected liquid. By contrast, demisters of hydrophobic fibres were found to achieve the high efficiencies theoretically predicted, and to be free from water logging. This was explained by differences in the mode of collection of droplets on fibres, which could be ascribed to the one being hydrophilic and the other hydrophobic, as revealed in the photographs reproduced as Figure 5.28. The wetting of the surface of the hydrophilic untreated glass fibre (Figure 5.28(a)) causes its diameter to increase and therefore its filtration efficiency to decrease, a deterioration not suffered by the unwetted hydrophobic silicone-treated glass fibre (Figure 5.28(b)).

This erstwhile ICI technology is the basis of the Becofil range of candle demisters summarized in Table 5.24 and produced by Begg Cousland, utilizing fibres of different sizes, materials and packing densities. The fibres need to be as fine as possible, and typically are less than 15 μm. In practice, however, it is customary to incorporate a proportion of coarser fibres of about 30–40 μm, so as to provide stability and strength; experience showed that, with aqueous mists,

Figure 5.27. Candle type demister filter cartridges. (Photograph: Begg Cousland Ltd)

fine fibres alone tended to become saturated and not to drain due to partial collapse of part of the bed.

The carded mixture of fibres is compressed into a mould at about 110–160 kg/m^2, to form sections up to 0.6 m long, 5 cm thick and with an outside diameter up to 60 cm. These are thermally stress relieved and made up into candles up to about 5 m long, with internal and external mesh screens; the preformed media can be replaced in the field. Flow may be either out-to-in or in-to-out, the relationship between velocity through the exit phase (at equilibrium, with continuous drainage) and pressure drop being shown for two styles of cartridge in Figure 5.29.

5.8 Selection of Gas Cleaning Equipment

Four very different kinds of filtration equipment have been described in this chapter:

- ventilation and other atmospheric air filters;
- industrial dust collectors;
- compressed air systems; and
- demisters.

Of these four, the choices in compressed air treatment and demisters are relatively simple: standard or special quality for the delivered air, and size of liquid droplet in demisting.

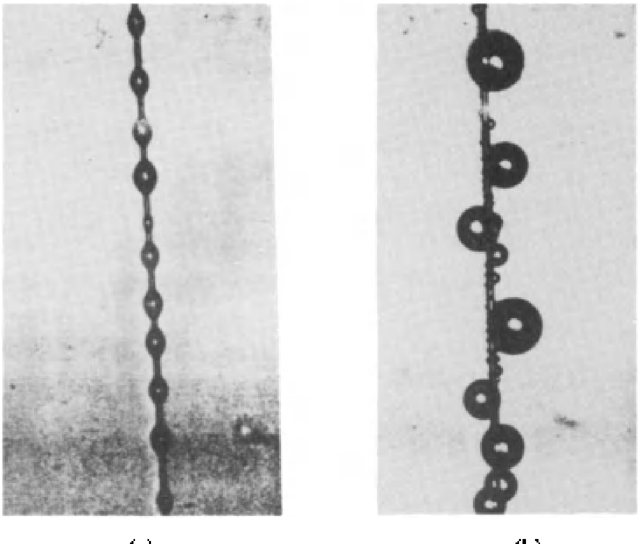

(a) (b)

Figure 5.28. The mechanisms of mist collection depends on the wettability of fibres: (a) film-wise collection on hydrophilic glass fibres, (b) drop-wise collection on silicone-treated hydrophobic glass fibres.

The choices in industrial dust collection have a major divider, the level of operating temperature: a high temperature (certainly above 150°C) needs inorganic media – ceramics or possibly glass fibre. For ambient temperature conditions, then the choice lies basically between achieving solids recovery (using fabric filters) or an adequately clean air stream (the two together are not

Table 5.24 Examples of "Becofil" non-wettable fibre demisters[a]

Style	Removal efficiency	Pressure loss (mm WG)	Typical service
FFG 25 FF	High throughput 100% above 3 μ 90% above 1 μ 70% above 0.5 μ	100–300	Acid plants
TGW 15	High efficiency 100% above 1 μ 98% above 0.5 μ	150–450	Acid plants High pressure systems Plasticizer mists
B.12	High efficiency 100% above 3 μ 95% above 1 μ 80% above 0.5 μ	100–250	Acid plants Soluble fume
P.F.12	High efficiency 100% above 3 μ 98% above 0.5 μ	100–350	Corrosive service Soluble fume
P.T.12	High efficiency 100% above 3 μ 95% below 3 μ	100–300	Wet chlorine systems
H.T.P.	High throughput 85%+ on 1–3 μ 70%+ on 0.5–1 μ	100–300	Restricted space Lower efficiency below 3 μ

[a] Begg Cousland Ltd.

[b] Types of fibre used: glass wools, polypropylene, polyester.

[c] Support cage materials: mild steel, stainless steels, titanium, high nickel alloys, etc., polypropylene, pvc, pvdf, grp.

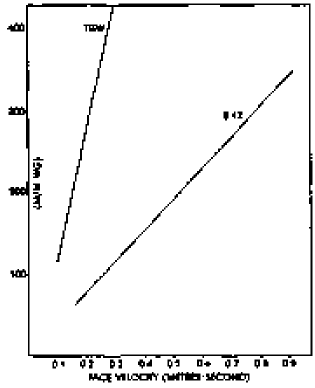


Figure 5.29. Pressure drop versus exit face velocity through 'Becofil' candle type demisters.

an impossible requirement). The choice among bag, pocket or cartridge is largely a matter of getting the correct medium – in addition to operating temperature, the parameters of abrasion, corrosiveness of the gas/solid system and flexibility govern the final choice. There may also be a problem in moisture content in the gas stream – too high a relative humidity may cause some media to weaken (especially polyester).

There is a bewildering choice available in the selection of ventilating filters, and here the decision will be influenced by the incoming dirt load and air flow required, but mostly on the degree of cleanliness in the delivered air.

5.9 References

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CHAPTER 6

Screens and Meshes

The several very different types of filter media gathered together in this chapter, woven meshes, perforated sheets and structures of shaped wires, have one main common feature – an accuracy of aperture size. Another common feature is that they are all made from metal, largely because abrasion is a normal problem in their application, although many forms are now available in plastic as well.

All the dry screening (sieving, sifting) operations are covered by the media in this chapter, as are almost all of the straining and coarse filtration applications.

6.1 Introduction

The prime feature of media made from meshes or screens is that of aperture shape – the size and shape of the apertures in the medium is critical for the intended application. The material of construction is less critical, although its high tensile strength may be vital as well.

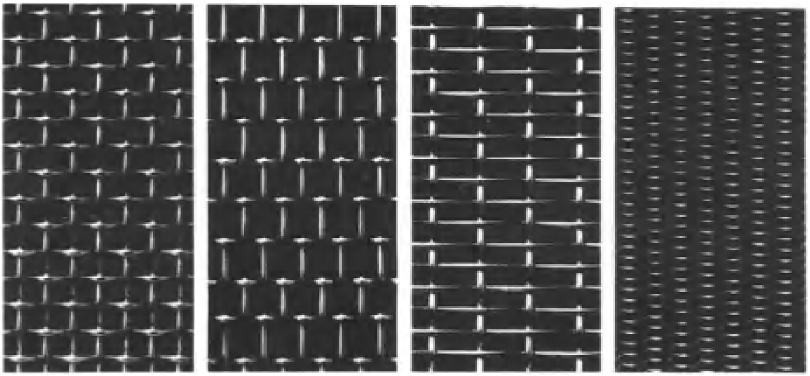
There are three broad classes of media covered under this heading: woven meshes, sheets perforated with a variety of holes, and elements made up from preformed materials. Some overlap exists between the woven meshes of this chapter and the woven monofilament materials of Chapter 2.

6.2 Woven Wire Mesh

The weaving of wire is no different, in principle, from the weaving of any other yarn – as described in Chapter 2. The product is a roll of woven material, which then is processed in a variety of ways, to produce the components of a filter medium. The term wirecloth is frequently used to refer to meshes woven from finer grades of wire, while the term *bolting cloth* refers to lightweight versions of square mesh cloths, comprising those based on the finest wires.

A wide variety of wire meshes is produced by weaving monofilaments of either ferrous or non-ferrous metals in widths of about 1 m up to 2 m. Two main categories can be distinguished, in terms of weave and of the shape of the apertures, as in Figure 6.1. One category utilizes plain weave with single wires of the same diameter for the warp and weft, to form rectangular apertures (the great majority being square): many of these are the screens typically used for sieving and sizing operations. The other category is 'zero aperture filter cloths', with the wires pressed closely together. These embrace a number of more complex weaves, such as dutch twills, which are commonly used in pressure and vacuum process filters.

Information on the metals used in wire mesh is given in Tables 6.1–6.7 (provided by Haver and Boecker). Each includes some guidance on resistance to corrosion, in terms of numerical values extending from 1 (= very good) to 5 (= poor); an added asterisk (*) indicates danger of localized corrosion.


Square Aperture

Rectangular "Oblong"

Rectangular "Broad"

Zero Aperture "Filter Cloth"

Figure 6.1. Some types of apertures in woven wire.

Table 6.1 Metals for woven wire cloth: steel

Material	Material no.	Trade name	Max service temp.		Finest weaving wire diameter		Resistance against:			
			°C	°F	mm	inch	Atmosphere	Sea water	Lyes	Acids
Plain steel	1.0010	Carbon steel	500	930	0.08	0.0030	5	5	2–4	4–5
Galvanized steel			200	390	0.16	0.0065	3	5	2–4	4–5
Tinned steel			150	300	0.10	0.0040	5	5	2–4	4–5
Spring steel	1.0500	NIA-Steel High carbon steel	500	930	0.125	0.0050	5	5	3–4	4–5

Table 6.2 Metals for woven wire cloth: stainless steels

Material no.	AISI	Symbols	Composition				Max service temp.		Finest weaving wire dia.		Resistance against:			
			Cr	Ni	Mo		°C	°F	mm	inch	Atmosphere	Sea water	Lyes	Acids
1.4016	430	X 6 Cr 17	17				500	930	0.04	0.0016	2	4*	2	3–4
1.4301	304	X 5 CrNi 1810	18	10			600	1110	0.016	0.0006	1	3*	1–2	2–4*
1.4306	304L	X 2CrNi 1911	19	11			600	1110	0.016	0.0006	1	3*	1–2	2–4*
1.4310	301	X 12 CrNi 177	17	7			600	1110	0.04	0.0016	1	3*	2	2–4*
1.4541	321	X 6 CrNiTi 1810	18	10		Ti	700	1290	0.05	0.0020	1	2*	2*	2–3*
1.4401	316	X 5 CrNiMo 17122	17	12	2		600	1110	0.018	0.0007	1	2*	2*	2–3*
1.4404	316L	X 2 CrNiMo 17132	17	13	2		600	1110	0.018	0.0007	1	2*	2*	2–3
1.4435	317L	X 2 CrNiMo 18143	18	14	3		600	1110	0.05	0.0020	1	2*	2*	2–3
1.4571	316Ti	X 6 CrNiMoTi 17122	17	12	2	Ti	700	1290	0.05	0.0020	1	2*	2*	2*

6.2.1 Square mesh

Listed in Table 6.9 is the range of square mesh wire meshes produced by one leading manufacturer, indicating which grades are available in specific metals. The tolerance of the aperture sizes specified varies according to the fineness of the cloth, as summarized in Table 6.8; a crucial factor in determining this is the tolerance of the diameter (including the extent to which it deviates from being truly round) of the wires from which the mesh is woven.

Crimping of the wires happens automatically as part of the weaving process, provided that the wires are sufficiently fine and ductile. With heavier and more rigid wires, however, such as those of high tensile steel for heavy-duty screens, a separate pre-crimping operation is necessary, both to form the desired apertures and to ensure appropriate stability during extended use. Various types of crimp are used, as outlined in Table 6.10.

Table 6.3 Metals for woven wire cloth: special steels

Material no.	AISI	Symbols	Composition			Max service temp.		Finest weaving wire dia.		Resistance against:			
			Cr	Ni		°C	°F	mm	inch	Atmosphere	Sea water	Lyes	Acids
HB 253		HITHERM	21	11		1200	2190	0.025	0.0010	1	2*	1–2	2–3*
HB 165		Corresist	20	25		900	1650	0.10	0.0040	1	2	2	2
1.4841	310 314	X 15 CrNiSi 25 20	25	20	Si 2	1200	2190	0.05	0.0020	1	3*	2–3	2–4*
1.4742		X 10 CrAl 18	18		Al 1	1050	1920	0.05	0.0020	1	4*	2–3	2–4*

Table 6.4 Metals for woven wire cloth: copper and alloys

Material		Material no.	Composition			Max. service temp.		Finest weaving wire dia.		Resistance against:			
			Cu	Zn		°C	°F	mm	inch	Atmosphere	Sea water	Lyes	Acids
Copper	E-Cu	2.0060	99.9			150	300	0.050	0.0020	2	3	3	2–5
Brass	CuZn 37 Ms 63	2.0321	63	37		200	390	0.050	0.0020	5	5	3	4–5
Low brass	CuZn 20 Ms 80	2.0250	80	20		200	390	0.050	0.0020	4	4	2	2–5
Common bronze	CuZn 10 Ms 90	2.0320	90	10		200	390	0.050	0.0020	2	3	2	2–5
Phosphor bronze	CuSn 6	2.1020	94		Sn 6 P	200	390	0.025	0.0010	1	2	3	2–5

6.2.2 'Zero aperture' filter meshes

The square mesh materials have a definite open area between successive warp or weft wires, however fine. The other main category of mesh has the wires as close

Table 6.5 Metals for woven wire cloth: nickel and monel

Material		Material no.	Composition		Max service temp.		Finest weaving wire dia.		Resistance against:			
			Ni		°C	°F	mm	inch	Atmosphere	Sea water	Lyes	Acids
Nickel NiMn 1		2.4106	≥98	Mn 0.3–1	250	480	0.036	0.0014	1	2	1–3	3–5
Nickel Ni 99.2	Alloy 200	2.4066	≥99.2	Mn <0.03	250	480	0.036	0.0014	1	2–3	1–2	3–5
MONEL® Metal NiCu 30 Fe	Alloy 400 Niccoros Silverin	2.4360	≥63	Cu 30 Fe	400	750	0.04	0.0016	1	1	2–3	1–5

Table 6.6 Metals for woven wire cloth: special metals

Material		Material no.	Composition			Max service temp.		Finest seaving wire dia.	
			Cr	Ni		°C	°F	mm	inch
Inconel 600	NiCr 15 Fe	2.4816	15	72		1050	1290	0.06	0.0023
Incoloy 825	NiCr 20 Mo	2.4858	20	38–46	Mo	900	1650	0.08	0.0030
Hastelloy C 4	NiMo 16 Cr 16 Ti	2.4610				1100	2012	0.05	0.0020
Titanium	995	3.7025			Ti 99.5	1000	1830	0.01	0.0020
Silver	Ag 900				Ag 99	300	570	0.04	0.0016
NiCr 80/20		2.4869	20	80		1250	2280	0.02	0.0008
Carpenter 20 CB 3	NiCr 20 CuMo	2.4660	20	37	Cu	950	1740	0.06	0.0023

Table 6.7 Metals for woven wire cloth: aluminium and alloys

Material		Material no.	Composition		Max. service temp.		Finest weaving wire dia.		Resistance against:			
			Al	Mg	°C	°F	mm	inch	Atmosphere	Sea water	Lyes	Acids
AlmG 5	Aluminoy	3.3555	95	5	180	360	0.05	0.0020	3	4	4–5	3–5
AlMg 3		2.3535	97	3	180	360	0.08	0.0030	3	4	4–5	3–5
Al 99		3.0205	99		180	360	0.16	0.0065	2	3	4–5	3–5

together as possible, thereby making the 'pore' diameter as small as possible. An illustration of the diversity of weaves embraced by this category, as typified by the 'Minimesh' range of Haver and Boecker, is provided by Figure 6.2. The diameters of the warp and weft wires are normally different.

For filtration purposes, the most widely used forms of woven wire are the dutch or hollander weaves, wherein the warp and weft are of different diameter, generally with a corresponding difference in the relative numbers of warp and weft wires. If the warp wires (i.e. those along the length of the loom) are thicker, the result is the 'plain dutch weave' of Figure 6.3: the alternative is for the weft wires (across the loom) to be the thicker, giving the 'reverse plain dutch weave' of Figure 6.4.

'Plain dutch weave' is also known as single plain dutch weave, basket weave, reps and corduroy. It forms a filter cloth that is easy to clean and has a low resistance to flow, but is of limited strength. 'Reverse plain dutch weave' is substantially stronger, and is in fact the strongest filter weave in commercial production; as a result, coupled with its good flow characteristics and high dirt-holding capacity, it is widely used industrially.

By a similar combination of warp and weft wires of different diameters, two basic forms of twilled dutch weave are produced. The use of heavy warp wires results in 'dutch twilled weave' (Figure 6.5), which permits the production of the very finest grades of woven wire cloths, while also having the advantage of a very smooth surface on both sides; its disadvantage is a relatively high resistance to flow. With heavy weft wires, 'twilled reverse dutch weave' is formed (Figure 6.6); this offers less resistance to flow but with a corresponding decrease in micron retention characteristics and with rough surfaces on both sides.

Numerous variations exist around these basic weaves. Thus the Haver and Boecker range of wire cloths includes not only the four dutch weaves described above, but also 'broad mesh twilled dutch weave' in which the weft wires are not arranged to give a 'light-tight' cloth but have a preset spacing between them; because of this, the weft mesh count and the retention vary somewhat at intervals. Their patented Zig-Zag weave uses the same weave but involves a special sequence, which guarantees the highest possible accuracy and regularity of spacing.

Another variation is to use twisted bundles of fine wires in place of a single wire. This is particularly favoured in the manufacture of the wire belts that form the heart of papermaking machines. One version is 'twisted plain weave', with

Table 6.8 Tolerance of aperture sizes of Bopp square-mesh wire cloths

Aperture sizes (μm)	(mm)	Average tolerance of apertures (%)
2 25	0.020–0.025	±7.5
32	0.032	±6.5
36–40	0.036–0.040	±5
55–67	0.056–0.067	±4.5
71–95	0.071–0.095	±4
100–170	0.100–0.170	±3.5
189–400	0.180–0.400	±3
425–1600	0.425–1.600	±2.5

Table 6.9 Bopp standard range of mesh wire cloths

Aperture size w	Wire diameter (mm) ddelete	Open area (%) Fo	Mesh[a]	Weight[b]	Stainless steel AISI 304/316	Phosphor bronze	Brass	Tinned steel	Galvanized steel	Plain steel
(mm)										
16	3.2	69.4	1.3	6.77	x					
	2.5	74.5	1.4	4.29	x				x	
	2.0	79	1.4	2.82	x					
14	2.8	69.4	1.5	5.93	x					
12.5	2.5	69.4	1.7	5.29	x					
	2.0	74.5	1.8	3.50	x				x	
	1.6	79	1.8	2.31	x					
11.2	2.5	67	1.9	5.79	x					
	1.6	77	2	2.54	x					
10	2.5	64	2	6.35	x					
	1.8	72	2.1	3.49	x				x	
	1.5	77	2.2	2.18	x					
9	2.2	64	2.3	5.49	x					
8	2.0	64	2.5	5.08	x					
	1.6	69.4	2.6	3.39	x				x	
	1.25	74.5	2.7	2.15	x				x	
7.1	1.8	64	2.9	4.62	x					
	1.4	69.4	3	2.93	x					
6.3	1.8	60	3.1	5.08	x					
	1.4	67	3.3	3.23	x	x	x	x	x	x
	1.25	69.4	3.4	2.63					x	
	1.0	74.5	3.5	1.74	x					
5.6	1.6	60	3.5	4.52	x					
	1.25	67	3.7	2.90	x					
	1.12	69.4	3.8	2.38					x	
5.0	1.6	57.6	3.8	4.93	x					
	1.25	64	4.1 (4)	3.18	x	x	x	x	x	x
	0.9	72	4.3	1.74	x					
4.5	1.4	57.6	4.3	4.22	x					
	0.8	72	4.8	1.53						x
4	1.4	54	4.7	4.61	x					
	1.0	64	5.1(5)	2.55	x	x	x	x	x	x
	0.71	72	5.4	1.36	x					
3.55	1.25	54	5.3	4.13	x					
	0.9	64	5.7	2.31					x	
	0.8	67	5.8	1.87	x					
3.35	0.9	62.1	6	2.43	x					
3.15	1.25	51	5.8 (6)	4.51	x					
	0.8	64	6.4	2.06	x	x	x	x	x	x
	0.56	72	6.8 (7)	1.07	x					
2.8	1.12	51	6.5	4.06	x					
2.5	1.0	51	7.3	3.65	x					
	0.71	60	7.9 (8)	1.99	x	x	x	x	x	x
	0.5	69.4	8.5	1.06	x					
2.24	0.9	51	8.1 (8)	3.28	x					
	0.63	60	8.9 (9)	1.77	x				x	
	0.36	74.5	9.8 (10)	0.64	x			x		
2	1.0	44.4	8.5	4.25	x					
	0.9	48	8.8 (9)	3.56	x					
	0.63	57.6	9.7 (10)	1.93	x					
	0.56	60	9.9 (10)	1.56		x	x	x	x	x
	0.32	74.5	10.9 (11)	0.56	x			x		

Table 6.9 (*continued*)

Aperture size w	Wire diameter (mm) ddelete Open area (%) Fo	Mesh[a]	Weight[b]	Stainless steel AISI 304/316	Phosphor bronze	Brass	Tinned steel	Galvanized steel	Plain steel	
(mm)										
1.8	0.8	48	9.8 (10)	3.13	x					
	0.32	72	12	0.61	x			x		
1.6	1.0	38	9.8 (10)	4.88	x					
	0.8	44.4	10.6	3.39	x					
	0.5	57.6	12.1 (12)	1.51	x	x	x	x	x	x
	0.36	67	13	0.84	x					
	0.28	72	13.5 (14)	0.53				x		
	0.22	77	14	0.34	x					
1.5	0.63	49.6	11.9 (12)	2.37	x					
1.4	0.71	44.4	12	3.03	x					
	0.45	57.6	13.7 (14)	1.39	x					
	0.25	72	15.4 (15)	0.48				x		
	0.22	74.5	15.7 (16)	0.38	x					
1.32	0.5	52.6	14	1.75	x					
1.25	0.8	38	12.4	3.97	x					
	0.63	44.4	13.5	2.68	x					
	0.4	57.6	15.4	1.23	x	x	x	x	x	x
	0.25	69.4	16.9 (17)	0.53				x		
	0.22	72	17.3 (17)	0.42	x					
1.18	0.63	42.5	14	2.78		x				
	0.22	71	18.1 (18)	0.44	x					
1.12	0.56	44.4	15.1 (15)	2.37	x					
	0.45	51	16.2 (16)	1.64	x					
	0.36	57.6	17.2	1.11	x				x	
	0.25	67	18.5 (19)	0.58				x		
	0.22	69.4	19	0.46	x					
1.06	0.22	68.6	19.8 (20)	0.48	x					
1	0.63	38	15.6 (16)	3.10	x					
	0.56	41	16.3 (16)	2.55		x				
	0.5	44.4	16.9 (17)	2.12	x					
	0.4	51	18.1 (18)	1.45	x					
	0.32	57.6	19.2 (19)	0.98	x	x	x	x	x	x
	0.22	67	21	0.50	x			x		
(μm)										
950	0.2	68.2	22	0.44	x					
900	0.5	41	18.1 (18)	2.27	x					
	0.36	51	20	1.30	x	x				
	0.2	67	23	0.46	x			x		
850	0.5	39.6	18.8	2.35						
	0.4	46.2	20	1.63	x					
	0.2	65.5	24	0.48	x					
800	0.5	38	19.5	2.44	x	x				
	0.32	51	23	1.16	x	x	x	x	x	x
	0.2	64	25	0.51	x			x		
750	0.18	65	27	0.44	x			x		
710	0.45	38	22	2.22	x					
	0.36	44.4	24	1.55	x	x				
	0.28	51	26	1.02	x				x	
	0.18	64	29	0.46	x			x		
670	0.16	65.2	31	0.40	x			x		
630	0.4	38	25	1.97	x	x				
	0.28	48	28	1.09	x					
	0.25	51	29	0.91	x	x	x	x	x	x
	0.16	64	32	0.41	x			x		

Table 6.9 *(continued)*

Aperture size w	Wire diameter (mm) ddelete Open area (%) Fo	Mesh[a]	Weight[b]	Stainless steel AISI 304/316	Phosphor bronze	Brass	Tinned steel	Galvanized steel	Plain steel	
(µm)										
600	0.4	36	25	2.03		x				
	0.16	62.3	33	0.42	x			x		
560	0.36	38	28	1.79	x					
	0.28	44.4	30	1.19	x					
	0.16	60	35	0.45	x			x		
530	0.16	59	37	0.47	x			x		
500	0.32	38	31 (30)	1.59	x	x				
	0.25	44.4	34	1.06	x	x	x	x	x	x
	0.16	57.6	38	0.49	x			x		
475	0.16	56	40	0.51	x			x		
450	0.28	38	35	1.37	x					
	0.2	48	39 (40)	0.78	x					
	0.14	57.6	43	0.42	x			x		
425	0.28	36	36	1.41		x				
	0.14	56.6	45 (44)	0.44	x			x		
400	0.25	38	39 (40)	1.22	x					
	0.22	41	41 (40)	0.99	x	x	x	x	x	x
	0.18	48	44 (45)	0.71	x					
	0.14	54	47	0.46	x			x		
375	0.14	53	49 (50)	0.48	x					
355	0.22	38	44	1.07	x					
	0.18	44.4	47	0.77	x	x		x	x	
	0.14	51	51 (50)	0.50	x					
335	0.14	49.7	53 (54)	0.52	x					
315	0.2	38	49 (50)	0.99	x	x	x	x	x	x
	0.16	44.4	53	0.69	x					
	0.112	54	59 (60)	0.37	x					
300	0.2	36	51	1.02		x				
	0.112	53	62	0.39	x					
280	0.22	31	51 (50)	1.23	x					
	0.18	38	55	0.90	x	x				
	0.112	51	65 (64)	0.41	x					
265	0.1	52.7	70	0.35	x					
250	0.2	31	56	1.13	x					
	0.16	38	62	0.79	x	x	x	x	x	x
	0.1	51	73 (74)	0.36	x					
236	0.1	49.3	76	0.38	x					
224	0.18	31	63 (64)	1.02	x					
	0.16	34	66	0.85	x	x	x			
	0.1	48	78 (80)	0.39	x					
212	0.14	36	72	0.71		x				
	0.09	49.3	84	0.34	x					
200	0.16	31	71 (70)	0.90	x					
	0.14	34	75	0.73		x				
	0.125	38	78 (80)	0.61	x	x	x			
	0.09	48	88	0.36	x					
190	0.09	46	91 (90)	0.37	x					
180	0.14	31	79 (80)	0.78	x					
	0.125	34	83	0.65	x	x	x			
	0.09	44.4	94	0.38	x					
160	0.125	31	89 (90)	0.70	x					
	0.112	34	93	0.59	x	x				
	0.1	38	98 (100)	0.49	x	x	x			
	0.071	48	110 (105)	0.28	x					

Table 6.9 (*continued*)

Aperture size w	Wire diameter (mm) ddelete Open area (%) Fo	Mesh[a]	Weight[b]	Stainless steel AISI 304-316	Phosphor bronze	Brass	Tinned steel	Galvanized steel	Plain steel
(µm)									
150	0.1	36	102 (100)	0.51	x				
140	0.112	31	101 (100)	0.63	x				
	0.1	34	106 (105)	0.53	x				
	0.09	38	110	0.45	x	x	x		
	0.063	48	125 (120)	0.25	x				
125	0.09	34	118 (120)	0.48	x				
	0.08	38	124 (125)	0.40	x	x	x		
	0.063	44.4	135	0.27	x				
118	0.056	46	146 (145)	0.23	x				
112	0.08	34	132 (130)	0.42	x				
	0.071	38	139 (140)	0.35	x	x	x		
106	0.063	39.3	150	0.30	x				
	0.05	46.2	163 (165)	0.20	x				
100	0.063	38	156 (150)	0.31	x	x	x		
	0.05	44.4	169 (165)	0.21	x	x			
95	0.045	46	181 (180)	0.18	x				
90	0.063	34	166 (170)	0.33	x	x			
	0.056	38	174	0.27	x				
	0.04	48	195 (200)	0.16	x				
85	0.04	46.2	205 (200)	0.16	x				
80	0.056	34	187 (190)	0.29	x				
	0.05	38	195 (200)	0.25	x	x			
75	0.05	36	205 (200)	0.26	x				
	0.036	45.7	230	0.15	x				
71	0.05	34	210	0.26	x	x			
63	0.045	34	235	0.24	x	x			
	0.04	38	245 (250)	0.20	x	x			
	0.036	41	255	0.17	x				
56	0.04	34	265 (270)	0.21	x				
	0.036	38	275 (270)	0.18	x	x			
	0.032	41	290 (300)	0.15	x				
53	0.04	32.5	275 (270)	0.22	x				
	0.036	35.5	285	0.19	x				
50	0.04	31	280	0.23	x	x			
	0.036	34	295 (300)	0.19	x	x			
	0.03	39	320 (325)	0.14	x				
45	0.036	31	315	0.20	x				
	0.032	34	330	0.17	x	x			
42	0.036	29	325	0.21	x	x			
40	0.032	31	355 (350)	0.18	x	x			
	0.025	38	390 (400)	0.12	x				
38	0.025	36.4	405 (400)	0.13	x				
36	0.028	31	395 (400)	0.16	x	x			
32	0.025	31	445 (450)	0.14	x				
25	0.025	25	510	0.16	x				
20	2.02	25	635	0.13	x				

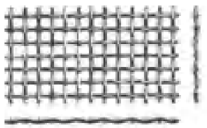
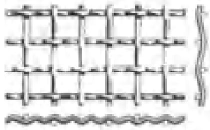
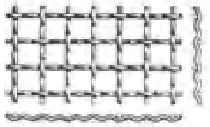
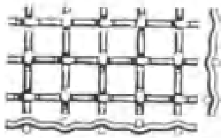
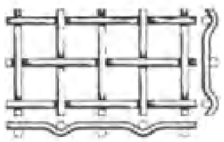
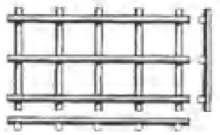
[a] True mesh count. in parentheses approximate mesh count.

[b] Calculated with a density of 7.85 for steel; please multiply by 1.01 for stainless steel. by 1.125 for phosphor bronze. by 1.083 for brass CuZn 37.

either the warp alone or both warp and weft composed of six strands of wire twisted around a core (known as a 'cable wire'). Another example is 'triple warp weave', with three wires twisted to form the warp of a plain weave; this is used for producing very thin papers.

The differences in weave affect the surface and depth structure of the resultant cloths and consequently also their performance characteristics in filtration, including their resistance to flow. For example, certain weaves favour surface filtration and facilitate cleaning by back washing, whilst others achieve higher particle retention efficiencies by utilizing depth filtration. Some of these factors are summarized in Table 6.11, while an overview of the relative retention characteristics of 'Minimesh' wire cloths is provided by Table 6.12. More detailed data in respect of the retention rating and permeability of the different weaves are given in Tables 6.13–6.17.

Table 6.10 Types of crimp in weaving wire screens to DIN 4192 and ISO 4783/3*

Type	Destination	Comments	
A	Double crimp	The rough surface on both sides permits a very intensive screening of the material, thus resulting in high grain accuracy.	
B	Single intermediate crimp	Plain warp wires, weft wires with intermediate crimps between wire intersections.	
C	Double intermediate crimp	Warp and weft wires with intermediate crimps. This type of weave is used for relatively thin wires or for oblong or slot mesh screens.	
D	Lock crimp	Warp and weft pre-crimped on both sides, thus locking the wires securely in place. This type offers a uniform aperture during the service life of the screen.	
E	Flat top screen	Wires are pre-crimped on one side only, leaving the other side flat. This minimizes friction on delicate feed material. Wear is equal over the whole upper surface of the screen.	
F	Pressure welded screen	Made from manganese steel wires and immovably locked together by pressure welding. The intersections remain in place until the wires are completely worn.	

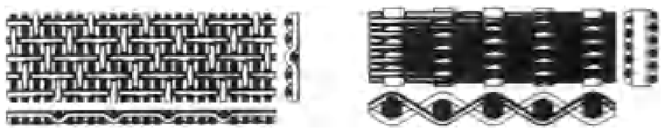
* Haver & Boecker.

In Tables 6.13–6.17 air permeabilities are expressed as values of the factors Y and M, for use with the following equation:

$$P = YV + MV^2$$

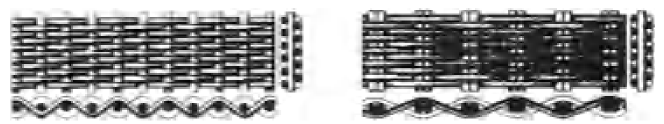
where P = pressure difference across wire cloth (10^{-3} mbar); V = flow velocity of atmospheric air at 20°C (cm/s). This simple relationship may be adapted for the flow of other fluids (excluding non-Newtonian fluids such as polymer melts) by multiplying the calculated pressure difference P by the ratio of the viscosities of the fluid and air:

$$P_{\text{fluid}} = P \times (\text{viscosity of fluid})/(\text{viscosity of air})$$



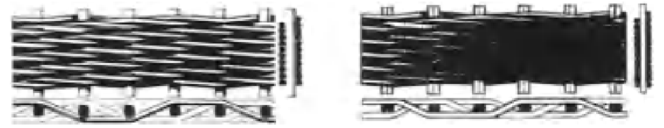
Oblong mesh, EGLA-5

HIFLO High capacity Filter weave, Patented



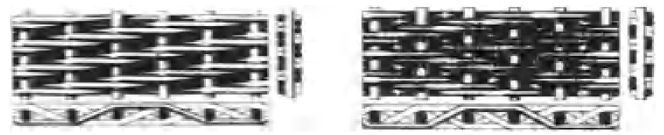
SPW Single Plain dutch Weave

SPW but with double warp wires



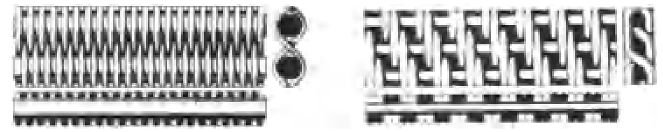
DTW Dutch Twilled Weave

DTW but with double warp wires



BMT Broad Mesh Twilled dutch weave

BMT-ZZ, Zig-Zag, Patented



RPD Reverse Plain Dutch weave

TRD Twilled Reverse Dutch weave

Figure 6.2. Examples of weaves of 'Minimesh' metal filter cloths.

6.2.3 Composite mesh-based media

The term 'composite' implies the combination of different types of material into one filter medium. The different types would be assembled to give different filtration characteristics or extra strength (or both). Woven wire mesh is an excellent material for use in composite media, because of its strength, especially with larger wire diameters. Thus it is used to support delicate screens in basket centrifuges, and cloth belts in belt presses.

When used in combination with other wire meshes and sintered, a very good filter medium is produced – discussed later in this chapter – while meshes are also used to support metal membrane media – discussed further in Chapter 8.

An interesting composite medium, recently developed by GKD, is the 'Ymax' mesh–fibre composite. This has the basic strength of a wire mesh surface filter combined with the depth filtration characteristics of bundles of fibres. The basic mesh is woven from single wires, 0.1–7.0 mm in diameter, and this is interwoven by bundles of non-twisted finer wires. These, in hundreds per bundle, are 5–30 µm in diameter.

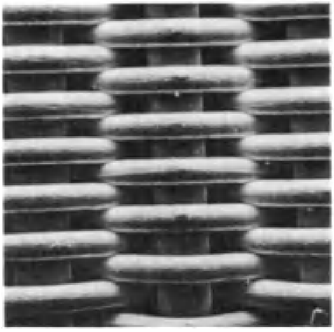


Figure 6.3. Plain dutch weave.

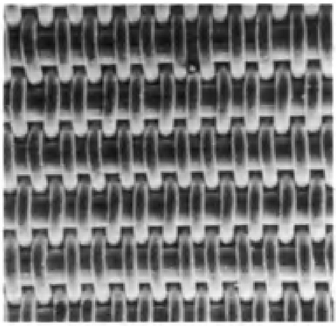


Figure 6.4. Reverse plain dutch twill.

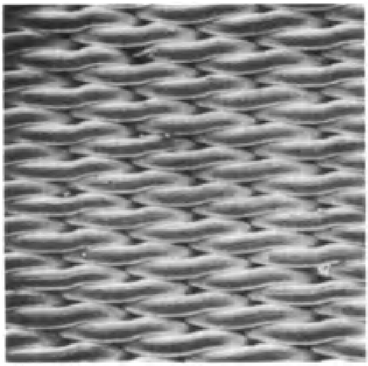


Figure 6.5. Dutch twilled weave.

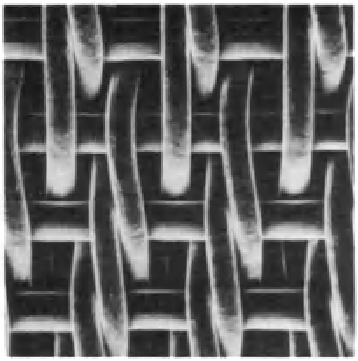


Figure 6.6. Twilled reverse dutch weave.

The material acts like a zero aperture mesh, in that there are no large pores between the basic wires. Larger particles are held on the surface, while smaller ones pass into the depth of the fibre bundles. The medium has porosities up to 60%, with retention figures from 3 to 100 μm. Ymax, available as single pieces up to 3.5 m wide, and 20 m long, is non-compressible, thus maintaining the integrity of pore size and filtration efficiency. Its cost is said to be comparable with that of metal fibre or powder media.

6.2.4 Sintered mesh

Sintered wire mesh refers here to any material, made basically from woven wire mesh, that has been sintered at a temperature sufficient to cause localized melting at the contact points between warp and weft wires. The applied heat and pressure during the sintering process allows some localized molecular diffusion between the wires such that, when cooled, the structure has become much more rigid. This adds considerably to the value of the material as a filtration medium, and overcomes one of the main problems of wire mesh as a filter medium, its inability to withstand fatigue in operation.

Unsintered woven wire meshes suffer from instability, with relative movement or deformation of the wires, resulting from the stresses imposed by vibration, pulsating flow or high differential pressure. This can result in the deterioration of the rated filtration efficiency; abrasion of the wires and the consequent generation of metal particles that contaminate the material being filtered; the unloading of previously trapped particles into the filtrate; and structural failure.

These problems can be avoided by sintering the mesh, so greatly increasing the rigidity of the mesh, producing an extremely strong structure that is resistant to deformation. Sintering also enables the use of finer wires, leading to a higher open area, with a consequential decrease in resistance to flow, and an increase in dirt-holding capacity. Sintered media also have the great advantage that they can be cut and shaped without risk of local disintegration, in a way not possible with unsintered meshes.

The key feature of sintered wire mesh is that it involves one layer of woven mesh (and occasionally two) to act as the filtration medium, with others, where necessary, to give the whole medium adequate stiffness and mechanical support.

Table 6.11 Influence of weave on cloth characteristics[a]

	SPW	HIFLO®	DTW	BMT	BMT ZZ	RPD	TRD
Surface filtration	●	●	●			●	
Depth filtration			●	●	●	●	●
Surface smooth on both sides			●	●	●		
Macroscopic surface unevenness	●	●				●	●
Higher tensile strength – wrap						●	●
Higher tensile strength – weft	●	●	●	●	●		
Easy cleaning by backwashing	●	●				●	

[a] Haver & Boecker.

Table 6.12 Micron retention[a] of 'Minimesh' metal filter cloths[b]

1 Micron retention[a] (μm)	2 Square mesh ISO 565 DIN 4189 w (mm)	3 Weave USA mesh	4 DTW mesh	5 BMT MBT ZZ mesh	6 SPW mesh	7 HIFLO[c] HB-code	8 RPD TRD HB-code	9 SPW+ DTW twin warp	1 Micron retention (μm)
2			510×3600						2
3									3
4			400×2800						4
5									5
6			375×2300						6
8			325×2300	325×1900 ZZ					8
10			250×1400					2/198×1700 DTW 2W 10	10
11									11
12			200×1400	325×1600 ZZ					12
14									14
15				250×1250ZZ			RPD 15		15
16									16
17							RPD 17		17
18			165×1400						18
20		635	165×1100			Hiflo 20			20
22				200×1200					22
23				200×900 ZZ					23
25	0.025	500				Hiflo 25	RPD 25		25
28	0.028			165×800 ZZ					28
30						Hiflo 30			
32	0.032	450		200×600 ZZ					32
34					80×300				34
36	0.036		80×700			Hiflo 36			36
38		400							38
40	0.040			120×600	80×400	Hiflo 40	RPD 40		40
45	0.045	325				Hiflo 45		2/50×250 SPW 2W 45	45
50	0.050			120×400		Hiflo 50			50
53		270							53
56	0.056								56
60							RPD 60		60
63	0.063	230			50×250				63
70						Hiflo 70			70
71	0.071		40×560		50×280				71

Table 6.12 (*continued*)

1 Micron retention[a] (μm)	2 Square mesh ISO 565 DIN 4189 w (mm)	3 Weave USA mesh	4 DTW mesh	5 BMT MBTZZ mesh	6 SPW mesh	7 HIFLO[b] HB-code	8 RPD TRD HB-code	9 SPW+DTW twin warp	1 Micron retention (μm)
75		200			40×200		TRD 75	2/24×128 SPW 2W75	75
80	0.080						RPD 80	2/30×150 SPW 2W80	80
85							RPD 85		85
90	0.090	170					RPD 90	3/12×250 DTW 3W90	90
95			30×360						95
100	0.10				30×150			3/12×200 DTW 3W 100	100
106		140	20×260						106
112	0.112		28×500						112
118			24×300						118
125	0.125	120			24×110		TRD 125		125
140	0.14								140
150		100							150
160	0.16				20×160				160
180	0.18	80							180
200	0.20				16×120				200
212		70							212
224	0.224								224
240					14×110				240
250	0.25	60							250

[a] The (absolute) micron retention is the diameter of the largest round particle just passing through the cloth. It can be determined by Glass Bead Test or Bubble Point Test or calculated theoretically.

[b] Haver & Boecker.

It is not normally intended that a multi-layer sintered material should act as a depth filter – surface (and/or cake) filtration is the aim.

In its simplest form, a single layer of wirecloth, intended probably to be pleated for inclusion in a filter cartridge, will be sintered in order to guarantee that the spacings between the wires will not change during the pleating process. This is a very common use of sintering for wire mesh, with the pleated construction

Table 6.13 SPW (single plain dutch weave) filter cloths[a]

HB-code	Nominal mesh count	Micron retention		Equation factors for permeability performance		Tensile strength[b]		Weight[c] (kg/m^2)	Cloth thickness (mm)
		Nominal (µm)	Absolute (µm)	Y[d]	M[d]	Warp wires N	Weft wires N		
SPW 34	80×300	25	32–36	3.78	0.06796	330	460	0.98	0.25
SPW 40	80×400	36	36–45	1.60	0.04908	310	430	0.82	0.23
SPW 45	2/50×250	30	42–48	8.88	0.04369	310	670	1.15	0.31
SPW 63	50×250	40	56–63	4.38	0.01851	310	640	1.00	0.32
SPW 71	50×280	45	71–75	4.39	0.01530	310	680	1.00	0.32
SPW 75	40×200	56	75–80	3.86	0.01297	320	730	1.30	0.40
SPW 100	30×150	63	100–112	3.83	0.00905	420	870	1.60	0.50
SPW 125	24×110	80	112–125	1.79	0.02748	930	1600	2.70	0.67
SPW 140	22×140		140–170	2.13	0.02561	570	980	2.10	0.66
SPW 160	20×160		160–180	3.57	0.00511	300	870	1.55	0.50
SPW 180	20×150		170–190	3.21	0.00621	260	1100	1.60	0.55
SPW 200	16×120		200–210	3.68	0.00019	280	1320	1.95	0.64
SPW 240	14×110		220–240	3.02	0.02103	390	1500	2.15	0.72
SPW 250	12×95		240–260	3.81	0.00053	330	1440	2.30	0.79
SPW 260	14×88		280–300	2.99	0.00300	640	1650	3.15	0.76
SPW 280	10×90		270–290	3.16	0.01701	510	1750	2.50	0.93
SPW 300	12×64		280–300	3.66	0.00026	750	2620	4.10	1.21
SPW 360	8×85		330–350	3.11	0.00174	400	2100	2.50	0.93

[a] Haver & Boecker.

[b] Tensile strength in Newtons for a 10 mm wide strip.

[c] Weight is for stainless steel, density 1.4301.

[d] Calculate permeability values from Y and M factors using equations in text.

Table 6.14 Patented HIFLO high capacity filter cloth[a]

HB-code	Nominal mesh count	Micron retention		Equation factors for permeability performance		Tensile strength[b]		Weight[c] (kg/m²)	Cloth thickness (mm)
		Nominal (µm)	Absolute (µm)	Y[d]	M[d]	Warp wires N	Weft wires N		
HIFLO® 20	165×1100	n/a	19–20	9.84	0.02935	88	137	0.29	0.093
HIFLO® 25	80×1020	n/a	20–25	13.31	0.00733	160	251	0.49	0.165
HIFLO® 30	80×820	n/a	28–30	7.99	0.00657	152	182	0.41	0.158
HIFLO® 36	80×700	n/a	34–36	10.00	0.00090	251	204	0.60	0.210
HIFLO® 40	80×525	n/a	38–40	5.27	0.01562	182	270	0.53	0.186
HIFLO® 45	70×450	n/a	42–45	4.91	0.02323	329	345	0.80	0.240
HIFLO® 50	53×480	n/a	48–50	3.14	0.02225	188	296	0.72	0.250
HIFLO® 70	53×380	n/a	67–70	2.11	0.12525	200	335	0.82	0.260

[a] Haver & Boecker.
[b] Tensile strength in Newtons for a 10 mm wide strip.
[c] Weight is for stainless steel, density 1.4301.
[d] Calculate permeability values from Y and M factors using equations in text.

Table 6.15 Dutch twill weave (DWT) metal filter cloth[a]

HB-code	Nominal mesh count	Micron retention		Equation factors for permeability performance		Tensile strength[b]		Weight[c] (kg/m^2)	Cloth thickness (mm)
		Nominal (μm)	Absolute (μm)	Y[d]	M[d]	Warp wires N	Weft wires N		
DTW 2	510×3600	<1	4–5	263.17	0.02525	92	250	0.30	0.06
DTW 4	400×2800	<1	5–6	231.47	0.22829	75	335	0.36	0.06
DTW 6	375×2300	1	6–7	210.93	0.07449	150	320	0.39	0.08
DTW 8	325×2300	2	7–8	172.55	0.15155	140	330	0.47	0.09
DTW 9	260×1550	3	8–10	151.0	0.18407	200	420	0.68	0.12
DTW 10	250×1400	4	11–12	126.93	0.15665	190	480	0.68	0.12
DTW 12	200×1400	5	11–13	84.85	0.11646	220	480	0.75	0.14
DTW 14	130×700	8	13–15	168.33	0.49690	390	640	1.60	0.28
DTW 16	200×1120	9	15–17	127.17	0.21465	240	600	0.95	0.16
DTW 18	165×1400	10	15–18	44.08	0.07645	200	510	0.70	0.15
DTW 20	165×1100	12	20–21	68.19	0.11284	220	620	0.90	0.16
DTW 36	80×700	25	34–36	25.81	0.10202	210	860	1.20	0.26
DTW 71	40×560	50	71–80	13.91	0.06452	240	1300	1.70	0.39
DTW 95	30×360	80	95–106	6.12	0.02134	560	1650	2.60	0.54
DTW 100	30×250	53	100–112	1.60	0.17216	520	2340	3.20	0.65
DTW 106	20×260	100	110–120	2.16	0.11361	290	2200	3.10	0.67
DTW 112	28×500	85	106\426–112	1.06	0.01124	550	1420	1.95	0.46
DTW 118	24×300	90	112\426–118	1.80	0.12094	390	2040	2.85	0.63

[a] Haver & Boecker.

[b] Tensile strength in Newtons for a 10 mm wide strip.

[c] Weight is for stainless steel, density 1.4301.

[d] Calculate permeability values from Y and M factors using equations in text.

Table 6.16 Broad mesh twilled weave (BMT) and BMT Zig-Zag filter cloth[a]

HB-code	Nominal mesh count	Micron retention		Equation factors for permeability performance		Tensile strength[b]		Weight[c] (kg/m^2)	Cloth thickness (mm)
		Nominal (μm)	Absolute (μm)	Y[d]	M[d]	Warp wires N	Weft wires N		
BMT 8 ZZ	325×1900	6	6–8	85.63	0.09000	135	195	0.43	0.092
BMT 12 ZZ	325×1600	8	10–12	73.82	0.07341	120	245	0.45	0.094
BMT 15 ZZ	250×1250	12	13–15	42.72	0.07337	200	350	0.64	0.120
BMT 22	200×1200	14	20–22	41.17	0.02134	240	420	0.71	0.140
BMT 23	200×900	16	22–24	21.73	0.02699	160	460	0.64	0.140
BMT 23 ZZ	200×900	16	22–24	10.12	0.01762	195	440	0.64	0.148
BMT 28	165×800	15	24–28	11.02	0.03468	200	430	0.71	0.160
BMT 28 ZZ	165×800	15	24–28	10.04	0.02116	205	350	0.71	0.170
BMT 32	200×600	20	28–32	9.84	0.01816	170	290	0.50	0.150
BMT 32 ZZ	200×600	20	28–32	9.38	0.01721	105	180	0.50	0.144
BMT 40	120×600	28	38–42	2.29	0.03504	270	450	0.90	0.230
BMT 50	120×400	32	48–53	1.07	0.00048	290	400	0.75	0.240

[a] Haver & Boecker.

[b] Tensile strength in Newtons for a 10 mm wide strip.

[c] Weight is for stainless steel, density 1.4301.

[d] Calculate permeability values from Y and M factors using equations in text.

Table 6.17 Reverse plain dutch weave (RPD) & twilled reverse dutch (TRD) cloths[a]

HB-code	Nominal mesh count	Micron retention		Equation factors for permeability performance		Tensile strength[b]		Weight[c] (kg/m²)	Cloth thickness (mm)
		Nominal (μm)	Absolute (μm)	Y^{d}	M^{d}	Warp wires N	Weft wires N		
RPD 15	720×150	15	16–20	35.63	0.01726	240	400	0.65	0.15
RPD 17	630×130	17	20–24	30.95	0.02967	210	480	0.85	0.22
RPD 25	600×100	25	34–38	10.14	0.01751	220	440	0.80	0.23
RPD 40	290×75	40	53–58	12.94	0.03460	540	700	1.55	0.40
RPD 60	175×50	60	67–75	8.29	0.03479	570	1200	2.40	0.57
TRD 75	400×120	75	75–80	4.00	0.00520	360	230	0.73	0.24
RPD 80	130×35	80	95–105	8.25	0.01614	860	1250	3.10	0.77
RPD 85	175×37	85	100–106	3.81	0.00255	780	720	2.10	0.57
RPD 90	170×40	90	106–118	4.03	0.01569	890	770	2.10	0.57
TRD 125	260×40	125	112–125	1.12	0.16700	2220	580	2.25	0.62
RPD 400	84×14		450–530	0.33	0.01028	1630	1160	3.50	1.15
TRD 400	132×17		400–450	1.00	0.01686	6700	750	4.65	1.35
RPD 500	80×14		560–630	0.10	0.01123	1550	1160	3.40	1.18
TRD 500	72×15		500–600	0.02	0.01567	55 220	770	6.35	1.85

[a] Haver & Boecker.

[b] Tensile strength in Newtons for a 10 mm wide strip.

[c] Weight is for stainless steel, density 1.4301.

[d] Calculate permeability values from Y and M factors using equations in text.

allowing the packing of quite a large filtration area into a relatively small filter volume, as with papers or non-woven media.

A single-layer sintered mesh is essentially a surface filtration medium. However, depending on the gauge of the wires, and the weave, relatively high dirt-holding capacities may be achieved. Typical of these materials are Pall's range of Rigimesh media, the characteristics of which are summarized in Table 6.18. Higher dirt-holding capacities, and hence longer on-stream times, may be obtained by using laminates of several meshes with decreasing aperture sizes in the direction of filtrate flow, so that the resultant composite medium acts as a depth filter.

The best-known format for sintered wire mesh is the laminated form, which permits the construction of fine-pore surface filtration media of very high mechanical strength. A five-layer version is supplied by several companies, typically under a '. . .plate' brand name (indicative of its stiffness). However, laminated sintered wirecloth is available with any number of layers of material that the end-user cares to specify, from 2 to as many as 20, depending on whether the objective is give mechanical strength and rigidity to a very fine mesh, or to increase the dirt-holding capacity in depth filtration applications.

The standard five-layer format consists of a coarse top layer to protect the second layer, which is the actual filter medium. This will normally be a fine mesh, with apertures as small as a few micrometres. Below the filtering mesh will be a layer of coarser mesh to act as a flow distribution device, and below this will be two layers of much coarser mesh to act as support for the whole medium, as exemplified by Bopp's Poremet material, illustrated in cross-section in Figure 6.7. The supporting

Table 6.18 Pall 'Rigimesh' and 'Supramesh' sintered metal media

Media grade	Micron removal rating				Nominal standard thickness (mm)	Permeability[c]	
	Liquid service[a]		Gas service[b]			to air	to water
	98%	100%	98% removal by weight	100% removal			
Supramesh Z	1.5	15	0.5	2	0.28	147	1.8
Rigimesh							
K	5	18	3.5	13	0.15	520	84
J	10	25	6	18	0.15	1524	98
M	17	45	11	25	0.15	2456	118
R	40	70	30	55	0.28	4912	295
S	70	105	50	85	0.25	8038	393
T	145	225	120	175	0.3	–[d]	–[d]
A	300	450	250	350	0.48	–[d]	–[d]

[a] Using AC dusts in water, efficiency measured by particle count.

[b] Based on AC FineTest Dust in air. Absolute retention rating based on particle count data.

[c] l/dm^2 min^{-1} @ 10 mbar pressure drop.

[d] Properties not readable.

meshes enable the filtration to be carried out under a pressure differential across the medium that the filtering layer on its own would be unable to contain.

Poremet is available in a range of nominal filtration ratings from 2 to 60 µm. which correspond to absolute (i.e. glass bead challenge ratings) of 5–75 µm. Technical data for these media are given in Table 6.19. while air and water flow rates are given in Figures 6.8 and 6.9, against pressure drop (these figures include curves for Bopp's other, more open, medium Absolta).

Sintered wire mesh is normally produced from stainless steels (304L and 316L being the most popular forms), but other metals are also available, such as phosphor bronze, while more exotic alloys, such as Hastelloy, can be supplied.

The five-layer format is quite stiff, and capable of supporting itself in quite large dimensions. It can also be machined and shaped like solid metal plate, and is available as tubes and as cylindrical cartridges.

A different form of composite combines sintered woven mesh with a layer of powder or fibre sinter-bonded to the upstream surface. An example of this is Pall's Supramesh Z, data for which are included in Table 6.18.

A sophisticated variant of this last type of composite provides the basis of Pall's PMM range of metal membranes, which are discussed further in Chapter 8.

6.2.5 Knitted mesh

By contrast with the structural forms produced by the weaving of filaments, knitting results in a mesh structure of asymmetrical interlocking loops as illustrated schematically in Figure 6.10. The knitted mesh emerges continuously from the machine as a stocking or flattened tube, and is thus a double-layered strip typically in widths up to 635 mm (Figure 6.11). This may then be subjected to a series of subsequent operations to form it into thick rigid pads for use either in filtration, notably as demisters, or in coalescers.

Meshes are knitted from one of, or a combination of, a wide variety of materials, including metals such as galvanized steel, stainless steels, aluminium, copper, nickel and its alloys, as well as polypropylene and fluorocarbon polymers. Filaments are generally circular in section, with diameters in the range 0.1–0.3 mm; a flattened section is possible with synthetic filaments, which increases the surface area.

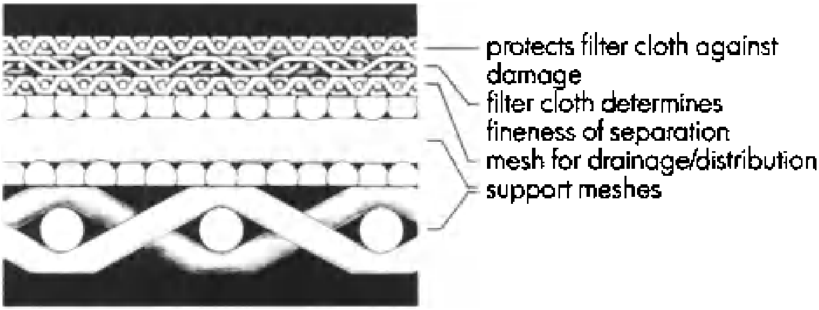


Figure 6.7. Section through 'Poremet' multilayer media.

Although much of the discussion in this section relates to mesh knitted from metal wire, the text can largely be taken to refer also to plastic filament meshes, especially in the comments about the need for plastic mesh in the coalescing of dispersed organic liquids.

Knitted mesh is generally specified by the number of stitches per centimetre in the two directions, along and across the machine (A and B in Table 6.20 – which includes plastic as well as metal meshes), with 1–6 being the most widely used. The stitch can be lengthened or shortened during knitting, while the mesh can be stretched lengthways to produce a narrower stocking with longer and thinner stitches, or opened out to form a wider stocking with a shorter and wider stitch. Crimping, which may be either diagonal or herringbone, increases both the thickness and the stiffness of the mesh; it also increases the free volume and reduces the resistance to airflow.

Filter elements are formed from multiple layers of crimped or uncrimped mesh by laying, folding, rolling and (where appropriate), compressing the layers. Exploitation of the variables outlined above permits the manufacture of a very wide range of different grades, with surface areas per m^3 extending from about 100 m^2 to more than 4000 m^2, with free volumes from 75 to 99.5%. Examples of rolls of uncrimped and crimped mesh and of some elements are shown in Figure 6.12.

6.2.5.1 *Demisters*

The particular use of knitted mesh in filtration is the removal of suspended liquid droplets in either a gas or a liquid stream. The structure of the mesh enables the captured droplets to coalesce into larger drops and then to drain out of the filter mass. The process is called demisting when done in the gas phase.

Table 6.19 Technical data for Bopp 'Poremet' multilayer media

Poremet	Filter rating (µm)		Thickness (mm)	τ_S[c] (N/mm^2)	σ_B[d] (%)	Elongation (N/mm^2)	σ_S[e] (%)	Space void (g/dm^2)	Weight
	Nominal[a]	Absolute[b]							
2	<2	5							
5	5	10							
10	10	15	1.6–2.0	220–230					
15	15	20							
20	20	25			100–130	10–15	55–60	35	90–92
30	30	35							
40	40	50							
50	50	60	1.8–2.2	230–240					
60	60	75							

[a] Nominal filter rating: approximate value for cake filtration.

[b] Absolute filter rating, determined by the glass beard test.

[c] Shear strength τ_s determined by stamping related to the cross.

[d] Breaking strength σ_B sections (thickness *X*).

[e] Yield point σ_s at 0.2% elongation stressed length.

Table 6.21 summarizes the types of standard demisters recommended by KnitMesh for various typical industrial applications. Further information is provided in Section 5.4 of Chapter 5 in the discussion of media for air and gas filters.

6.2.5.2 Coalescers

Pads of mesh knitted from a single material are effective in removing dispersed droplets of an insoluble or immiscible liquid from a second liquid (e.g. oil droplets

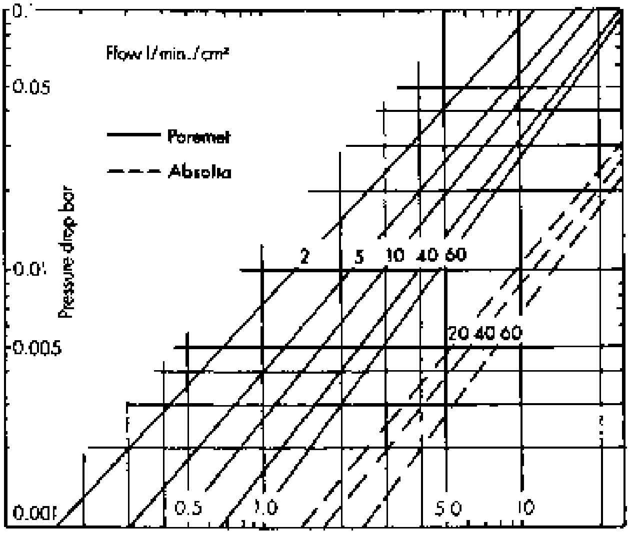


Figure 6.8. Flow rates of air through 'Poremet' and 'Absolta' multilayer media.

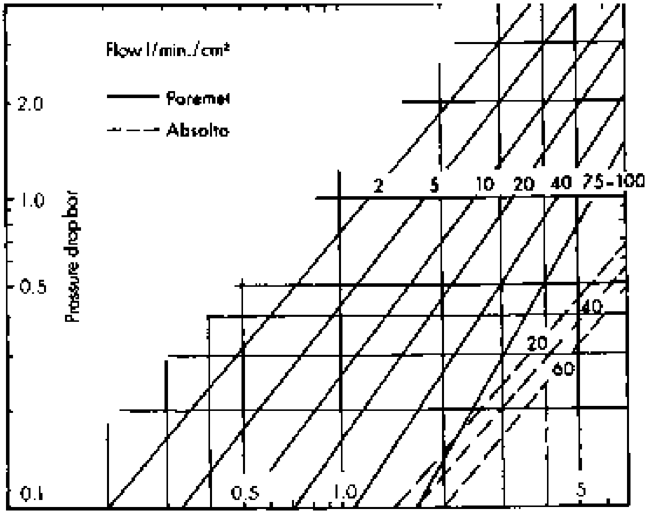


Figure 6.9. Flow rates of water through 'Poremet' and 'Absolta' multilayer media.

from water or water droplets from oil), provided the droplets are larger than about 30 µm. This corresponds to unstable *primary dispersions*, the two phases of which separate rapidly in the absence of agitation or shear.

The efficient functioning of a conventional coalescer of this type is dependent on the mesh filaments being preferentially wetted by the dispersed phase. This interaction between the liquid and the filament is related to the respective surface free energies, which vary considerably for different solids and liquids. Therefore, the material of the filaments must be selected to be compatible with the dispersed liquid; for example, aqueous liquids preferentially wet metals, which have high surface free energies, whereas organic liquids require filaments of low surface free energy, such as plastics.

By contrast, the KnitMesh DC coalescer combines both metal and plastic filaments in the one pad, to exploit the greatly enhanced coalescence observed to occur at 'junction points' where the two materials are in contact and produce a discontinuity of surface free energy. Variations of the filament type, filament diameter and stitch size provide a structure containing many such 'junction points'.

Advantages claimed for the KnitMesh DC coalescer include a higher separating efficiency due to the 'junction effect', as well as higher flow rates and lower pressure drops. Moreover, the coalescer can be used with either phase dispersed, so that there is no loss of performance even if phase inversion occurs. Examples of

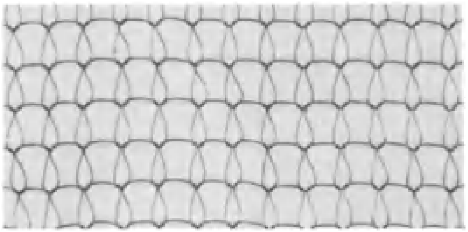


Figure 6.10. Illustration of mesh patterns formed by knitting.

Figure 6.11. Examples of stocking or double-layered knitted mesh.

Table 6.20 Examples of KnitMesh metal and plastic meshes

Reference no.	Diameter of wire (mm)	Width as knitted (cm)	Number of stitches/cm	
			A	B
Fine mesh – metal				
9002	0.11–0.15	1.6	3.5	4.4
9022	0.11–0.15	2.2	4.0	5.9
9028	0.11–0.15	6.4	3.5	3.1
9046	0.11–0.15	6.4	3.5	4.7
9035	0.11–0.15	8.3	4.0	3.4
9001	0.11–0.15	8.3	4.0	4.3
9029	0.11–0.15	13.0	4.0	5.5
Medium-fine mesh – metal				
9037	0.15	3.8	2.8	3.7
9077	0.15	23.0	2.4	3.2
9059	0.15	32.0	2.4	3.1
9055	0.15	50.0	2.4	4.2
Standard mesh – metal				
9017	0.25–0.28	5.4	1.6	1.9
9043	0.25–0.28	5.7	1.6	2.1
9041	0.25–0.28	13.7	1.6	1.5
9033	0.25–0.28	14.3	2.0	1.8
9056	0.25–0.28	23.0	2.0	1.8
9030	0.25–0.28	32.0	2.0	1.8
9063	0.25–0.28	40.0	2.0	1.7
9052	0.25–0.28	50.0	2.0	1.6
Coarse mesh – metal				
9039	0.25–0.28	17.0	1.6	0.74
9057	0.25–0.28	23.0	1.6	0.90
9036	0.25–0.28	35.0	1.6	0.80
9066	0.25–0.28	40.0	1.6	0.85
9054	0.25–0.28	50.0	1.6	0.80
Fine mesh – plastic and fibre				
9029	0.13	12.0	5.0	6.0
9062	0.13	14.0	6.7	4.3
9059	0.13	36.0	2.7	2.8
Standard mesh – plastic and fibre				
9017	0.25	5.0	1.7	2.0
9040	0.25	12.0	1.7	1.7
9003	0.25	14.0	1.9	1.8
9030	0.25	36.0	1.9	1.6
9063	0.25	43.0	1.9	1.6
9052	0.25	55.0	1.9	1.5
9045	0.25	70.0	1.9	1.4
Coarse mesh – plastic and fibre				
9039	0.25	13.0	1.6	1.0
9036	0.25	33.0	1.6	0.9
9049	0.25	64.0	1.6	0.8
Extra coarse mesh – plastic and fibre				
9049	0.25	31.0	1.6	0.6

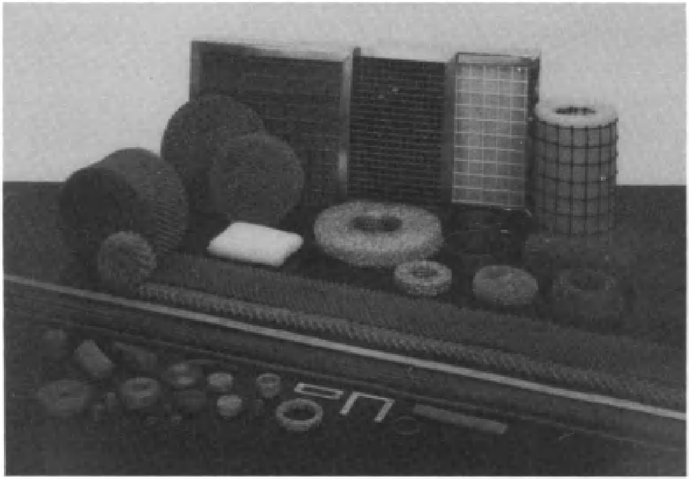


Figure 6.12. Examples of crimped stocking and multi-layer elements. (Photograph: KnitMesh Ltd)

Table 6.21 Applications of standard KnitMesh demisters

Type no.	% free volume	Density[a] (kg/m^3)	Surface area (m^2/m^3)	Special materials included	Applications
9001	97.6	192	680	None	Very high efficiency, very clean service
9033	97.6	192	400	None	Heavy duty
9032	97.6	170	350	None	For general use
9030	92.2	144	300	None	Standard, general purpose media
9030L2	98.2	144	500	None	High efficiency for fine entrainment
9059	98.7	107	380	None	Fine entrainment
9036	98.8	96	200	None	High velocity, dirty service
4530	98.8	96	200	None	High velocity, clean service
4536	99.1	72	150	None	Minimum pressure drop, dirty service
9036	93.0	185	1500	Glass wool	Coalescer – very fine mist
9048	95.0	128	1000	Glass wool	Coalescer – fine mist
9008	95.7	45.5	1050	Polypropylene	High performance – acid mist
9030	93.2	72	820	Polypropylene	
9036	95.8	44	495	Polypropylene	Acid mists and marine engine intakes with minimum pressure drop
9048	97.0	32	360	Polypropylene	
9033	94.0	290	1115	Glass wool/ss316	
9030	95.0	205	820	Glass wool/ss316	Fine mist where stainless steel is valid and minimum pressure drop is important
9036	96.0	138	525	Glass wool/ss316	
9048	94.0	128	820	Teflon FEP	Highly corrosive conditions
9048	95.1	85	725	Hostaflon ET	Highly corrosive conditions

[a] Density is for stainless steel. For nickel/copper alloys, add 13%.

Table 6.22 Examples of applications of KnitMesh DC coalescer

System	Application	Coalescer type
Xylene–water	Condensation of vapour	DC 9201 SS/PPL
Ethylene dichloride–water	Condensation	DC 9201 Fibreglass PPL
Hydrocarbon–water	Steam stripping	DC 9201 SS/Hostaflon
Oil–water	Effluent oil separation	DC 9230 SS/PPL
Oil–water	Effluent oil separation	Composite DC 9201 SS/PPL/GW
Fatty acid–water	Contamination of wash water	DC 9201 SS/PPL
Diesel fuel–water	Washing operation	DC 9201 SS/PPL
Benzene–caustic solution	Entrainment	DC 9201 SS/PPL
Hexane–water	Extraction	DC 9201 SS/PPL
Propane–water	Extraction	DC9201 SS/Teflon
Vegetable fats–water	Fat sweetening, extraction process	DC 9201 SS/PPL

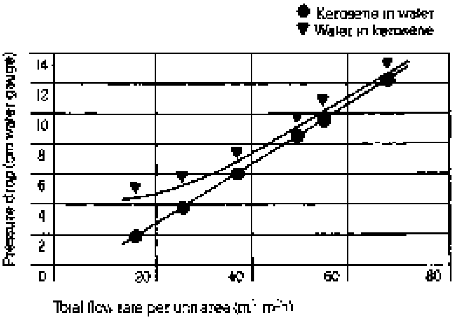


Figure 6.13. Performance tests of KnitMesh DC9201 SS/PPL coalescer: flow rate versus pressure drop.

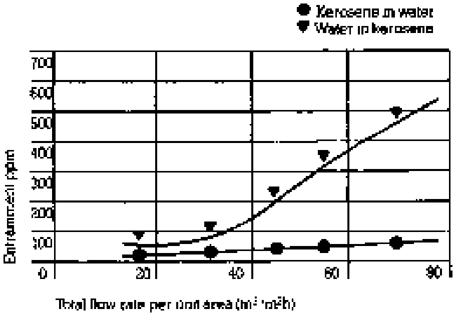


Figure 6.14. Performance tests of KnitMesh DC9201 SS/PPL coalescer: flow rate versus entrainment.

applications are given in Table 6.22. Figures 6.13 and 6.14 show the typical relationships between flow rate, pressure drop and entrainment for 1/1 kerosene-in-water and water-in-kerosene dispersions with mean drop size in the range 100–150 µm, filtered through a 300 mm thick DC9201 SS/PPL coalescer.

6.3 Woven Plastic Mesh

Everything that has been written above about metal wire meshes can apply in principle to the use of plastic monofilament as warp and weft – whether as square mesh or 'zero aperture' weaves. The use of multifilament yarns is more common in plastic materials than for wire mesh. Even sintering is possible, although much less commonly used, despite the less rigid nature of the meshes, and hence the lower degree of accuracy of aperture, especially after use.

Data on monofilament plastic meshes are to be found in Section 2.3.2 of Chapter 2.

6.3.1 *Coated plastic mesh*

Interesting alternatives to conventional metal or plastic meshes are the 'Metalester' products of Saati, a manufacturer of an extensive range of precision woven monofilament meshes and fabrics. The Saatifil Metalester materials are hybrid materials, for which electrolytic techniques are used to deposit a coating of metal all over a polyester mesh substrate. The standard coating metal is nickel, but copper, silver, gold and platinum are also used.

The metal coating is stated to cover the plastic completely, and to result in a totally stable structure in which the individual filaments are bonded to each other at every intersection. Advantages claimed are freedom from the static problems common with plastic meshes, the ability to cut, bend and weld, as well as freedom from migration. Table 6.23 summarizes the standard grades, with apertures from 20 to 2000 µm.

6.4 Perforated Sheets and Plates

Perforated sheets are produced by high-pressure presses that punch groups of holes through a metal sheet as it is indexed through the press. This process may leave very slight burrs around the edges of the holes on the underside of the sheets; when applied as a support for a filter cloth, it may therefore be advisable to orientate a perforated sheet accordingly.

Despite the extreme simplicity of this structure, the multiplicity of variations in the geometrical parameters associated with holes in sheets, combined with the different metals available, potentially permit the production of an immense variety of perforated metal sheets. In addition to the thickness and type of metal, the variable parameters include the shape of the holes, their size, the pattern in which they are arranged, the number of holes per unit area, and the distance

Table 6.23 Examples of 'Metalester' nickel coated polyester precision screens[a]

Reference no.[b]	2000-65	1380-57	545-44	401-55	205-47	200-41	146-39	109-34	76-29	65-34	52-27	43-26	36-22	31-19	25-16	25-11	20-12
Aperture (µm)	2000	1380	545	401	205	200	146	109	76	65	52	43	36	31	25	25	20
Mesh/cm	4.25	6.5	12	15	24	31	45	55	71	90	100	120	130	140	165	180	190
Thread dia. (µm)	500	305	260	260	120	100	80	63	55	40	40	38	34	34	11	14	11
Thickness of fabric (µm)	990	600	470	530	215	175	140	130	100	69	70	66	67	62	68	75	64
Open area (%)	65	57	44	55	47	41	39	35	29	34	27	26	22	19	16	11	12
Weight (g m^{-2})	125	210	184	235	84	75	60	51	51	52	57	53	57	40	15	45	40

[a] SAATI SpA and Sericol Ltd.

[b] All reference numbers should be prefixed MET.

between adjacent holes; various combinations of these parameters determine the percentage of open area.

Perforated sheets are used for some of the coarsest separation duties in industry – the grading of pebbles, for example – with hole diameters measured in centimetres, not millimetres, let alone micrometres.

At one time it was customary for suppliers to include literally hundreds or even thousands of items in their nominal list of standard products. By contrast, modern rationalization of manufacturing and stock control procedures has tended to result in a much shorter standard product range, tailored to careful analysis of the market, but to supplement this with producing special grades as required. For example, Table 6.24 lists the standard mild steel perforated sheets held in stock by one supplier and Table 6.25 is the same company's stock list of stainless steel and non-ferrous perforated sheets, all of these being based on round holes.

Plastic sheets can be perforated by the same pressing techniques as used to perforate metal, and more easily. Although limited ranges of plastic sheets were formerly available, they appear now only to be produced to special order partly because most perforated sheet applications are for dry screening of abrasive materials, to which plastic materials are not very resistant.

Table 6.24 Standard perforated mild steel sheets (round holes)[a]

Pattern no.	Hole diameter (mm)	Pitch (mm)	Open area (%)	Thickness of sheet (mm)	
				2 m × 1 m	2.5 m × 1.25 m
3703A	1.10	2.00	27	1	
613	1.60	2.84	28	1.2/1.5	
82	1.96	3.07	36	1.2	
127	2.84	3.80	50	1.2/1.5	
109	2.46	3.97	36	0.91/1.2/1.5	
1614A	3.20	5.0	37	3.0	
1614	3.17	4.75	40	0.9/1.2/1.5	
694	4.75	7.14	40	0.9/1.2	
2136	3.17	6.35	23		3.0
467	4.75	7.93	32	0.9/1.2/1.5/3.0	1.5/3.0/5.0
214	6.35	8.71	47	1.2/1.5	1.2/1.5
567	6.35	9.53	40	0.9/1.2/3.0	3.0/6.0
600	6.35	12.70	23	6.0	5.0/6.0
249	9.53	12.70	50	1.5	
252	9.53	14.27	40	3.0	3.0/5.0
273	12.70	17.46	47	1.5/2.0	
497	12.70	19.05	40	3.0/6.0	3.0
605	12.70	25.40	23	10.0	
285	22.20	27.00	61		3.0
1024	25.40	34.90	48		6.0

[a] Associated Perforators & Weavers Limited.

6.4.1 Expanded metal media

Expanded metal is made from metal sheets by a repetitive process that involves first cutting it to form a series of short slits, and then stretching the sheet to open up these slits into the characteristic diamond apertures of Figure 6.15. This may be followed by calendering so as to flatten the resultant metal strands from the sloping profile imposed on them during stretching.

Measurement of the dimensions of the apertures and the strands is defined in Figure 6.16 for both uncalendered mesh ('conventional') and for calendered mesh ('flattened'). Typical data for the finer grades of both types in various metals are given in Tables 6.26 and 6.27.

Plastic sheets can be expanded by the same slitting and stretching techniques as used to expand metal. Although limited ranges of plastic sheets are available,

Table 6.25 Standard stainless steel and non-ferrous perforated sheets (round holes)[a]

Pattern no.	Hole diameter (mm)	Pitch (mm)	Open area (%)	Metal	Thickness (mm)	Stocked size (mm)
1533	0.55	1.02	26	Brass	0.45	1220×610
1762A	0.80	1.50	26	S/S 304	0.50	2000×1000
613A	1.50	2.60	30	S/S 304	1.0	2000×1000
441	2.16	3.00	46	Zinc	0.35	2440×915
668	2.46	4.75	24	Pre-galvanized	0.7	2500×1250
668	2.46	4.75	24	Pre-galvanized	1.2	2500×1250
951	3.17	5.33	32	Pre-galvanized	0.7	2500×1250
951	3.17	5.33	32	S/S 304	1.2	200×1000
951	3.17	5.33	32	S/S 304	0.9	2000×1000
1614	3.17	4.75	40	Aluminium	1.2	2000×1000
1614	3.17	4.75	40	S/S 304	1.5	2000×1000
694	4.75	7.14	40	Aluminium	1.2	2000×1000
467	4.74	7.03	32	S/S 304	1.2	2000×1000
567	6.35	9.53	40	S/S 304	2.0	2000×1000
567	6.35	9.53	40	S/S 304	1.2	2000×1000

[a] Associated Perforators & Weavers Limited.

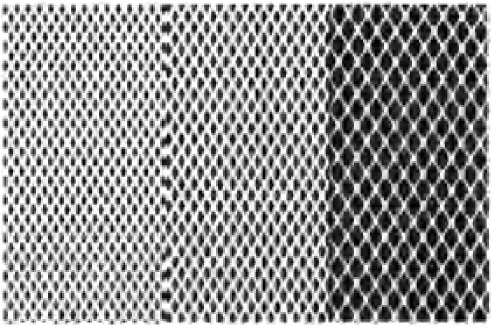


Figure 6.15. Examples of expanded metal mesh. (Illustration: The Expanded Metal Co. Ltd)

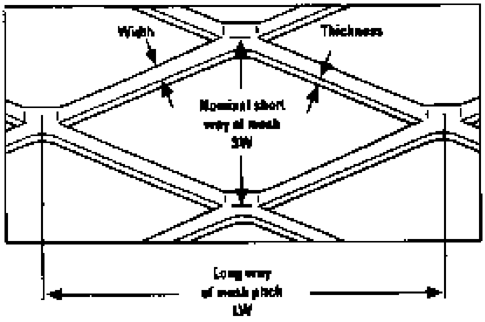
these products have largely been replaced by the extruded materials discussed below (Section 6.6).

6.4.2 Electrolytically formed sheets

The processes of photo-etching and electroforming are used by Stork Veco to produce a substantial range of finely perforated metal sheets, 15–1500 µm in thickness, and a smaller range of screens for continuous basket centrifuges. Photo-etching involves the removal of metal from a continuous sheet, while electroforming creates the perforated sheet by building up a layer of metal by depositing it upon a substrate. These two processes (plus laser cutting) provide a wide range of delicately structured items for industrial use, covering electric shaver foils to ink-jet orifice plates.

Photo-etching is applicable to almost all metals and their alloys. It begins with the production of a photo-mask in the precise shape of the required product, which is superimposed on a metal sheet. This sheet, already coated with a photo-emulsion, will become the perforated plate. After exposure through the mask to suitable UV light, and subsequent development and washing of the coating, the unexposed parts of the photo-emulsion protect the metal during etching; if both

1. For conventional meshes with angled strands dimensions from centre to centre of knuckles are shown.



2. For flattened meshes dimensions of the aperture point to point are shown

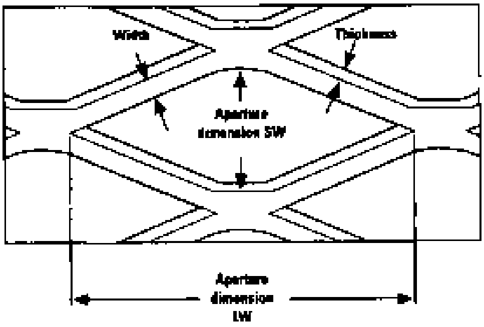


Figure 6.16. Defining the dimensions of expanded metal meshes. (Illustration: The Expanded Metal Co. Ltd.)

Table 6.26 Conventional expanded metal mesh[a]

Mesh no.	Metal	Nominal aperture (mm)		Size of strand (mm)		Open area (%)		Weight/sheet (kg)	Sheet size (mm)	
		LW[b]	SW[c]	W[d]	T[e]	Normal	Max.		LW[b]	SW[c]
941MM	SS316-S11	1.05	0.67	0.30	0.15	12	16	0.170	212	600
957MM	SS316-S11	1.50	0.91	0.22	0.15	46	54	0.194	315	600
926S	SS304-S15	3.15	1.95	0.79	0.44	12	31	1.899	610	1070
927S	SS316-S11	3.175	2.51	0.254	0.152	40	66	1.083	420	7620
921A	Aluminium	3.15	2.41	0.28	0.32	40	66	1.255	610	7620
707S	SS304-S15	4.75	2.36	0.56	0.46	41	51	1.258	1250	1250
220	Steel	5.84	3.50	0.79	0.60	42	54	1.570	1200	610
601A	Aluminium	5.84	3.50	0.79	0.60	42	54	0.506	1200	610
602A	Aluminium	5.84	3.39	1.17	0.54	25	31	0.774	1200	610
227S	SS304-S15	5.84	3.39	0.81	0.46	51	61	1.267	1250	1250
221S	SS304-S15	5.84	3.39	1.22	0.56	24	37	2.159	1250	1250
204	Steel	10.24	5.44	1.55	1.00	42	55	4.900	1220	915
351A	Aluminium	10.24	5.44	1.55	0.90	42	57	1.496	1220	915
201	Steel	10.24	5.44	0.79	0.60	70	78	1.462	1220	915
199	Steel	14.29	5.44	1.17	1.00	57	48	1.628	1220	915
196S	SS304-S15	14.29	5.44	1.30	0.90	45	57	1.162	1250	915
197S	SS304-S15	14.29	5.44	1.33	0.70	56	74	1.003	1250	915
0798	Steel	19.05	7.41	1.70	1.00	51	65	10.687	2440	1220
0798A	Aluminium	19.05	7.41	1.70	0.90	52	65	3.154	2440	1220
0798S	SS304-S15	19.05	7.36	1.71	0.90	52	66	7.613	2500	1250
1196	Steel	25.50	9.52	1.98	1.20	61	74	11.669	2440	1250
1196A	Aluminium	25.50	9.52	1.95	1.20	61	74	4.019	2440	1250
1197S	SS304-S15	25.50	9.55	2.24	0.90	55	75	7.564	2500	1250
1296	Steel	30.48	11.72	2.36	1.30	61	76	11.282	2440	1220
1296A	Aluminium	30.46	11.72	2.36	1.30	62	74	5.500	2440	1220

[a] The Expanded Metal Company Limited. [b] LW = long dimension of mesh. [c] SW = short dimension of mesh. [d] W = width of strand.
[e] T = thickness of strand.

Table 6.27 Flattened expanded metal mesh[a]

Mesh no.	Metal	Nominal aperture (mm)		Size of strand (mm)		Open area (%)		Weight sheet (kg)	Sheet size (mm)	
		LW[b]	*SW*[c]	*W*[d]	*T*[e]	Normal	Max.		*LW*[b]	*SW*[c]
706F	Steel	2.79	0.81	0.76	0.58	26	26	3.360	1220	915
226F	Steel	3.81	2.03	0.79	0.58	46	46	1.570	1220	915
228SF	SS304/S15	3.00	1.00	1.22	0.56	19	19	2.359	1250	1250
217F	Steel	6.855	3.56	1.30	0.90	52	52	8.930	1220	2440
217AF	Aluminium	6.86	3.56	1.27	0.89	52	52	2.585	1220	2240
0974F	Steel	14.22	4.83	1.85	0.96	52	52	9.823	1220	2240
0974AF	Aluminium	13.97	4.83	1.80	0.89	52	52	3.066	1220	2440
0792SF	SS304/S15	14.22	4.58	1.83	0.86	53	53	3.360	1250	1250
197SF	SS304/S15	10.50	3.50	1.33	0.70	52	52	3.003	1250	1250
1276SF	SS304/S15	25.00	8.00	1.98	1.09	57	57	6.542	2500	1250
1280F	Steel	24.38	7.11	2.39	1.14	57	57	10.836	2440	1220
1280AF	Aluminium	24.13	6.86	2.39	1.14	58	58	3.751	2440	1220
1282F	Steel	24.38	7.62	2.08	1.14	63	63	9.436	2440	1220

[a] The Expanded Metal Company Limited. [b] *LW* = long dimension of mesh. [c] *SW* = short dimension of mesh. [d] *W* = width of strand.
[e] *T* = thickness of strand.

sides of the metal sheet are being etched simultaneously, the sheet is sandwiched between two precisely aligned photo-masks. After etching is complete, the photo-emulsion is stripped off prior to post-treatment operations such as protective plating and passivation.

Electroforming employs the same masking process, but now the unexposed parts of the photo-resist lacquer protect the surface of the substrate from deposition of the metal layer that will form the screen medium. The sheet of metal and unexposed resin form a matrix that serves as the cathode in an electrolytic bath, where metal from a pure metal anode deposits on the areas where the photo-resist was removed. A thick layer of photo-resist allows the deposition of a thick-film product, while a thin layer leads to the deposition of metal firstly within the spaces between the photo-resist, and then over its edges, to create an overgrow product. As with photo-etching, various post-deposition operations are possible, most commonly adding a hard protective layer of chromium.

The Stork range of screens for continuous centrifuges (as used mainly in the sugar industry) are deformable structures, and as such are supported in use on a coarse wire mesh backing screen. They are made in electroformed nickel, and are usually chrome plated. They range in thickness from 280 to 420 μm, and have slots, rather than round holes, with slot widths between 40 and 130 μm, as shown in Table 6.28.

The VecoStandard type of screen is for normal applications, with a mirror-smooth working surface. Its conical holes reduce binding and clogging, while the slots can be oriented in the screen to suit the travel direction of the sugar crystals (Figure 6.17(a)). The VecoFlux type is for higher filtrate rates, with an open area double that of the standard screens or more, for a given slot size (Figure 6.17(b)), while the VecoLife screens are significantly thicker to give a longer screen life by reducing the deformation into the support screen (Figure 6.17(c)).

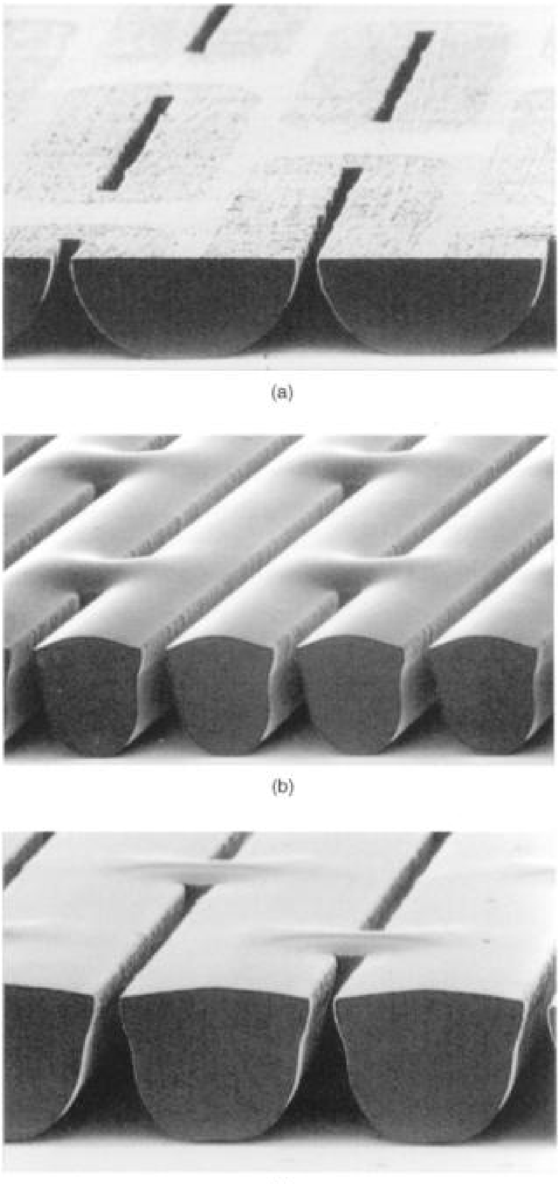
The other filtration media are rigid homogeneous structures, made mainly by electroforming. They have sharp separation characteristics, with perforations down to 10 μm, having a high throughput and being easily cleaned. The standard

Table 6.28 Technical specifications for Veco centrifuge screens*

Screen type	Slot size (mm)	Open area (%)	Thickness (mm)
VecoStandard A	0.04 × 1.67	4.2	0.31
	0.06 × 1.69	6.4	0.29
	0.09 × 1.72	9.6	0.28
	0.13 × 1.76	14.2	0.25
VecoStandard B	0.06 × 2.11	6.4	0.34
	0.09 × 2.14	9.6	0.32
VecoFlux	0.04 × 2.18	9.6	0.33
	0.06 × 2.20	14.4	0.33
	0.09 × 2.23	21.8	0.33
VecoLife	0.06 × 2.65	9.0	0.42
	0.09 × 2.68	13.5	0.42

*Stork Veco BV

range, called Veconic, has a smooth working surface. It is electroformed in pure nickel, but can be chrome plated. The perforations are sharp-edged and conical in cross-section; they may be round or slot-shaped. Veconic screens are available in standard sheet dimensions of 1 m by 1 m. The range of sizes is shown in Table 6.29 for round holes, and in Table 6.30 for slotted holes. The wide range in open area is to be noted.


(a)

(b)

(c)

Figure 6.17. Stork Veco centrifuge screens: (a) VecoStandard, (b) VecoFlux, (c) VecoLife.

The Veconic *plus* range of screens is made by a special, patented electroforming process, also from pure nickel, which permits the variation in sheet thickness with the same perforation dimensions. As with the Veconic screens, Veconic *plus* is available with round or slotted holes, in sheets 1 m by 1 m. Veconic *plus* has a

Table 6.29 Stork Veco Veconic filter screens with round holes[a]

Hole diameter (mm)	Mesh no.[b]	Open area (%)	Thickness (mm)
0.02	125	1	0.09
0.04	125	4	0.08
0.06	125	8	0.07
0.10	40	2	0.25
0.13	40	4	0.23
0.15	50	8	0.18
0.20	40	9	0.20
0.25	50	23	0.12
0.30	20	5	0.45
0.35	30	16	0.25
0.40	30	21	0.18
0.45	30	27	0.16
0.50	25	23	0.20
0.75	20	33	0.20
1.00	15	33	0.20
1.50	12.5	52	0.20
2.00	9	48	0.28
2.50	7	45	0.42

[a] Stork Veco BV.

[b] Mesh number is the number of holes on a line 1 inch long, and on a line 1 inch long at 60° to the first.

Table 6.30 Stork Veco Veconic filter screens with slotted holes[a]

Slot dimensions (mm)	Mesh no.[b]	Open area (%)	Thickness (mm)
0.04 × 1.10	60/15	6	0.17
0.06 × 1.66	40/10	6	0.28
0.08 × 1.67	40/10	8	0.27
0.10 × 1.70	40/10	11	0.26
0.13 × 1.72	40/10	14	0.24
0.13 × 2.36	28/7	9	0.34
0.15 × 3.50	17/5	7	0.75
0.18 × 2.42	28/7	13	0.30
0.20 × 2.46	28/7	16	0.29
0.25 × 2.49	28/7	20	0.26
0.30 × 3.65	17/5	14	0.59
0.35 × 3.70	17/5	17	0.54
0.40 × 3.75	17/5	20	0.49
0.50 × 3.85	17/5	25	0.43
0.75 × 4.10	17/5	41	0.30

[a] Stork Veco BV.

[b] Mesh number gives, first, the number of slots on a line 1 inch long, and then the number on a line 1 inch long at 90° to the first.

Table 6.31 Stork Veco Veconic *plus* filter screens with round holes[a]

Hole diameter (mm)	Mesh no.[b]	Open area (%)	Thickness (mm)
0.03	125	2	0.15
0.03	125	2	0.30
0.03	125	2	0.50
0.04	125	4	0.15
0.04	125	4	0.30
0.04	125	4	0.50
0.06	125	8	0.15
0.06	125	8	0.30
0.06	125	8	0.50
0.08	125	14	0.15
0.08	125	14	0.30
0.08	125	14	0.50
0.10	80	23	0.20
0.10	80	23	0.35
0.10	80	23	0.50
0.15	80	20	0.20
0.15	80	20	0.35
0.15	80	20	0.50
0.20	50	14	0.20
0.20	50	14	0.35
0.20	50	14	0.50
0.25	50	22	0.20
0.25	50	22	0.35
0.25	50	22	0.50

[a] Stork Veco BV.

[b] Mesh number is the number of holes on a line 1 inch long, and on a line 1 inch long at 60° to the first.

Table 6.32 Stork Veco Veconic *plus* filter screens with slotted holes[a]

Slot dimensions (mm)	Mesh no.[b]	Open area (%)	Thickness (mm)
0.01 × 0.42	160/40	5	0.30
0.01 × 0.42	160/40	5	0.50
0.02 × 0.43	160/40	10	0.30
0.02 × 0.43	160/40	10	0.50
0.03 × 0.44	160/40	15	0.30
0.03 × 0.44	160/40	15	0.50
0.04 × 0.45	160/40	20	0.30
0.06 × 0.47	160/40	30	0.30
0.08 × 0.88	80/20	18	0.30
0.08 × 0.88	80/20	18	0.50
0.10 × 0.89	80/20	23	0.35
0.10 × 0.89	80/20	23	0.50

[a] Stork Veco BV.

[b] Mesh number gives, first, the number of slots on a line 1 inch long, and then the number on a line 1 inch long at 90° to the first.

greater thickness, and hence strength, and is supplied in the finer perforation sizes, as shown in Tables 6.31 and 6.32.

The Veronic range is made in the same way as the Veconic screens, but thicker, and hence stronger. It too is available in 1 m^2 sheets, with round and slotted perforations, but the range is much smaller, with 6 sizes of round hole (0.08–1.75 mm) and 7 slotted hole sheets (0.10–0.50 mm wide), but all have quite large open areas for the size of hole.

A small range of Vecopore screens, made from pure nickel by the same special electroforming process as Veconic *plus*, has fine holes (20–50 μm) with high mesh numbers, and consequently large open areas. These are available in sheets 500 mm by 600 mm.

The final member of the Stork Veco perforated sheet range is the Veconox range, made by photo-etching from AISI 316 stainless steel. These have quite large perforations – the slotted sheets having slot widths from 0.13 to 0.4 mm.

6.4.2.1 *Track-etched sheets*

A very specialised case of etched pores in a sheet of material relates to the formation of minute pores by the bombardment of the material by rays of subatomic particles, followed by the chemical etching of the material, to form pores at the sites where it was bombarded. This is a technique used for making specialized membranes, exemplified by Whatman's Nuclepore range, and is further discussed in Chapter 8.

6.4.3 Laser-cut sheets

The application of laser techniques provides the unique benefit of forming precision-cut micro-slots in hard, wear-resisting metals such as stainless steel. In this way holes can be formed in the sheet with widths narrower than the thickness of the metal. Laser-cut screens are intended for applications needing a high proportion of open area, and a resistance to clogging of the medium. The holes are usually slots, but circular holes can also be formed in this way. The slots

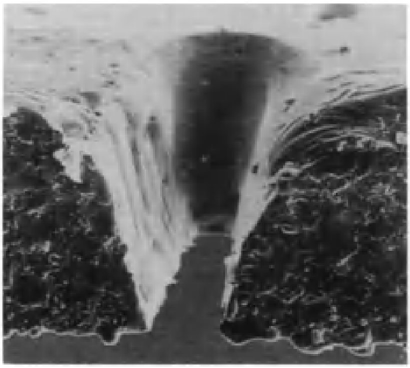


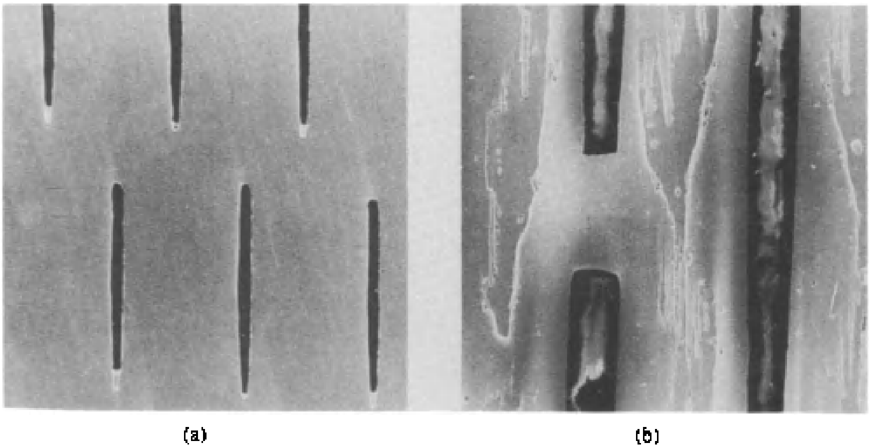
Figure 6.18. Cross section of 60 μm SSL slot @ ×150 magnification, showing high relief angle and extremely sharp edges. (Photograph: Laser Action Pty Ltd)

have sharp working edges, and the high relief angles act to prevent clogging. The smooth surface of the screen is an aid to fluid flow.

A typical format is available in the patented process developed in Australia by the Commonwealth Scientific and Industrial Organization, in cooperation with the Sugar Experimental Station Board. Commercialization of the resultant SSL (stainless steel laser-cut) screens and sieve products, and those of other metals such as titanium, is in the hands of LaserAction Pty; the products are available in the UK from Croft Engineering Services.

Figures 6.18 and 6.19 show the characteristic tapered form of the slots, with extremely sharp edges, a high relief angle and smooth working face, while Figure 6.20(a) reveals the narrowing of the slots at each end. Slot widths may be from 40 to 200 μm corresponding to the high open areas listed in Table 6.33; as compared with conventional slotted screens, SSL slots are shorter and thinner on average (because

Figure 6.19. Smooth working face of 60 μm SSL slot (at × 260), showing sharp slot edges. (Photograph: Laser Action Pty Ltd)



(a) (b)

Figure 6.20. Comparing, at the same magnification, the wear after 1350 h of operation of 60 μm slots in (a) laser-cut screen and (b) electroformed chrome nickel screen. (Photograph: Laser Action Pty Ltd)

of their narrower ends), but are several times more numerous. The metal thickness is usually 20 µm; screens may be up to 0.9 m wide and as much as 2 m long.

Extensive full-scale side-by-side comparative trials are reported to have demonstrated the benefits of using SSL screens in centrifuges separating sugar crystals from molasses. Although they cost some four times more than conventional centrifuge screens, this is claimed to be more than offset by process savings accruing from higher yields of sugar because of a much greater resistance to wear by the tough SSL screens. This is illustrated in Figure 6.20, which compares SSL and conventional electroformed chrome nickel 60 µm slot screens at the same magnification after 1350 hours of operation: the slots of the conventional screen are visibly much enlarged, whereas those of the SSL show little change in sharpness or width even at the high (× 720) magnification in Figure 6.21.

6.5 Bar and Wire Structures

The remaining metal media in this chapter are fabricated from individual bars, or from rod or wire that has been processed to change its shape. The filter elements

Table 6.33 SSL laser-cut screens[a]

Slot width (µm)	Maximum open area (%)
40	7.5
50	10.0
60	12.0
70	14.0
80	16.0
90	18.0
100	20.0
120	24.0

[a] Laser Action Pty Ltd.

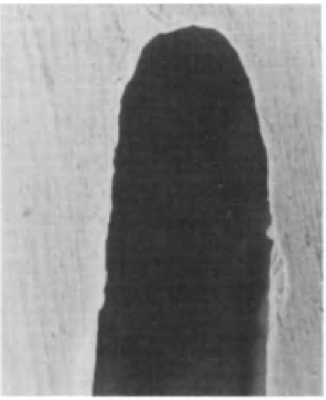


Figure 6.21. High magnification (× 720) of SSL slot after 1350 h operation. (Photograph: Laser Action Pty Ltd)

made from these media are thus assembled rather than produced in sheets or rolls. As a result they are more expensive on a unit area basis than woven mesh or perforated sheet. and so are used where their particular combination of strength and accuracy of aperture size is necessary.

6.5.1 Looped wedge wire

Looped wedge wire (Figure 6.22) is made from round wire by a two-stage process. First it is looped at regular pitched intervals and then pressed so that the sections between consecutive loops are formed into deep wedge-shaped sections. The loops themselves are also pressed to flatten the sides into accurately sized spacing shoulders that butt together when the wires are assembled into panels using locking cross rods passed through the loops. as in Figure 6.23.

The width of the resultant slit apertures between adjacent wedge wires is determined by the extent to which the width across the spacing shoulders is greater than the width of the top face of the wedge profile. The strength of the assembled panels depends on the dimensions of the wedge sections, and on the diameter and pitching of the cross rods. All of these dimensional factors can be varied to suit the application.

Another important variable is the profile of the top surface of the wedge wires. the typical options being listed in Table 6.34. which includes comments on their applications. Table 6.35 summarizes the dimensions and profiles of wedge wires and the diameters and pitches of cross rods used by one manufacturer to produce the standard screens in Table 6.36 and the finer Mini-Wedge Wire screens in Table 6.37; whilst the latter are obviously less robust than standard wedge wire, they are many times stronger than equivalent fine woven meshes.

Looped wedge wire screens are available in a variety of different metals, as indicated by Table 6.38. which provides factors to convert the mild steel weights included in Table 6.36.

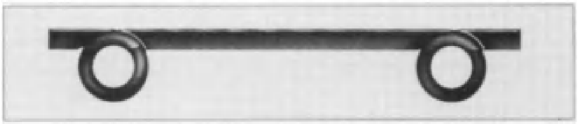


Figure 6.22. A looped wedge wire. (Photograph: CAE Trislot N.V.)

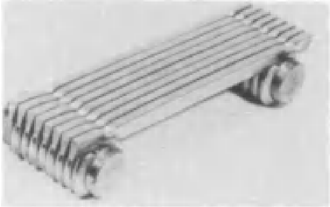


Figure 6.23. Looped wedge wire screen. (Photograph: CAE Trislot N.V.)

6.5.2 Welded wedge wire screens

Welded wedge wire, usually in 304 or 316 stainless steel but also in special metals such as Hastelloy, is produced by sophisticated automated welding techniques that permit preformed profiled wedge wires to be welded directly to

Table 6.34 Typical profiles of wedge wire[a]

Section	Name	Code	Comment
	Flat top wedge wire	F	The most commonly used profile, giving good screening efficiency over the whole range in most applications. It is excellent for dewatering slurries and is extensively used in coal washeries.
	Conical top wedge wire	C	Designed particularly for fine mesh screens for dewatering slurries.
	Square top wedge wire	S	Suitable for the larger aperture screens used with highly abrasive materials.
	Riffle top wedge wire	R	Combines most of the dewatering qualities of both flat and conical top profiles, and is also widely used as an attractive non-slip finish for drainage grids and walkways.

Table 6.35 Profiles and dimensions of looped wedge wires[a]

Profile[b]	Section no.	Profile		Cross rod	
		Width (mm)	Depth (mm)	Diameter (mm)	Pitch (mm)
C	12	1.02	1.64	3.2	25.4
C	16	1.37	2.20	4.8	38.1
F	20	1.70	2.74	7.9	70
F	23	1.93	3.07	7.9	70
FCSR	28	2.33	3.83	7.9	70
FCSR	32	2.66	4.32	7.9	70
FCSR	33	2.77	4.50	7.9	70
FCSR	35	2.90	4.70	7.9	70
FCSR	39	3.28	5.31	7.9	70
FCSR	42	3.50	5.72	7.9	70
FCSR	44	3.66	5.90	7.9	70
F	41	3.91	4.87	9.5	102
FCSR	49	4.08	6.63	12.7	102
FCSR	51	3.43	6.98	12.7	102
FS	54	4.52	7.34	12.7	102

[a] Screen Systems Limited.

[b] F = flat top; C = conical top; S = square top; R = riffled top.

deep section cross bars (Figure 6.24). As with looped wedge wire, considerable variation is possible in the profile and dimensions of the wedge wire, and also in the shape and dimensions of the cross bars. A representative list of the standard products of Screen Systems Ltd is reproduced in Table 6.39.

Table 6.36 Standard looped wedge wire screens[a]

Apertures (mm)	Section no.	Open area (%)	Apertures per metre	Weight[b] (kg/m^2)
0.125	20P[c]	6.7	547	25.6
	23P	6.0	486	29.4
	28P	4.8	407	34.4
	32P	4.3	358	38.6
0.25	20P	12.5	511	24.3
	23P	11.1	460	28.0
	28P	9.2	387	32.8
	32P	8.2	341	37.1
0.375	20	16.5	479	23.1
	23	15	433	26.7
	28P	12.7	367	31.6
	32P	11.3	328	35.9
	20	20.7	53	22.1
0.75	23	18.8	410	25.6
	28	16.1	351	30.4
	32P	14.4	315	34.7
1.0	23	25.2	370	23.7
	28	21.9	325	28.6
	32	19.8	292	32.6
	23	30.9	341	22.2
	28	27.2	300	26.7
	32	24.8	273	30.7
	49	17.5	197	54.3
1.25	35	26.9	243	32.4
1.5	23	38.8	292	19.8
1.75	28	34.7	259	23.9
	35	30.2	226	30.6
	49	23.4	177	49.8
	28	37.0	246	22.9
	35	32.6	215	29.1
2.0	39	32.8	189	32.9
	49	27.4	164	46.9
	63	24.8	137	53.5
2.5	42	36.0	166	33.3
	49	32.1	151	43.9
3.0	44	38.5	151	32.9
	51	35.9	136	43.6
	54	34.9	133	46.8
4.0	51	42.0	120	40.0
	54	41.0	117	42.5

[a] Screen Systems Limited.

[b] Mild steel. For other metals, multiply by factor in Table 6.38.

[c] P: for severe side loading, spacing pips can be provided.

The Trislot screens developed by Bekaert (but now available from Trislot) include a configuration in which the slots can be as small as 10 µm. The total range of configurations comprises flat, curved, conical and tubular; it is a particular version of the last of these that makes the 10 µm slot possible, namely 'out-to-in' flow with tubes up to 70 mm in diameter. For all other versions and configurations, the smallest slot size is 50 µm (with an average tolerance of 10%).

A distinction is made between two versions of the spirally wound tubular configuration, depending on whether flow is intended to be out-to-in (Figure 6.25) or in-to-out (Figure 6.26). The 'slot tubes' of the former version were originally developed to serve as well screens, which required them to be large and heavy; subsequent developments have refined the construction and extended the applications, with Trislot tubes produced in standard nominal diameters from 30 to 620 mm. The minimum internal diameter of 'slotted cylinders' of the in-to-out configuration is 25 mm.

Table 6.37 Looped 'Mini-Wedge Wire' screens[a]

Apertures (mm)	Section no.	Open area (%)	Apertures per metre	Weight[b] (kg/m^2)
0.10	12	8.3	890	15.3
	16	6.4	685	20.9
0.125	12	10.1	870	15.0
0.25	12	18.2	785	13.8
	16	14.3	615	19.3
0.375	12	25.0	715	12.6
	16	20.2	575	18.2
0.50	12	30.5	655	11.9
	16	24.8	535	17.2
0.75	12	39.0	560	10.5
	16	32.8	470	15.1
1.0	16	39.0	425	14.4

[a] Screen Systems Limited.

[b] Mild steel. For other metals, multiply by factor in Table 6.38.

Table 6.38 Weight conversion factors for various metals

Metal	Specific gravity	Conversion factor
Magnesium/aluminium alloy	2.65	0.337
17% chrome steel	7.70	0.980
Mild steel	7.85	1.000
Galvanized steel	7.85	1.000
Stainless steel 18/8	7.90	1.006
Brass	8.50	1.083
Silicon bronze	8.54	1.088
Phosphor bronze	8.70	1.108
Monel	8.80	1.121
Copper	8.90	1.133

Johnson channel rod screens have a distinctive internal structure, as shown in Figure 6.27. These are available in a range of 10 standard sizes (internal diameters from 25 to 200 mm), with slot openings upwards from 75 μm. They are used in the underdrain systems of sand filters with the claimed advantage of eliminating the need for several layers of graded support gravel beneath the sand bed (Figure 6.28).

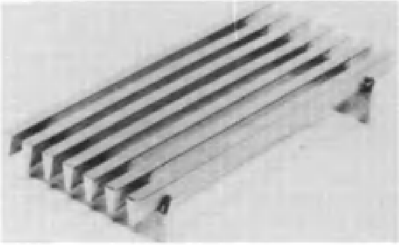


Figure 6.24. Welded wedge wire screen. (Photograph: CAE Trislot N.V.)

Table 6.39 Welded wedge wire screens[a]

Aperture[b] (mm)	Profile no.	Profile width (mm)	Profile depth (mm)	Open area (%)
0.25	28	2.2	4.5	10.2
	34	2.8	5.0	8.1
	42	3.4	6.5	6.8
0.53	28	2.2	4.5	18.5
	34	2.8	5.0	15.2
	42	3.4	6.5	12.8
0.75	28	2.2	4.5	25.4
	34	2.8	5.0	21.1
	42	3.4	6.5	18.1
1.0	28	2.2	4.5	31.1
	34	2.8	5.0	26.3
	42	3.4	6.5	22.7
1.25	28	2.2	4.5	36.2
	34	2.8	5.0	30.9
	42	3.4	6.5	26.9
1.5	28	2.2	4.5	40.5
	34	2.8	5.0	34.9
	42	3.4	6.5	30.6
1.75	28	2.2	4.5	44.3
	34	2.8	5.0	38.5
	42	3.4	6.5	34.0
2.0	28	2.2	4.5	47.6
	34	2.8	5.0	41.7
	42	3.4	6.5	37.0
2.5	28	2.2	4.5	53.2
	34	2.8	5.0	47.2
	42	3.4	6.5	42.4

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[a] Screen Systems Limited.

[b] Apertures up to 10 mm are available.

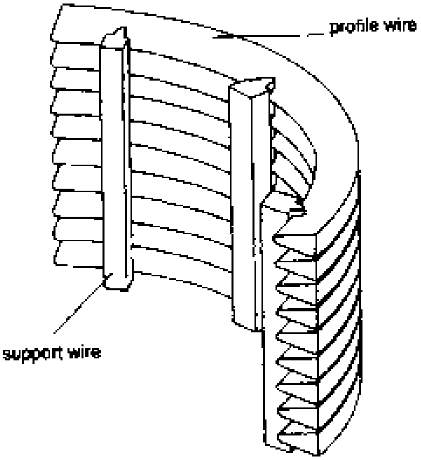

Figure 6.25. 'Trislot' tubes for out-to-in flow. (Illustration: CAE Trislot N.V.)

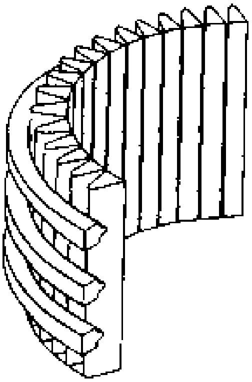

Figure 6.26. 'Trislot' cylinders for in-to-out flow. (Illustration: CAE Trislot N.V.)

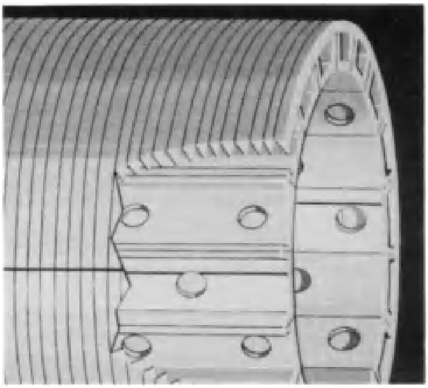

Figure 6.27. Wedge wire channel rod screen. (Illustration: Johnson Filtration Systems)

As an alternative to their stainless steel cylindrical screens for use in collector and distributor systems for sand filters (see Figure 6.27), Johnson Filtration Systems also produce a corresponding range of plastic screens (Figure 6.29). These are of sonic-welded PVC construction, tailored to integrate with standard PVC pipe fittings; the slot sizes extend from 150 μm to 3.175 mm.

6.5.3 Bar screens

A screen surface can be formed by assembling a number of separated flat bars. The huge flat or sloping screens used for separating crushed ores in mineral processing works are often made in this way. A more delicate example of this structure is incorporated in the high-pressure screw press for dewatering rubber crumb shown in Figure 6.30. As can be seen, this is of very robust construction so as to withstand operating pressures up to some 1300 bar. The drainage cage is therefore built up from 28 cm long stainless steel bars laid side by side, with spacers between them, to give a replaceable cartridge; several such cartridges placed end to end make up the full length of the cage.

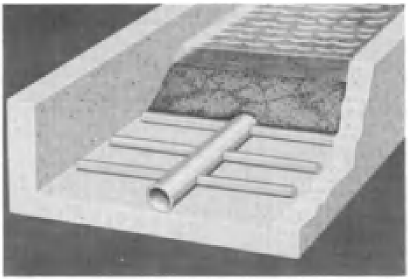

Figure 6.28. Johnson channel rod underdrain for sand filter.

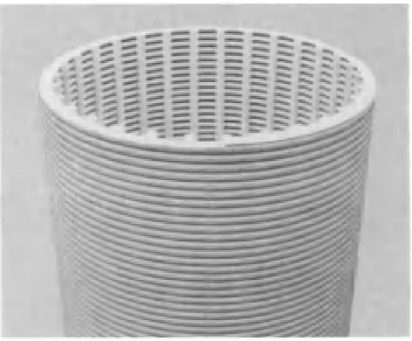

Figure 6.29. PVC wedge wire cylindrical screen.

A quite different form of bar screen is the *sieve bend* used in the wet classification of slurries. The screen is mounted vertically, with a surface that is flat across the screen, but concave downwards from a vertical portion at the top. The bars are arranged across the screen, with slurry flow downwards across the face of the screen, and almost tangential at the top. Also known as the DSM screen (as sold by Dorr-Oliver), this filter can be used as a classifying device, separating fine solids from coarse.

6.6 Extruded Plastic Meshes

Extensive ranges of mesh and sheet products are manufactured in plastics by the Netlon extrusion process, and by the embossing and stretching process similar to that described in Section 2.2.2.4 of Chapter 2, there referring to the production of fibrillated tapes. Products of both of these processes have very wide application in industry, far beyond their use in filtration, where they are most often used for components of filter media systems, other than the medium itself.

6.6.1 Stretched sheet media

Meshes can be made by stretching an extruded film of polymer that has been weakened in a regular pattern. The process involves embossing the pattern into the film by passing it over rollers, on whose surfaces the pattern has been photo-etched, as in gravure printing. The embossed film is then heated and stretched in one or more directions, thus causing the film to rupture in a structured way at

Figure 6.30. Assembling the bar screen cage of a high pressure screw press. (Photograph: The French Oil Mill Machinery).

the impressed indentations. Variation in type of polymer, film thickness, embossed pattern and stretching process all permit the manufacture of a wide range of products, from coarse net to fine membranes.

Examples of stretched film netting are provided by the Delnet products of Applied Extrusion Technologies Inc. Two different styles are available, respectively identified as the filament type and the boss type, illustrated in Figures 6.31 and 6.32. Typical data for the two types are included in Tables 6.40 and 6.41.

Stretched film membranes made in the same way are typified by the Goretex products described in Chapter 8.

6.6.2 Extruded mesh

Fully bonded plastic mesh and other netting can also be produced by the Netlon extrusion process. Although akin to melt spinning, this is a unique method for the production of a wide variety of integral meshes. It uses two concentric,

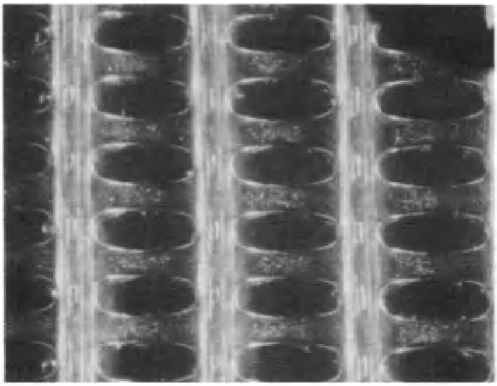

Figure 6.31. 'Delnet' plastic netting: filament type RB0707-30P @ × 10 magnification.

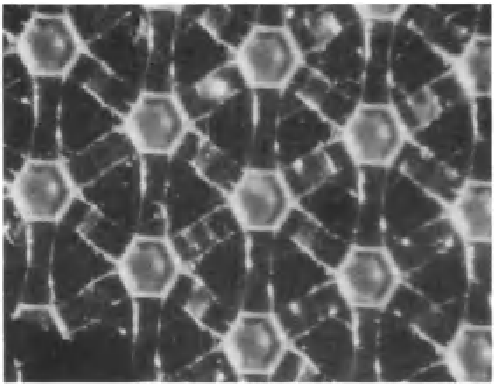

Figure 6.32. 'Delnet' plastic netting: boss type AC530 @ × 30 magnification.

Table 6.40 Examples of filament type 'Delnet' polypropylene nonwoven fabrics[a]

Reference no.	RB0404-10P	RB0404-12P	RB0404-28P	RC0707-20P	RC0707-24P	RB0707-30P	RO412-10PR
Basis weight (g/m^2)	33.8	27.0	18.6	18.6	30.4	30.4	43.9
Filaments per cm							
Machine direction	8.3	8.3	6.3	22.4	22.4	19.7	23.6
Across machine	5.1	5.1	6.3	9.1	9.1	9.8	5.5
Thickness (μm)	254	203	152	127	127	114	267
Tensile strength (g/cm)							
Machine direction	1430	1430	733	268	214	357	1787
Across machine	1430	1430	733	1251	965	1251	1787
Permeability to air[b]	4886	4886	6835	3158	4051	3763	4147

[a] Applied Extrusion Technologies Inc.

[b] Air permeability, l/dm^2/min @ 20 mm WG.

Table 6.41 Examples of boss type 'Delnet' high density polyethylene nonwoven fabrics[a]

Reference no.	AC530	D218	D220	EXP167	KX215	P520HF	P520	P525	P530	P620	PQ214	PQ218	X215	X220	X230	X530	X550
Basis weight (g/m^2)	17.9	33.8	29.1	24.3	37.2	22.6	27.0	21.6	21.0	28.4	54.1	30.4	33.8	27.0	21.0	18.3	12.2
Filaments per cm																	
Machine direction	9.8	9.1	7.9	10.2	5.1	11.8	12.6	13.4	8.7	16.1	4.3	4.3	5.5	4.3	3.9	9.4	8.7
Across machine	11.8	4.3	4.7	11.8	5.5	11.0	13.8	11.0	14.2	15.7	4.7	4.3	4.7	4.3	4.7	9.8	9.4
Thickness (μm)	114	142	142	114	191	124	109	114	112	117	183	114	251	262	196	145	109
Tensile strength (g/cm)																	
Machine direction	804	322	447	590	1215	894	894	590	876	822	1573	1055	733	715	447	536	518
Across machine	447	1948	1555	661	1305	804	804	1019	375	894	1072	929	1198	661	465	357	447
Permeability to air[b]	3638	2246	3177	1910	6077	1709	1574	2438	3418	1546	3331	2294	3100	5818	6106	4090	5376

[a] Applied Extrusion Technologies Inc.

[b] Air permeability, $l/dm^2/min$ @ 20 mm WG.

counter-rotating heads, each extruding a set of filaments around its perimeter; the two sets of filaments overlay each other to form a continuous tube of netting, which is slit as required to make flat strips. The net pattern, square, diamond, etc., depends upon the angle between the heads, while post-treatment, such as stretching, can produce other aperture shapes.

The Netlon process was invented in 1955 by the British textile technologist Brian Mercer and is now exploited in various forms by manufacturers in more than 40 countries throughout the world. The resultant diversity of products

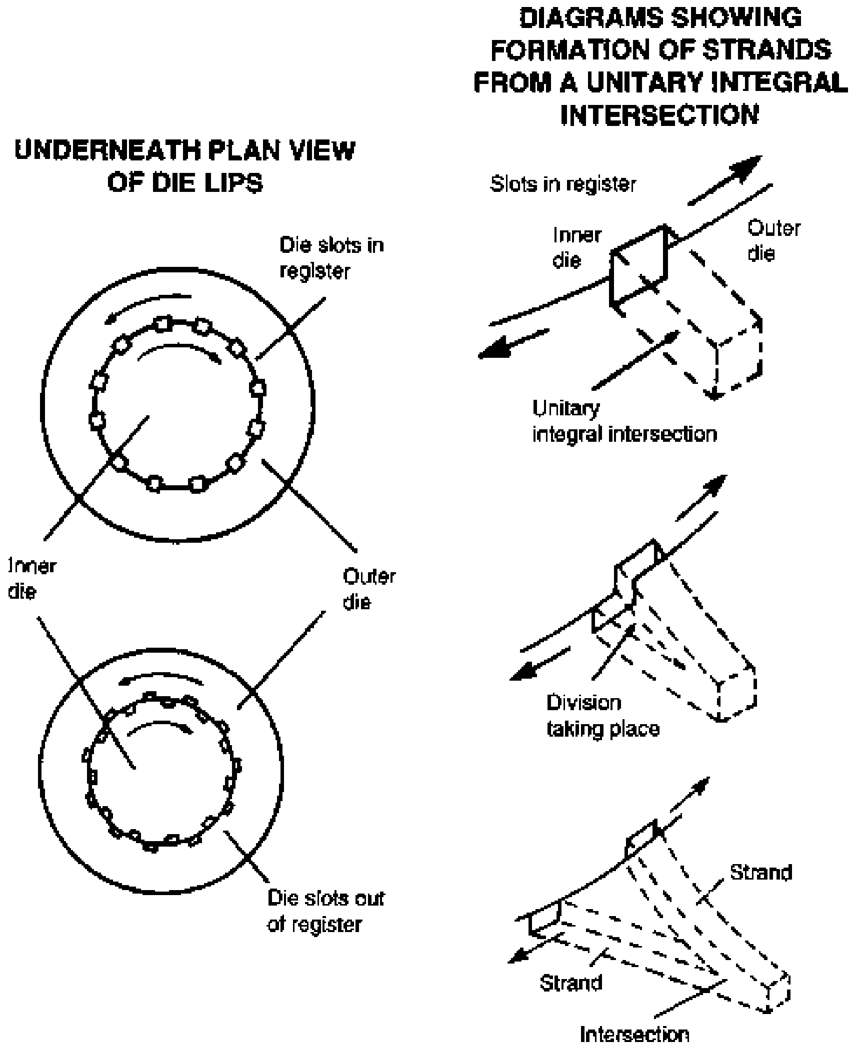

Figure 6.33. Basic principles of the Netlon counter-rotating dies and the formation of strands of extruded polymer.

have many applications, perhaps the most significant being as geotextiles in civil engineering, agriculture, horticulture and gardening, as well as in packaging.

The crucial component of the Netlon extrusion machine is the die head that, in the simplest version shown schematically in Figure 6.33, comprises two concentric counter-rotating dies, with a series of slots cut into the two edges or lips which are in contact with each other. When the slots are in register, the polymer melt is extruded as streams of double thickness; but rotation to bring them out of register causes each stream to be divided until they reunite as a slot in the inner die registers with the next one in the outer die. The result is the formation of a continuous mesh structure in tubular form, which is then drawn over a mandrel and subjected to stretching, slitting and quenching operations as required.

If the slots are regular and both dies are counter-rotated at the same speed, the mesh is of regular diamond pattern. Many variations are possible on this basic form, some of which are indicated in Figures 6.34. The characteristics of any particular mesh are largely determined by the profile and position of the slots (the precision of which is of crucial importance), the speed of rotation and the nature of the movement (which need not be constant).

A flat square mesh sheet is made as follows. One die is kept stationary, initially producing a diamond mesh with right-angled intersections. The tension of the sheet, as it is hauled off the extruder and passed under a roller set at 45° to the material path, causes the mesh to rotate as it is drawn down the mandrel. A cutter is set against this mandrel in such a position that it slits the material helically between a pair of adjacent strands, to form the desired flat square-meshed sheet.

The strands forming the mesh need not be of equal cross-section. Further variations, such as oscillation of one or both dies, permit a very wide range of figured pattern effects to be obtained. It is also possible to make a three-strand mesh by inserting a stationary die between the usual two rotating dies.

A highly important method of improving the strength, flexibility and lightness of Netlon mesh is by stretching the material, using rollers of varying speed and hot water as necessary; the stretching may be either longitudinally, transversely or both (i.e. biaxially), at production speeds up to 100 linear metres per minute.

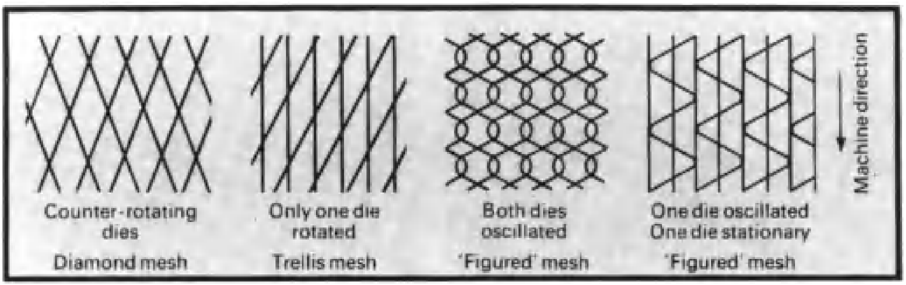

Figure 6.34. Typical Netlon mesh patterns resulting from process variables.

The effect is to increase the mesh area and also to strengthen the material very considerably by molecular orientation.

Simple methods of orientation stretch the mesh strands but leave the intersections unorientated. However, it is possible to make the intersections with a cross-section that ensures that they also orientate under suitable stress.

Although polyolefins are the most common materials used, the Netlon process is applicable to numerous other polymers, including nylon, vinyls, polystyrene and elastomers. An indication of the diversity of products possible is given in Figure 6.35. The range extends from very fine and flexible meshes containing as many as 1500 strands per linear metre and weighing only 10 g/m^2, to rigid tubular or sheet structures with 7 mm thick strands.

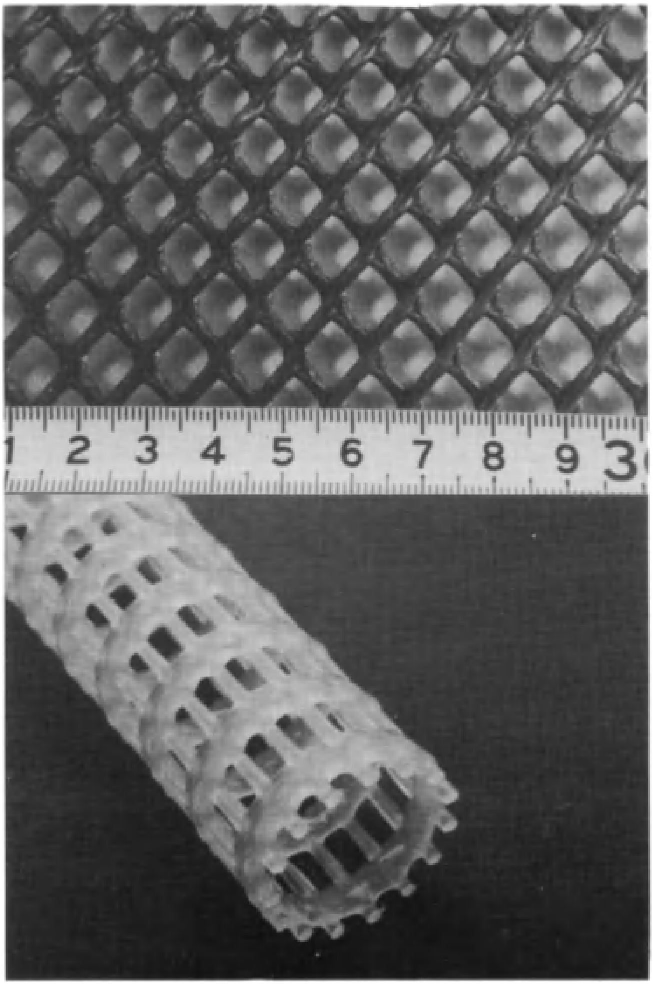

Figure 6.35. Two examples of products of the Netlon process.

Filtration applications range from simple heavy weight meshes, used as coarse strainers and separators and as backing cloths in filter presses, through to very fine meshes with apertures below 0.5 μm serving as separators between media layers in pleated cartridges. Rigid tubes are ideal as the cores of some styles of cartridge; examples of variations in the specifications of these tubes are given in Table 6.42.

Other examples of this process are the polypropylene and polyethylene Plastinet products from AET (Figure 6.36). Depending upon the thickness of the filaments, normally from 0.4 to 6 mm in diameter, the resultant netting may be soft and flexible, ranging up to fully rigid structures. Strand counts can vary from 1.2 to 6.8 per cm, giving products that can be flexible, 'lay flat' tubes, or rigid tubes, or flat sheets 5–245 cm in width.

Table 6.42 Specifications of typical Netlon rigid tubes[a]

Structure number	Inside diameter (mm)	Outside (mm) (typical)	Aperture size diameter (mm) (typical) MX×TD		Open area (typical) (%)	Polymer type	Weight
10/87A	22 (+0.5 – 0)	27	3.0	4.5	28	PP	88 (±5)
52/95M	25 (+1 – 0)	33	8.5	3.5	37	PP	130 (±5)
7057	0	33 (+0 – 0.5)	2.5	3.8	27	HD	120 (±5)
7/96B	26 (+0.5 – 0)	34.5	3.5	4.5	27	HD	180 (±10)
52/95D	26.7 (+1 – 0)	36	5.3	8.3	37	PP	150 (±5)
X125B	27.6 (+0.9 – 0)	35.5	5.3	3.7	28	PP	150 (±5)
X125A	27.7 (+0.5 – 0)	34.8	4.2	3.7	37	PP	135 (±5)
X197A	30.5 (+0.5 – 0)	36.4	5.6	5.0	29	PP	130 (±5)
52/95L	33 (+1 – 0)	40.4	8.0	5.0	34	PP	150 (±5)
X193	38.2 (+0.6 – 0)	43	6.4	6.2	44	PP	140 (±5)
4/88A	61 (+0 – 0.5)	66	5.5	4.3	33	PP	170 (±10)

[a] Netlon Ltd.

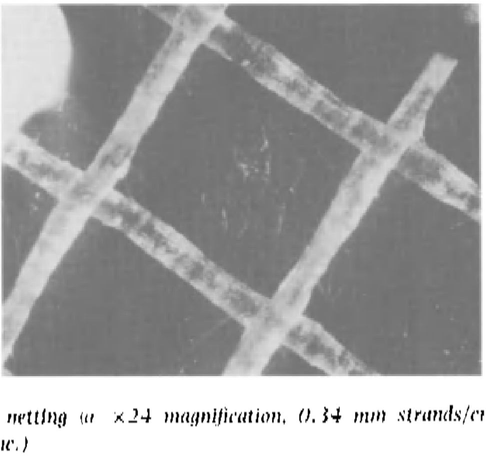

Figure 6.36. 'Plastinet' netting (a ×24 magnification, 0.34 mm strands/cm. (Photograph: Applied Extrusion Technologies, Inc.)

6.7 Selecting Screens and Meshes

The prime characteristics of screens and meshes from the point of view of filtration lie in their accuracy of separation, and in their operating features of resistance to high temperatures, corrosion and abrasion – these latter features referring essentially to metal media, although polymeric media can now operate at quite high temperatures. Thus they should be chosen where accuracy of size separation is an important requirement – the most obvious example being their use in sets of test sieves, used for analysing the particle size composition of a mixture of solids.

The presence in the feed slurry of chemically corrosive liquids or abrasive solids indicates that the first place to look for a suitable medium is among the materials covered in this chapter.

A high proportion of coarse filtration is done by woven mesh screens – in such devices as in-line strainers and inlet screens. There is a strong element of unattended operation in many of these applications, especially where the screens are automatically cleaned.

By virtue of the fact that these media largely operate by surface filtration, they are prone to the risk of plugging, where a particle lodges in a pore, thereby blocking it. This means that prolonged operation requires some form of backflushing to clear the plugged holes. However, the nature of these materials means that this cleaning operation is relatively easy – by shaking or rapping, by brushing, by pressurized water or by chemical cleaning.

The heaviest duties in separation in terms of abrasion, such as mineral dressing operations, are satisfied with bar screens and punched or milled perforated sheets, while, at the other extreme, in, say, the sifting of flour, fine wire or plastic meshes are required.

Apart from the finest levels of separation, which might require membranes, and situations where very high degrees of solid removal are required, then woven meshes and screens now offer a good choice to the filter designer. They include some of the strongest constructions, such as bar screens or laminated sintered wire mesh, and are, of course, widely used also as supports for other media.

CHAPTER 7

Coarse Porous Sheets and Tubes

Considerable attention has been given to natural and synthetic organic fibres as the main materials for dry- and wet-laid filter media in the earlier chapters of this Handbook. A quite different group of media is based on inorganic materials, with the use of granules or fibres bonded together, usually by the process of sintering. They are covered here, together with similar materials made from plastics, where the granules are also sintered.

7.1 Introduction

A group of porous media that provide filtration of coarser particles, from suspension in gases or liquids, is made by the aggregation of small particles (granules or fibres) of the basic material into useful shapes, either between rolls or in a mould. The aggregate is then heated to a temperature close to the melting point of the material, under pressure, so that there is localized melting at the points of contact among the particles (and any binder used in the aggregation is driven off or incinerated).

This sintering process confers an element of rigidity upon the resulting materials, so that they are used, for filtration purposes, either as sheets (including sheets cut into appropriately shaped pieces), or as tubes (open ended or closed at one end). This is a very useful group of media, with the inorganic nature of some of the materials enabling their use at quite high temperatures.

Included here are media made from the same basic materials (plastics, metals and ceramics), but now from the molten bulk material as foams – still rigid and strong in their solid form. For the sake of completion, tubes made from sintered glass fibres are also included in this chapter, even though the bulk of glass fibre media is covered in detail in Chapters 4 and 5 (as wet-laid glass paper and pads). There is also an overlap, in application terms, between the sintered metal fibre media discussed here, and the sintered metal meshes covered in Chapter 6.

As already mentioned, a major feature of the inorganic materials included here is their ability to operate at high temperatures. The importance of this particular set of applications is continually growing, although Bergmann's review of high-temperature gas cleaning requirements[1] still has a great deal of relevance. The topic is reviewed at a series of symposia, arranged at approximately three-yearly intervals.

7.2 Porous Plastic Media

By virtue of their organic nature, the media made from plastics stand apart from the other media discussed in this chapter, which are all inorganic. Nevertheless, their filtration characteristics merge seamlessly into those of the inorganic materials, the only significant difference being the reduced applicability in temperature terms.

The plastic media covered here are those made by the sintering of polymeric powders or granules, and those made from the molten state as foams. Not covered are sintered plastic fibre materials – because most of the non-woven media of Chapter 3 could be classified as sintered plastic fibre, since most synthetic fibre needlefelts and spun media have an element of sintering in their manufacture.

7.2.1 Sintered granular plastics

Thermoplastic powders may be moulded and sintered to produce flat porous sheets or a wide variety of three-dimensional shapes, as indicated in Figure 7.1. The most commonly used materials are high-density polyethylene and polypropylene, others being PTFE and PVDF. Table 7.1 summarizes the properties of the 1 m^2 sheets of one supplier. Examples of moulded discs and cylinders are given in Table 7.2, while a good view of the structure of such materials is shown in Figure 7.2.

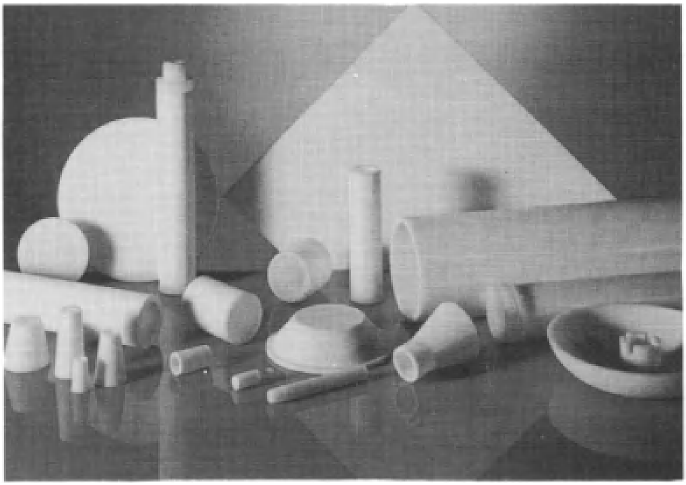

Figure 7.1. Examples of sintered porous plastic mouldings.

Table 7.1 Porvair's 'Vyon' porous sintered plastic flat sheets

Trade name	Material type			Thickness (mm)	Pore size (μm)			Typical air flow (m^3/min/m^2 at various pressures) (mbar)					Removal efficiencies (μm)	
	HDPE	PP	UHMWPE		Max	Mean flow	Min	1.27	2.45	5.00	10	20	Air nominal	Water nominal
Vyon D	*			3.20±0.18	30	16	8	–	–	2	3	8	6	10
	*			4.75±0.25	27	16	8	–	–	2	3	8	6	10
	*			6.00±0.40	–	35#	–	–	–	2	3	8	6	10
	*			8.00±0.40	–	30#	–	–	–	1	3	6	6	10
	*			10.00±0.40	–	27#	–	–	–	1	2	5	6	10
Vyon PPD		*		3.20±0.25	30	8	2	–	–	1	2	5	1	5
		*		4.75±0.25	30	8	2	–	–	1	2	5	1	5
		*		6.00±0.40	–	35#	–	–	–	1	2	5	1	5
Vyon F	*			0.75±0.12	127	40	12	–	28	–	66	106	25	40
	*			1.00±0.12	120	38	10	–	22	–	56	92	20	35
	*			1.50±0.15	105	36	10	–	14	–	43	75	20	30
	*			1.68±0.15	95	35	9	–	–	23	38	62	–	–
	*			2.00±0.20	78	30	9	–	–	16	30	53	20	30
	*			2.50±0.25	65	25	8	–	–	13	24	44	15	25
	*			3.20±0.25	55	23	8	–	–	10	20	36	15	25
	*			4.75±0.25	50	20	7	–	–	7	13	24	10	20
	*			6.00±0.40	56	22	10	–	–	4	8	16	10	20
	*			8.00±0.40	–	57#	–	–	–	3	6	11	–	–
	*			10.0±0.40	–	57#	–	–	–	3	5	11	–	–
Vyon PPF		*		1.50±0.15	145	40	8	–	–	20	38	58	10	20
		*		2.00±0.20	140	35	8	–	–	15	28	44	10	20
		*		2.50±0.25	105	30	5	–	–	14	27	43	5	15
		*		3.20±0.25	75	23	5	–	–	6	13	24	5	15
		*		4.75±0.25	75	23	4	–	–	6	12	24	5	15
		*		6.00±0.40	–	88#	–	–	–	4	8	18	5	15
Vyon Porvent	*			2.00±0.20	55	20	6	–	–	7	14	26	5	15
	*			2.50±0.25	55	20	6	–	–	7	14	26	5	15
	*			3.20±0.18	55	20	6	–	–	7	14	26	7	17
Vyon Porvent PP		*		2.00±0.20	72	28	6	–	–	7	14	26	5	15
		*		3.20±0.18	60	19	5	–	–	7	14	24	5	15
		*		4.00±0.25	65	20	4	–	–	7	14	26	5	15
Vyon HP	*			2.00±0.20	> 300	91	27	29	46	–	–	–	50	70
	*			2.50±0.25	> 300	98	21	34	62	–	–	–	80	100
	*			3.20±0.25	> 200	100	30	29	58	–	–	–	50	70
	*			5.30±0.30	–	125#	–	12	19	32	–	–	50	70
	*			6.00±0.40	–	180#	–	9	17	29	–	–	50	70
	*			10.0±0.40	–	125#	–	6	22	41	–	–	50	70
Vyon PPHJP		*		2.00±0.20	> 300	90	15	28	43	–	–	–	50	70
		*		2.50±0.25	> 300	87	14	24	38	–	–	–	50	70
		*		3.20±0.25	> 300	80	22	18	32	–	–	–	40	60
		*		4.75±0.25	170	60	10	11	20	34	–	–	40	60

Table 7.1 (*continued*)

Trade name	Material type			Thickness (mm)	Pore size (µm)			Typical air flow ($m^3/min/m^2$ at various pressures) (mbar)					Removal efficiencies (µm)	
	HDPE	PP	UHMWPE		Max	Mean flow	Min	1.27	2.45	5.00	10	20	Air nominal	Water nominal
		•		6.00±0.40	–	135#	–	11	19	34	–	–	40	60
Vyton T			•	1.00±0.07	40	18	10	–	–	4	8	20	2	10
			•	1.50±0.07	30	12	8	–	–	3	4	13	2	8
			•	2.00±0.10	15	10	6	–	–	2	4	8	1	5
			•	2.50±0.12	15	9	6	–	–	1	3	6	1	5
			•	3.20±0.16	15	9	6	–	–	1	3	6	1	5
			•	5.00±0.16	20	9	4	–	–	1	3	6	1	5
Vyton RT			•	3.20±0.25	28	11	3	–	–	1	6	9	6	10
			•	6.35±0.40	–	25#	–	–	–	1	3	5	6	10
			•	10.0±0.40	–	21#	–	–	–	–	1	3	6	10

Table 7.2 Properties of moulded HDPE discs and cylinders[a]

Grade	Pore size distribution			Permeability (darcies $\times 10^{-8}$)	Density (g/cm^3)	Minimum thickness (mm)	Porosity (%)	Removal rating from liquid[b] (µm)
	Min (µm)	Mean (µm)	Max (µm)					
P05	4	15	35	30	0.4–0.6	3.0	45	15
P10	7	30	75	40	0.4–0.6	3.0	45	30
P20	10	60	100	70	0.4–0.6	3.0	45	60
P30	15	75	175	70	0.4–0.6	4.0	45	75
P40	20	90	275	280	0.4–0.6	5.0	45	90
P50	30	125	350	440	0.4–0.6	6.0	45	125

[a] Porvair Technology Ltd.
[b] @ 99.9% efficiency.

7.2.2 Plastic foams

Polyurethanes are a conglomerate family of polymers in which the formation of the urethane group, –NH–CO–O–, by reaction between hydroxyl and isocyanate groups, is an important step in polymerization. This provides a linkage mechanism that may involve a variety of aromatic or aliphatic groups: aliphatic isocyanates tend to form the more flexible polyurethanes, such as the polyether and polyester types, which are used as filter media. Polyester foams are stiffer and less resilient than the polyether type.

Urethane foam formulations consist of low viscosity liquids, which, when mixed in appropriate proportions, react to form a foam and then cure into a cellular mass. Typically formulations contain isocyanates and polyols, together with catalysts, surfactants for stabilizing the foam structure, and blowing agents to generate gas and expand the mass. Most urethane foams are produced by one-shot processes in which all the raw materials are combined in a single step. Foam is produced in blocks that can be sliced to give thicknesses from 3 to 200 mm, and form sheets 2 m × 1 m.

An important feature of these foams is that the cells are reticulated, which means that they are open and interconnected, with a porosity of some 97%. This results from thermal chemical treatment, which causes shrinkage of material enclosing cells to leave the very open skeletal structure illustrated in Figure 7.3; in so doing, the thickness of the residual contracted walls is increased, with a corresponding increase in tensile strength and in resistance to heat, abrasion and chemical attack.

Appropriate regulation of the manufacturing process enables foams to be produced with pores of predetermined sizes. It is usual practice to characterize the pores in terms of the number per linear inch (e.g. 30 ppi); the average pore diameter corresponding to foams graded on this basis is indicated in Figure 7.4.

An alternative basis for classifying reticulated foams for use as filter media is in terms of the resistance of a 25 mm thick pad to the flow of air at 175 m/min, foam grades being expressed in nominal forms such as PPI-60. The relationship between these two grading scales is given in Figure 7.5.

Both polyester and polyether urethanes have good chemical resistance excepting against strong acids, alkalis and solvents; soaps, detergents, mineral

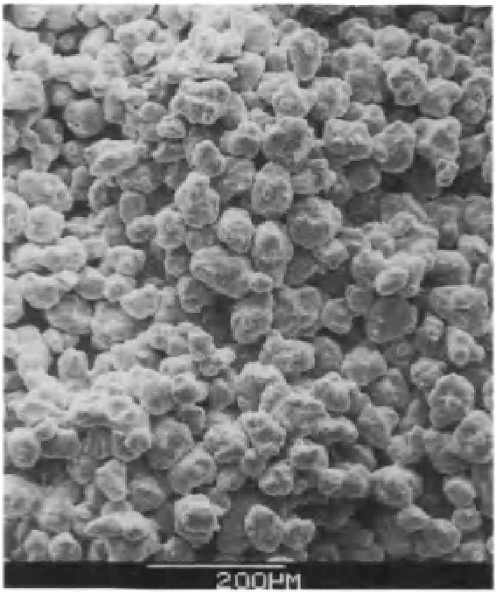

Figure 7.2. Micrograph of the fracture surface of 'Filtroplast' porous sintered plastic media.

oils and grease have no noticeable effect, allowing the foams to be easily cleaned and reused. Sterilization with boiling water or steam up to 105°C is not harmful for short periods.

Data for the Poret polyester type products of one manufacturer are given in Table 7.3; special foams based on silicon are completely nonflammable for operation at temperatures up to 220°C. Typical efficiencies available in air filtration are reported to be in the range 70–90% (ASHRAE 52-68).

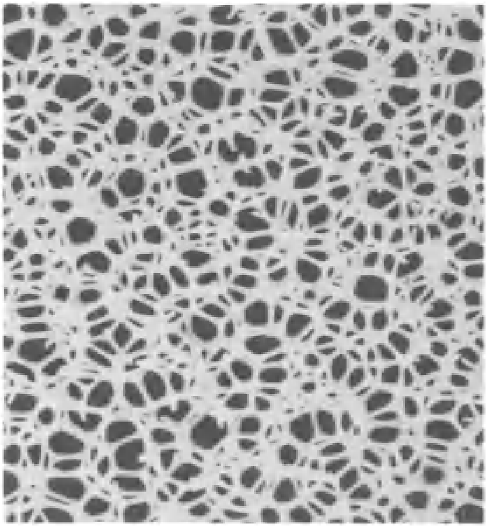

Figure 7.3. ×4 magnified view of Scott reticulated foam.

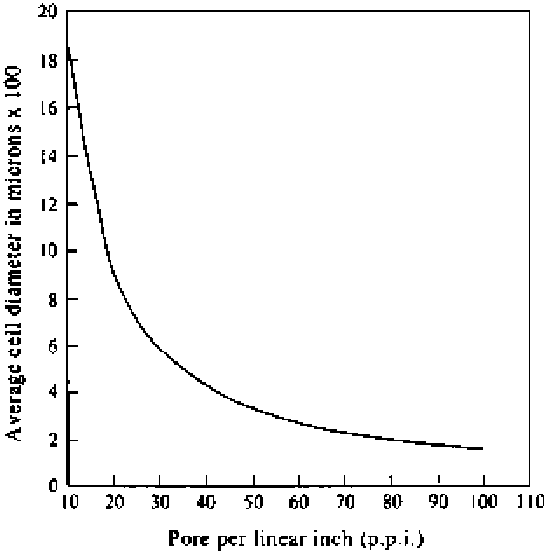

Figure 7.4. Average pore diameter versus pores per linear inch in polyurethane foam.

7.2.3 Microporous polyurethane

Figure 7.6 shows an electron microscope scan of a cross-section through Porvair's microporous Permair F medium developed for the filtration of liquids and gases. This is made from high molecular weight polyurethane using a process that involves leaching of soluble salts to form pores with an average size of 27 µm and a porosity of 80%. Available in continuous rolls approximately 1 m wide, and in thicknesses from 0.5 to 1.5 mm, its properties are summarized in Table 7.4.

7.3 Metallic Media

A wide variety of filter media is available based upon metals as the fundamental material. Such media carry the advantages of the characteristics of the metals, namely corrosion resistance, abrasion resistance and ability to operate at elevated temperatures. Metallic material is also quite easily workable, and this enables metallic media to be made from granules, fibres and filaments (wires), as required for the filtration needs of the media.

7.3.1 Metal fibre webs

Under the trade name Bekipor WB, the Belgian company NV Bekaert SA produces a range of webs of very fine 316L stainless steel fibres of diameters 22 µm down to 1 µm. The standard grades, extending down to 2 µm, are listed in Table 7.5; 1.5 and 1.0 µm grades are under active development. Some grades (8, 12 and 22 µm) are also available in Inconel 601 or Hastelloy: in addition, the 22 µm grade can be supplied in Fecralloy.

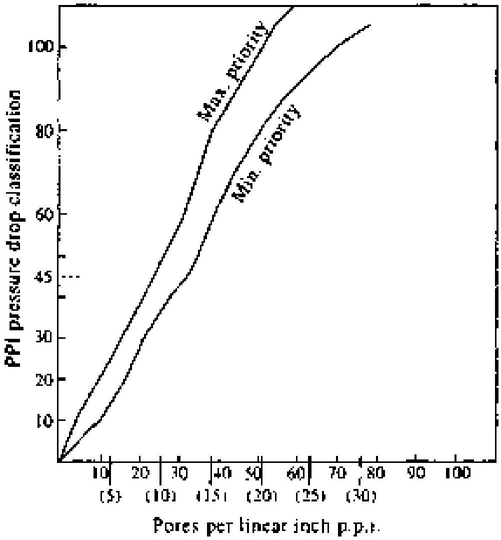

Figure 7.5. Relationship between the two pore grading scales for polyurethane foam.

Table 7.3 'Poret' reticulated polyurethane foams[a]

Nominal pore rating (ppi)	10	20	30	45	60	66	80
Nominal pore tolerance	8–15	15–20	25–35	40–50	55–56	60–70	70–90
True cell count tolerance (pores per linear inch)	5–11	11–20	20–28	33–43	43–58	58–62	62–76
Pressure drop[b] range @ air velocity of 100 m/min (mm WG)	0.7–1.1	1.1–2.2	2.2–3.4	4.5–6.4	6.4–12.2	7.6–12.7	12.7–14.7
Tensile strength (kg/cm^2)							
Average	1.34	1.55	1.83	2.04	2.20	2.20	2.25
Minimum	1.05	1.13	1.48	1.55	1.69	1.69	1.76
Elongation @ break%							
Average	300	325	350	400	400	400	400
Minimum	200	250	250	300	300	300	300
Tear strength (kg)							
Average	2.27	2.27	2.27	2.27	2.27	2.27	2.27
Minimum	1.36	1.36	1.36	1.36	1.36	1.36	1.36
Hardness to BS 3367 (kg)							
Minimum	15.00	15.00	15.00	15.00	15.00	15.00	15.00
Minimum sheet thickness recommended for air filtration (mm)	10	8	6	6	4	3	2.5

[a] Automet Filtration Ltd.

[b] Pressure drop through minimum recommended thickness.

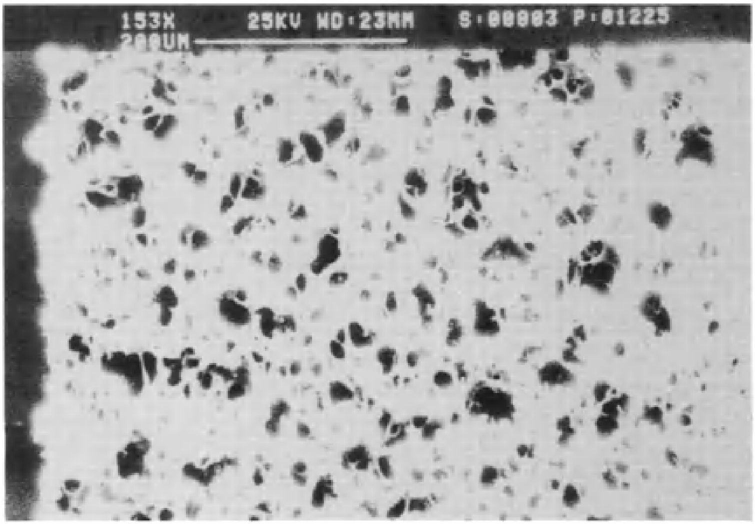

Figure 7.6. A cross section (magnification ×208) of 'Permair F'.

Table 7.4 Properties of 'Permair F' microporous polyurethane[a]

Average pore size (μm)	27
Porosity (%)	80
Operating temperature (°C)	
Maximum	150
Minimum	−20
Ultimate tensile strength (kg/cm^2)	1.9
Elongation (%)	300
Air permeability, m^3/m^2/min @ 25 mm WG	
0.5 mm thick sheet	9.2
0.7 mm thick sheet	3.9

Table 7.5 Standard grades of 'Bekipor WB' stainless steel fibre web[a]

Bekipor grade	Fibre diameter (μm)	Weight (g/m^2)
WB 02/150	2	150
WB 04/150	4	150
WB 08/300	8	300
WB 12/300	12	300
WB 22/300	22	300

[a] N.V. Bekaert S.A.

These very fine fibres are produced from metal rods by sophisticated adaptations of conventional wire drawing techniques. The final stages involve drawing bundles of wires, in some cases comprising several thousands in a bundle. The bundle-drawn fibres can be produced in the form of continuous bundles, broken bundles (slivers), cut fibres, spun yarns, threads, strands, web, sintered web, needlefelt, etc.

Web is supplied in standard panels of 1.2 m × 1.5 m. It is described as being composed of loose metal fibres in a non-woven labyrinth structure, and is used in coalescing, in air filtration (including HEPA filters) and demisting. It is also the basic material used by Bekaert to manufacture its range of sintered media.

7.3.2 Sintered metal media

Four main types of sintered metal media are available, depending upon the form of the metal prior to sintering: powders, fibres, woven meshes and composites that utilize combinations of media, such as powder and a mesh, or two or more layers of mesh.

This inevitably leads to major structural differences, which are reflected in properties such as porosity, pore size distribution, permeability and filtration efficiency. Both powder and fibre media function primarily by depth filtration: they are therefore generally less easily cleaned than surface-filtering sintered meshes.

Whilst bronze and stainless steel are the most commonly used metals, others available include nickel, Monel, Hastelloy, Inconel, titanium, aluminium and tantalum. Their mechanical properties are similar or identical to those of the virgin metal, the tensile strength decreasing as the porosity increases, but generally remaining high. One of the advantages of porous metals is that they can be rolled, cut, welded and generally fabricated by standard metalworking techniques (although localized blinding of pores may occur).

Many factors need to be taken into account in selecting the appropriate type of sintered metal for any specific duty. Some of these are listed in Table 7.6, in which the media types are crudely rated in respect of factors such as dirt-holding capacity or permeability, using a simple numerical scale; a high number (such as 4) is a poor rating. This preliminary selection matrix is based on experience of Pall Corporation who manufacture in-house all four basic types of media, the absolute micrometre removal ratings of which are included in the table. It is emphasized, however, that the relative performance of different media can vary widely with the nature of the suspension being filtered and operating conditions including filtration rate.

7.3.2.1 Sintered metal powder

Whereas earlier forms of sintered metals were made from particles of irregular shape, modern practice is based on powders comprising carefully graded spherical particles, typically in the range 0.5–100 μm. The free-flowing nature of these metal powders facilitates the use of moulding techniques to manufacture a wide diversity of shapes, such as shown in Figure 7.7. The manufacturing process may either involve a compression stage prior to sintering of moulded shapes, or it may effectively rely on sintering alone. Bronze and stainless steel are the most commonly used metals; examples of the standard products of one manufacturer are summarized in Table 7.7.

Although cylinders and tubes may be formed by conventional moulding methods, other techniques are also available. Isotropic moulding involves an inflatable insert that creates an annular space within which powder can be compressed radially. A proprietary process developed by Pall uses centrifugal force to form tubes with high-performance characteristics, as indicated for the four standard grades of Pall's S-Series PSS stainless steel medium in Table 7.8;

Table 7.6 Preliminary selection matrix for sintered metal media[a]

Basic type of medium Pall medium	Powder PSS	Fibre PMF	Mesh Rigimesh	Composite PMM
Absolute micron rating of finest grade (μm)				
Liquid duty	5	2.5	18	2
Gas duty	0.4		13	0.4
Dirt-holding capacity	2	1	4	3
Permeability	3	1	2	4
Gel removal	1	1	4	3
Durability	1	4	1	1
Cleanability	4	1	3	1
Area/1001[b]	4	1	3	1
Cost/1001[b]	1	4	3	2

[a] Pall Corporation.

[b] For a Pall 1001 cartridge, 254 mm long × 60 mm diameter.

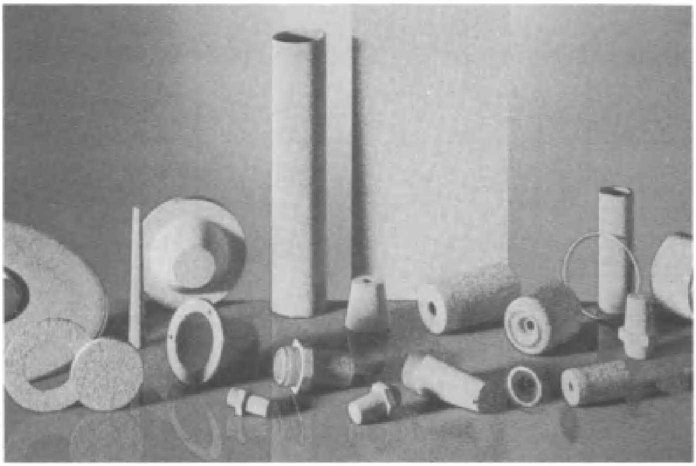

Figure 7.7. Examples of sintered bronze powder porous filter elements.

Table 7.7 Moulded bronze and stainless steel powder media[a]

Grade[b]	Pore size distribution			Permeability (darcies × 10^{-5})	Density (g cm^{-3})	Minimum thickness (mm)	Porosity (%)	Micron removal rating	
	Min (μm)	Mean (μm)	Max (μm)					Liquid (μm)	Gas (μm)
B05	0.75	2	9	1.0	6.4–7.5	1.5	25	2	–
B10	2.5	6	25	2.5	6.0–7.0	2.0	30	6	–
B20	7.5	20	85	7.0	5.0–6.0	2.5	40	23	–
B30	10	55	150	50	5.0–6.0	3.0	40	35	–
B40	15	90	250	90	5.0–6.0	3.5	40	52	–
B50	20	75	120	150	4.5–5.5	4.0	45	75	–
S10	1.5	6	20	1.0	5.5–5.5	1.5	55	6	3
S20	2	10	30	2.0	5.5–5.5	2.0	55	10	3.7
S30	3	15	70	7.5	5.5–5.5	2.5	55	15	4.1
S40	5	30	160	25	5.5–5.5	3.0	55	33	5.5
S50	10	60	150	70	5.5–5.5	4.0	55	43	6.5

[a] Porvair Technology Limited.

[b] B = bronze 89/11; S = stainless steel 316L.

Table 7.8 Pall's PSS sintered metal powder media

Media grade	Form as produced	Micron removal rating					Nominal standard thickness (mm)	Permeability[e]	
		Liquid service[a]				Gas service[b] absolute[c] (100%)		to air	to water
		$\beta=2$ (50%)	$\beta=10$ (90%)	$\beta=100$ (99%)	absolute[c] (100%)				
P05	Sheets	0.5	2	3	5	0.3	1.3	5.3	0.07
P09	Sheets	2	4	7	9	0.5	1.3	7.0	0.22
H	Sheets	5	7	9	13	1	1.6[d]	17.7	0.26
F	Sheets	8	12	15	20	3	1.6[d]	53	1.13
E	Sheets	15	22	25	35	11	1.6[d]	98	3.7
D	Sheets	20	28	40	55	20	1.6[d]	340	8.7
H150	Discs	–	6.5	9	15	–	2	77	–
H250	Discs	–	10.5	18	25	–	2	218	–
H550	Discs	–	33	54	55		2	285	–
S050	Cylinders	0.5	2	3	5	0.4	1.6[d]	9	0.11
S100	Cylinders	4	7	8	10	0.8	1.6[d]	28	0.28
S200	Cylinders	7	10	14	20	2.8	1.6[d]	147	1.48
S350	Cylinders	13	17	24	35	11	1.6[d]	442	5.90

[a] Using AC dusts in water, efficiency measured by particle count.

[b] At air flow velocities of 3–5 m/min.

[c] Absolute ratings based on particle count.

[d] 3.1 mm thick also available as standard.

[e] l/dm²/min @ 10 mbar pressure drop.

these are available in lengths up to 50.8 cm and in four standard diameters: 12.7, 38.1, 50.8 and 60.3 mm.

Cylinders, as well as other shapes, can also be fabricated from flat sheet, by conventional metalworking techniques such as cutting, rolling and welding. Besides being versatile, this method has the added advantage of permitting close control of the thickness of the sintered metal, and facilitates the use of a wide range of different metals. For example, whilst 316L stainless steel is the standard material for sheets of Pall's PSS media, most of the six grades in Table 7.8 can also be supplied in the other metals listed in Table 7.9; these sheets are relatively large in size (585 × 1500 mm), with nominal thicknesses of 1.5 or 3.0 mm. Another variant of Paul's PSS media is the H-Series, which is produced only in the form of discs intended for the manufacture of the stacks of capsules widely used for polymer filtration. These items are similar to those shown in Figure 7.8.

Sintered metal powder media are generally of isotropic structure, with the same pore size distribution throughout their depth. They function by depth filtration, with small particles that pass through large pores in or near the inlet surface been subsequently trapped in smaller pores. Whilst this mechanism has the advantage of providing a high dirt-holding capacity, cleaning a filter element

Table 7.9 Alloys in which Pall PSS sintered powder media are produced

Stainless steel	316L, 304L, 310S, 347
Inconel	600, 671
Nickel	200
Hastelloy X	B2, C276
Carpenter	20

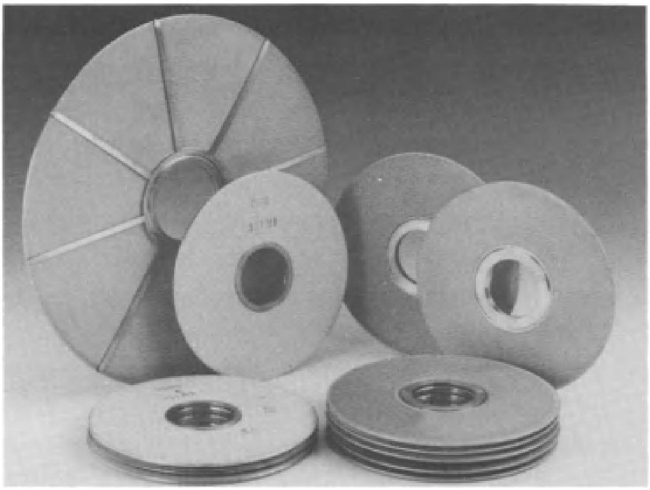

Figure 7.8. Examples of disc capsules used for polymer filtration. (Photograph: Fairey Microfiltration)

so that it can be repeatedly reused may require more vigorous methods than simple back-washing: the usual alternatives are ultrasonics and/or chemical cleaning, perhaps involving the use of an off-site service station. On the other hand, where bronze is chemically compatible with an application, its relative cheapness may justify discarding dirty elements with little or even no attempt to clean them.

GKN Sintermetal has developed an anisotropic sintered powder element, its Sika-R AS, which has a 200 μm coating of fine powder bonded on to the face of a coarse substrate. As compared with an isotropic medium of the same particle retention performance, the flow rate achieved is 3–4 times higher, while also backwash cleaning is improved(2). As this material is effectively a membrane, it is further discussed in Chapter 8.

7.3.2.2 Sintered metal fibres

Sintered metal fibre media are made from long fibres of controlled diameters ranging upwards from 2 μm, and an outstanding characteristic of such media is their very high porosity. This is some twice that of typical powder-based media, with the consequential benefits of much lower resistance to flow and higher dirt-holding capacity. The pore size distribution is equally distinctive, as illustrated in Figure 7.9, which compares four different types of metal media for all of which the maximum pore size is approximately 30 μm; curve 1 for sintered fibres shows that the greatest flow goes through the smallest pores, thereby increasing the

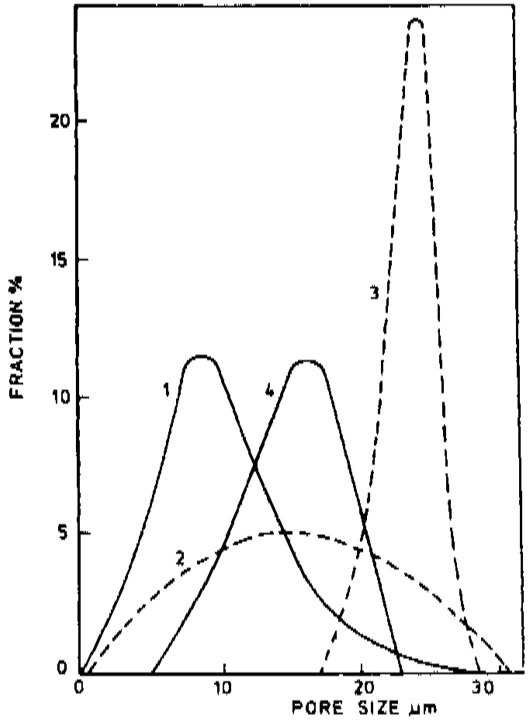

Figure 7.9. Pore size distribution curves for different types of media, as identified in Table 7.10.

probability of trapping the smallest particles, and resulting in achieving the smallest absolute filter rating, as shown in Table 7.10.

Figure 7.10 illustrates the close relationships between fibre diameter, porosity, the maximum pore size (d_m) and the absolute filter rating (a), as determined by challenging with glass beads. Note that, for these fibrous media, De Bruyne reported(3) $d_m = 2.4a$; moreover, as predicted theoretically(4), the absolute filter rating equals the mean flow pore size (i.e. the size at which 50% of the flow passes through the larger pores):

$$a = a_{MFP}$$

The high dirt-holding capacity of sintered fibre media is demonstrated by Figure 7.11, which shows the increase in pressure drop as different types of media, all of the same 20 µm absolute filter rating, become loaded with deposited solids.

Bekaert produces a variety of sintered media, based on the Bekipor web (see Section 7.3.1), as standard 1.1 m × 1.50 m panels; these may be fabricated by normal techniques (cutting, welding, pleating) to form filter elements in the shape of discs, cylinders, etc. Collectively identified as Bekipor ST, there are three standard series, identified by the suffixes AL, BL and CL, with a final numerical digit indicating the product generation (3 or 4): the characteristics of the standard grades are summarized in Table 7.11. The standard metal is 316L stainless steel but Inconel 601, Hastelloy X and Fecralloy are also available in some grades.

Table 7.10 Pore size comparisons for four different metal media

Curve	Type of medium	Maximum pore size[a] (µm)	Absolute filter rating[b] (µm)
1	Sintered fibre	30.9	13
2	Sintered powder	30.8	20
3	Wire mesh	28.4	23
4	Sintered wire mesh	22.8	17

[a] Maximum pore size from initial bubble point pressure.

[b] Absolute filter rating from challenge with glass beads.

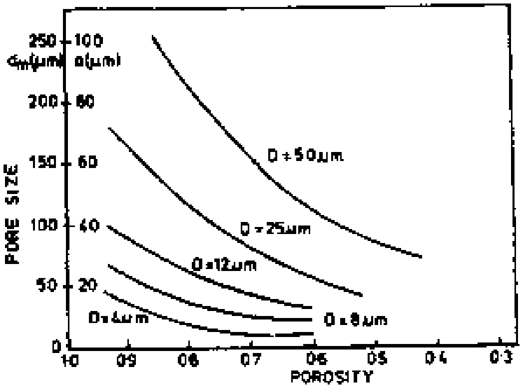

Figure 7.10. Porosity versus pore diameter for sintered metals made from fibres of various diameters.

Of the media listed in Table 7.11, both ST-AL3 and ST-CL3 are of graded multi-layered construction. Flow in the direction coarse-to-fine gives a high dirt-holding capacity and gel retention capability; the reverse direction of flow permits cake filtration and facilitates backwash cleaning. Sheets of these media are relatively soft and flexible, requiring adequate support in use. They may be supplied with supporting mesh sintered to both sides (indicated by the suffix SS) or to one side only (S), this being the flow-out side; this support is a 48 mesh of 0.125 mm wire with 400 μm openings, 0.17 mm thick and weighing 380 g/m^2. A distinguishing feature of the fourth generation media (ST-AL4 and ST-CL4) is their non-compressibility even at the high hydraulic pressures in polymer filtration.

Bekipor ST-BL is a non-graded sintered metal fibre medium that functions in the same way with flow from either side. One of the most common uses for this economical and lightweight material is for the filtration of low-viscosity fluids such as fuels and hydraulic fluids.

Pall's PMF fibre media are available in three distinct types, all in 316L stainless steel. The FH-Series, which can be corrugated or pleated (as in Figure 7.12), is suitable for pressures up to 69 bar and has been optimized for polymer melt filtration. The FL-Series, which can also be pleated into high area packs, is intended for low-pressure applications up to 17 bar. FS-Series media are composites, comprising a profiled pore structure of fibres sandwiched between supporting and protective layers of mesh; with high dirt-holding capacities, their application is for polymer filter segments. Removal efficiencies and flow characteristics of these media are summarized in Table 7.12.

7.3.2.3 Sintered woven metal

Unsintered woven meshes suffer from instability, with relative movement or deformation of the wires possible, resulting from stresses imposed by vibration, pulsating flow or high differential pressure. This can result in deterioration of the

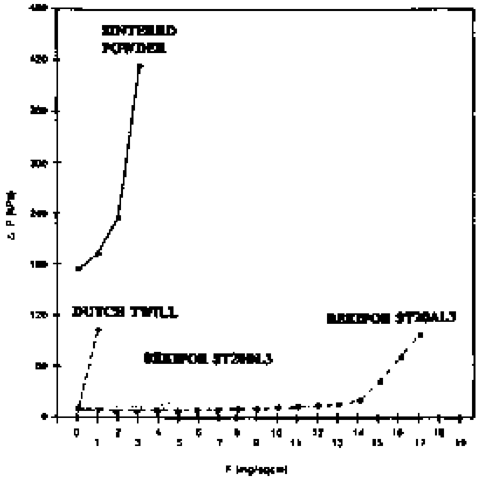

Figure 7.11. The rate of increase in pressure drop as dirt collects on a filter depends on the type of the medium.

Table 7.11 Characteristics of Bekipor ST sintered metal fibre media[a]

	Absolute filter-rating (μm)	Bubble point pressure[b] (Pa)	Average air permeability at 200 Pa[c] (l/dm^2/min)	Permeability factor, *k* (m^2)	*H*/*k* (l/m)	Thickness, *H* (mm)	Weight (g/m^2)	Porosity (%)	Dirt holding capacity[d] (mg/cm^2)
3AL3	3	12 300	9	4.80E-13	7.29E+08	0.35	975	65	6.40
5AL3	5	7600	34	1.76E-12	1.93E+08	0.34	600	78	5.47
7AL3	7	5045	57	2.35E-12	1.15E+08	0.27	600	72	6.47
10AL3	10	3700	100	4.88E-12	6.56E+07	0.32	600	77	7.56
15AL3	15	2470	175	9.87E-12	3.75E+07	0.37	600	80	7.92
20AL3	20	1850	255	1.91E-11	2.57E+07	0.49	750	81	12.44
25AL3	25	1480	320	2.98E-11	2.05E+07	0.61	1050	79	19.38
30AL3	30	1235	455	4.37E-11	1.44E+07	0.63	1050	79	23.07
40AL3	40	925	580	5.84E-11	1.13E+07	0.66	1200	77	25.96
60AL3	59	630	1000	1.07E-10	6.56E+06	0.70	750	87	33.97
5BL3	5	7000	45	1.17E-12	1.46E+08	0.17	300	78	4.00
10BL3	10	3700	100	2.59E-12	6.56E+07	0.17	300	78	4.63
15BL3	15	2470	175	4.54E-12	3.75E+07	0.17	300	78	4.70
20BL3	20	1850	255	6.61E-12	2.57E+07	0.17	300	78	6.10
40BL3	40	925	580	1.50E-11	1.13E+07	0.17	300	78	14.60
60BL3	59	650	1100	2.43E-11	5.96E+06	0.15	300	74	21.50
5CL3	6	6100	35	4.38E-12	1.87E+08	0.82	975	85	11.67
10CL3	11	3500	95	1.07E-11	6.90E+07	0.74	900	85	17.13
15CL3	15	2400	200	2.29E-11	3.28E+07	0.75	900	85	18.95
20CL3	22	1700	325	3.67E-11	2.02E+07	0.74	900	85	29.10
5CL4	5	7400	27	1.65E-12	2.43E+08	0.40	900	72	6.80
10CL4	10	3700	71	4.33E-12	9.23E+07	0.40	900	72	9.50
15AL4	15	2450	140	7.26E-12	4.68E+07	0.34	750	73	8.20
15CL4	16	2400	150	9.15E-12	4.37E+07	0.40	900	72	11.90
20CL4	20	1850	200	1.22E-11	3.28E+07	0.40	900	72	12.00

[a] N.V. Beckaert S.A.

[b] Determined according to ASTM E128-61 equivalent ISO 4003.

[c] Determined according to NF A 95-352 equivalent ISO 4022.

[d] Determined according to Multipars method ISO 4572. Differential pressure = 8 × Initial differential pressure.

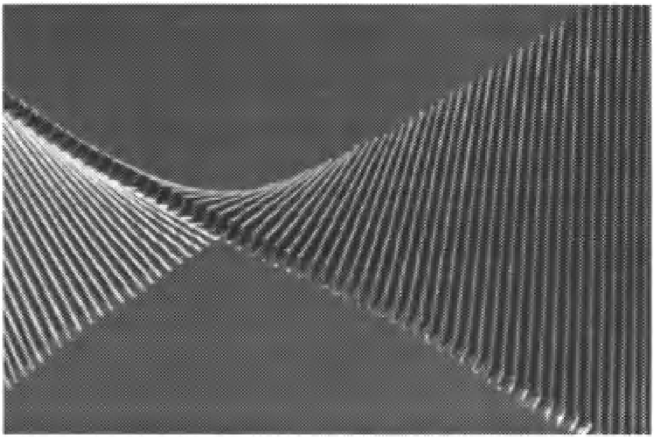

Figure 7.12. Pleated 'PMF' filter medium.

Table 7.12 Pall's PMF sintered metal fibre media[d]

Media grade	Micron removal rating in liquid service[a]				Thickness[b] (mm)	Permeability[c]	
	90%	98%	99%	100%		to air	to water
FH025	< 1.0	< 1.0	1.4	2.5	0.35	21.5	4.76
FH050	0.5	1.0	2	5	0.51	94	1.18
FH080	2	3	4	8	0.38	130	1.69
FH100	5	7	8	10	0.33	233	2.95
FH150	6	9	11	15	0.38	442	5.9
FH200	8	12	14	20	0.38	737	9.83
FH250	10	14	17	25	0.38	884	11.8
FH300	12	18	20	30	0.38	1105	14.75
FH400	14	20	24	40	0.38	1474	19.67
FL050	2	2.5	3	5	0.28	138	1.97
FL080	3.5	4	5	7	0.41	340	4.54
FL100	6	8	9	10	0.36	491	6.56
FL150	7	9	1	15	0.23	737	9.83
FL200	11	14	15	20	0.30	1474	19.67
FL250	13	18	19	25	0.30	2210	29.5
FS025	0.5	0.8	0.9	2.5	1.40	36	–
FS050	1.7	2.5	3	7.5	1.17	68	–
FS075	2.5	4	5	7.5	1.12	92	–
FS100	4.5	6	7	10	1.09	158	–
FS150	6.5	8.5	10	15	1.07	201	–
FS200	9	12	13	20	1.07	233	–
FS300	14	18	19	30	0.94	737	–

[a] Removal efficiency ratings are based on a modified F2 test method and actual particle count data.
[b] Thickness includes upstream mesh and downstream support.
[c] /dm^2/min @ 10 mbar.
[d] Pall Inc.

rated filtration efficiency, abrasion of the wires, the generation of metal particles that contaminate the filtrate, the unloading of previously collected particles into the filtrate, and structural failure.

These problems can be avoided by sintering the mesh so as to bond together the wires at all their points of contact. This greatly increases the rigidity of the mesh to produce an extremely strong structure that is resistant to deformation; it also permits the use of finer wires, resulting in more voids per unit area with a consequential decrease in resistance to flow and an increase in dirt-holding capacity. In addition, these media have the great advantage that they may be cut and shaped without risk of disintegration, in a way not possible with unsintered mesh.

Because of the similarity of application between sintered and unsintered meshes, these media are discussed in more detail in Chapter 6.

7.3.3 Metal foams

Retimet is a metal foam, developed by Dunlop, produced by replicating the skeletal or reticulated structure of the polyurethane foam described earlier in this chapter. The process involves electroplating the plastic foam with a metal such as copper, nickel, nickel-chrome or iron, and then removing the plastic by pyrolysis, to leave a structure of hollow metal struts as shown in Figure 7.13.

By controlling the thickness of metal deposited by electroplating, the density of Retimet can be controlled within the wide range of 1.55–15% of the density of the pure metal. The standard nickel foam has a nominal density of 0.45 g/cm^3, as compared with 0.65 g/cm^3 for nickel-chrome foam. Although certain prefabricated shapes can be produced, Retimet is most conventionally produced as sheets up to 20 mm thick, in grades determined by the number of pores per inch (see Table 7.13); the maximum sheet size is 700 mm × 375 mm in nickel, and 600 mm × 350 mm in nickel-chrome.

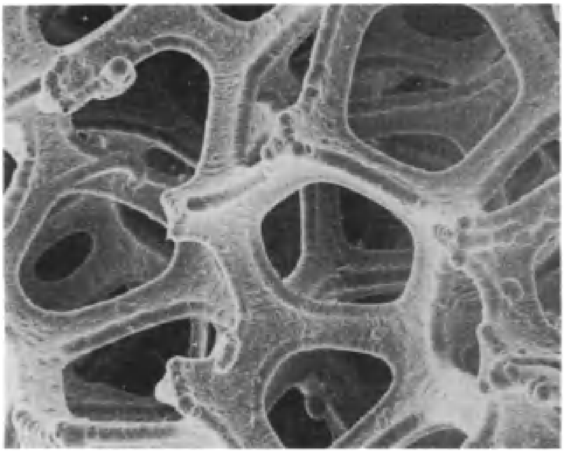

Figure 7.13. The pore structure of 'Retimet' metal foam.

The pore size and structure of Retimet are very similar to those of the precursor polyurethane foam. Its filtration characteristics are therefore generally also similar, but with some exceptions that are attributable to differences in electrostatic properties. For example, inorganic dusts are reported to blind polymer foam significantly faster than similar metal foam, probably because the polymer arrests much smaller particles; on the other hand, metal foam can be more readily and completely cleaned(5).

Retimet is a highly permeable material with a low pressure drop proportional to thickness and flow velocity. Figure 7.14 shows the pressure drop for air at 1.78 m/s through various grades of 10 mm thick Retimet, while Figure 7.15

Table 7.13 Thickness versus grades of Retimet metal foam*

Thickness (mm)	Grade (pores per inch)			
	10	20	45	80
2	No	No	Yes	Yes
4	No	Yes	Yes	Yes
7	Yes	Yes	Yes	Yes
13	Yes	Yes	Yes	Yes
20	Yes	Yes	No	No

* Dunlop Ltd.

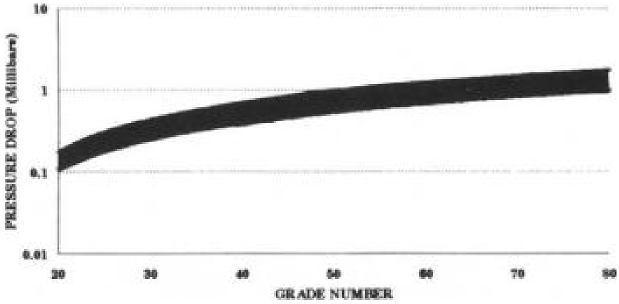

Figure 7.14. Pressure drop with air flowing at 1.78 m/s through 10 mm thick 'Retimet' metal foam.

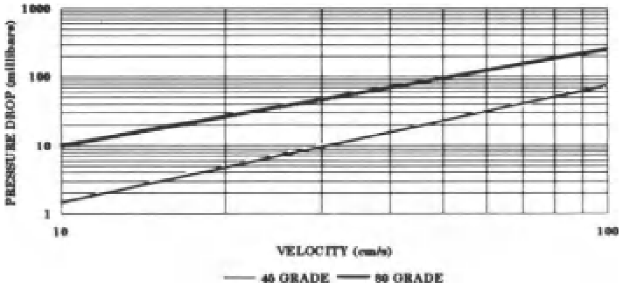

Figure 7.15. Pressure drop versus velocity of water flowing through 10 mm of 45 grade and 80 grade 'Retimet' metal foam.

correlates the pressure drop versus velocity for water through a 10 mm thickness of either 45 or 80 grade material.

The strength of Retimet is approximately proportional to its nominal density, nickel-chrome material being some 10 times stronger than nickel. A current application for the material is in the air/oil separation duty in jet engines.

7.4 Ceramic Media

It is appropriate to distinguish among four broad categories of ceramic filter media:

- conventional ceramics, including stoneware, which have long been used for industrial filtration, and are characterized as being hard and of high density;
- 'soft' low-density ceramic media, which are a recent development in response to the increasingly rigorous demands of the rapidly evolving field of hot gas filtration;
- ceramic membranes, important in cross-flow filtration, which are available with either ceramic or metal substrates; and
- ceramic foams, which have a unique role in the filtration of molten metals.

The key application for ceramic media is in the filtration of fluids, especially gases, at moderate to high temperatures. Whereas conventional ceramics are used for this application, Table 7.14 shows that low-density media offer both technical and economic advantages(6).

The media discussed in separate sections below: sintered particles and fibres, and foams, do not include all the types of ceramic media under development. Although formally classifiable as woven media, 3M's Nextel media(7) are based on extruded chemical sols of ceramic materials. The resultant filaments, after firing, can be combined into yarns and then woven, to give a ceramic medium that works well as a bag for use in fabric filters.

A quite different type of filter(8) for hot gases employs the ceramic material in the form of a honeycomb, with a series of 'dirty' gas channels arranged in parallel, in the direction of the gas flow, with a matching set of clean channels, into which the gas flows through the dividing walls. The collected dust is removed by a pulse jet.

Table 7.14 Properties of ceramic materials used for hot gas filter elements

Characteristic	Mullite	Bonded SiC	Vacuum-formed ceramic fibre	Post-treated vacuum-formed ceramic fibre
Relative hardness	'Hard'	'Hard'	'Soft'	'Soft'
Temperature limit (°C)	1000	> 1000	> 1250	> 1250
Weight (10 mm wall)	1.25	2.2	0.3	0.3
Resistance to thermal and physical shock	1.0	1.25	1.75	1.85
Cost	1.0	1.6	0.5	0.7

A major problem with ceramic filters is the achievement of adequate dust cake discharge, and this remains the current topic of greatest research effort[9]. By comparison with fabric elements, there is no movement of the medium during back flushing, and so the cleaning air pressures need to be significantly higher.

7.4.1 *High-density ('hard') ceramics*

This category of media embraces the porous ceramic tubes and sheets that have long been used for a variety of industrial filtration duties, especially for hot gases, and the now old-fashioned moulded stoneware filters for industrial liquids. Typically made from granules of refractory materials such as aluminosilicates, silicon carbide and silicon nitride, the void fraction of hard porous ceramic media is of the order of 40% with pore sizes ranging from several hundred micrometres down to about 10 μm, as illustrated by the data in Table 7.15.

Whilst this Table 7.15 includes pore size data, the microphotograph of Pyrolith in Figure 7.16 provides a useful reminder that pores are rarely circular. Eight grades of these media and the corresponding range of Coralith media are made by the techniques of powder metallurgy, rather than by traditional ceramic methods. Carefully graded particles are mixed with solid additives, which form high-temperature bonds, and with liquid additives, which give unfired strength. Semi-dry techniques are used to form the required shapes, which are fired, ground to the final dimensions if necessary, and checked for pore size. Examples of standard tubes and plates are summarized in Table 7.16; typical flow/pressure characteristics are illustrated in Figures 7.17 and 7.18.

The extensive Schumacher range of ceramic media is summarized in Tables 7.17 and 7.18. The three Dia materials (Dia-Brandol, Dia-Kermodur and Dia-Schumalith) are the result of the development of asymmetric structures that favour surface instead of depth filtration; they combine a thin fibrous fine pore layer with a coarse substrate, as shown in the example of Figure 7.19. They are thus membranes within the definition of Chapter 8, but reference to them and their characteristics are included here to show the differences between the two categories, with more data in Section 7.4.3.

Pall Vitropore ceramic candles were developed specifically to meet the demanding needs of CHP (combined heat and power) systems, but have proved successful in other aggressive gas-phase environments, such as petrochemical processing. Made entirely of silicon carbide (with sodium aluminosilicate as binder), with a fine outer coating on a coarse substrate, they are available in only one high-performance grade and one diameter, but of four different lengths; their dimensions, physical properties and performance characteristics are summarized in Table 7.19.

7.4.2 *Low-density ('soft') ceramics*

In contrast to the high-density ceramics, the modern low-density ceramic media are made from chopped ceramic fibres and have void fractions of about 90%. They are the basis of the novel filter candles developed for use in multiple

Table 7.15 Fairey Industrial Ceramics range of high density ceramic media*

Composition	Chemical resistance	Trade name	Grade	Pore diameter (μm)		Porosity (%)	Cross breaking strength (kg/cm^2)	Average specific weight (g/cm^3)	Nominal micron retention	
				Average	Maximum				Air/gas	Liquid
Alumino-silicate particles bonded by glass based flux	Hot and cold acids (not hydrofluoric acid or acid fluorides) and alkaline solutions up to pH 9 and hot gases up to 900°C	Pyrolith	P0	11	15	35	175	1.5	0.3	1
			P9	20	25	35	161		1	2
			P8	30	35	35	140		2	6
			P6	50	70	45	105		10	20
			P5	90	110	45	88		20	40
			P4	155	200	45	70		30	60
			P3	300	400	45	53		50	150
			P2	525	650	45	35		100	230
Alumina particles bonded by a glass based flux	Hot and cold acids (not hydrofluoric acid or acid fluorides) and alkaline solutions up to pH 9 and hot gases up to 1000°C	Coralith	C0	11	15	35	263	1.5	0.3	1
			C9	20	25	35	242		1	2
			C8	30	35	35	210		3	6
			C6	50	70	45	158		10	20
			C5	90	110	45	133		20	40
			C4	155	200	45	105		30	60
			C3	300	400	45	79		50	150
			C2	525	650	45	53		100	230
Alumino-silicate particles bonded by refractory agents	Poor resistance to chemical and physical abrasion (not usually critical as main use is hot gases up to 1400°C)	TR Media	TR6	90	110	45	35	1.5	20	-
			TR5	155	200	45	35		30	-
			TR4	300	400	45	35		50	–

Composition	Chemical resistance	Trade name	Grade	Pore diameter (μm)		Porosity (%)	Cross breaking strength (kg/cm²)	Average specific weight (g/cm³)	Nominal micron retention	
				Average	Maximum				Air/gas	Liquid
Siliceous material	Good resistance to acids although liable to attack by physical abrasion (main use is on domestic water systems)	KN Media	KN	–	4.5	65	42	0.8	–	–
Porcelain mullite	High resistance to acids and alkalis up to 1400°C	Celloton	VI	–	1	50	350	1.5	–	–

[a] Fairey Industrial Ceramics Ltd.

assemblies with pulse jet or reverse flow cleaning, as shown in Figure 7.20, used for the rigorous needs of high-temperature dust filtration associated with processes such as coal combustion and gasification, incineration and catalyst recovery. However, their use is by no means restricted to such arduous conditions, many installations having operating temperatures well below 500°C.

The candles are formed by vacuum filtration of a water suspension of chopped fibres and a ceramic or clay binder, using a suitably shaped porous forming tool on which a filter cake is deposited. This cake is then removed from the former and thermally treated to evaporate water and solidify the binder; the candle may also be subjected to post-treatment with a variety of ceramic coatings, such as colloidal alumina to increase corrosion resistance. Clift(10) stated that appropriate techniques ensure that the orientation of the fibres is generally normal to the direction of flow through the candle, which is important in ensuring good filtration properties.

Their typical form and dimensions are as indicated in Figure 7.21 and Table 7.20, although the details vary from one manufacturer to another; for example, Tenmat utilizes multiple tubular sections to achieve lengths up to 4 m or more.

Table 7.16 Standard sizes of ceramic filter tubes and plates[a]

Dimensions, inches (mm)			Grades	
			Pyrolith	Coralith
Max. length	*i.d.*	*o.d.*		
4 1/2 (114)	1 1/8 (29)	1/2 (13)	P3–P0	C3–C0
10 (254)	1 1/8 (39)	1 (25)	P4–P9	C4–C9
10 (254)	2 (50)	1 1/4 (32)	P2–P0	C3–C0
15 (381)	2 3/4 (70)	2 (50)	P3–P0	C3–C0
20 (508)	2.9 (74)	2.4 (61)	P5 only	–
18 (458)	3 (77)	2 (50)	P3–P0	C3–C0
12 (305)	4 (102)	3 (77)	P3–P0	C3–C0
39 3/8 (1000)	2 3/8 (60)	1 1/2 (40)	P5–P9	C5–C9
39 3/8 (1000)	2 3/4 (70)	2 (50)	P5–P9	C5–C9
Flanged elements				
1000 mm Flanged 70 mm dia.	60	40	P5–P9	C5–C9
Tiles/filter plates *Sizes, inches (mm)*			*Grades*	
12 (305)×2 (50)×1 (25)			Pyrolith P2–P8	
12 (305)×4 (100)×1 (25)				
12 (305)×6 (153)×1 (25)				
12 (305)×12 (305)×1 (25)			Coralith C2–C8	
20 (508)×16 (406)×1 (25)				
20 (610)×12 (305)×1 (25)				
20 (610)×16 (406)×1 (25)			TR4–TR6	

[a] Fairey Industrial Ceramics Ltd.

Table 7.17 Properties of Schumacher high density ceramic filter media[a]

Filter media		Filtration fineness (nominal) (μm)	Pressure drop (mbar)[b]	Specific permeability (m²)	Porosity (%)	Density (g/cm³)	Linear expansion coefficient (10⁻⁶/K)	Temperature resistance (°C)	Bending strength (Pa)	Bursting pressure (bar 10⁵ Pa)	Test piece dimensions (mm) i.d.-o.d.
AEROLITH	5	1.0	25	2.52 × 10[illegible]	45	1.40	16	400	17	50	070-40
	10	1.5	10	4.30 × 10[illegible]	45	1.25	16	400	15	10	060-40
	20	2.0	10	1.49 × 10[illegible]	45	1.25	15	400	7	15	070-40
	30	4.0	4	3.15 × 10[illegible]	45	1.25	15	400	6	10	060-40
	40	5.0	1	4.19 × 10[illegible]	45	1.20	15	400	5	10	060-40
	60	ca 150	1	6.24 × 10[illegible]	45	1.20	15	400	4	–	tile h=50
BRANDOL	30	–	12.5	2.01 × 10[illegible]	15	1.65	–	190	13	–	tile h=20
	60	–	2	9.44 × 10[illegible]	10	1.68	–	190	10	40	070-50
	80	–	1.5	1.25 × 10[illegible]	10	1.70	–	190	10	40	070-50
	120	–	0.5	3.77 × 10[illegible]	10	2.70	–	190	9	30	070-40
DIA-BRANDOL	60	0.5	5.5	2.28 × 10[illegible]	10	1.6	–	190	10	30	060-40
DIA-KERAMOTHERM	10	1.0	12	1.57 × 10[illegible]	40	2.1	8	1000	15	25	060-50
DIA-SCHUMALITH	10	1.0	12	1.57 × 10[illegible]	15	2.0	5.5	1000	15	30	060-50
	40	1.0	4.5	1.98 × 10[illegible]	15	2.0	5.5	1000	30	40	060-50
DIAPOR	640	<0.05	3500	4.17 × 10[illegible]	55	1.5	6.8	1000	14	–	tile h=5
	640	<0.05	2000	5.15 × 10[illegible]	55	1.5	6.8	1000	14	–	tile h=5
DURATEL	5	<0.04	70	2.68 × 10[illegible]	65	0.6	–	150	–	6	070-40
	30	0.5	45	5.56 × 10[illegible]	60	0.6	–	150	–	15	070-40
CERAMOTEC	10	1.5	22	6.29 × 10[illegible]	40	2.1	8	1000	25	50	060-40
	20	2.0	10	1.25 × 10[illegible]	40	2.1	8	1000	20	30	060-40
	30	3.0	5	2.52 × 10[illegible]	40	2.1	8	1000	15	30	060-40
	50	ca 150	2	9.18 × 10[illegible]	45	1.8	8	1000	10	–	tile h=15
	100	ca 250	0.3	1.05 × 10[illegible]	45	1.8	8	1000	6	–	tile h=25

Table 7.17 *(continued)*

Filter media		Filtration fineness (nominal) (μm)[a]	Pressure drop (mbar)[b]	Specific permeability. (nPm)[c]	Porosity (%)	Density (g/cm³)	Linear expansion coefficient (10^{-6}·1/K)	Temperature resistance (°C)	Bending strength (Pa)	Bursting pressure (bar 10^5 Pa)	Test piece dimensions (mm) i.d./o.d.
KERMODUR KK	20	2.0	10	1.26×10^2	55	1.5	7.5	1000	9	25	Ø60/40
	30	3.0	5	2.52×10^2	55	1.4	7.5	1000	8	25	Ø60/40
SCHUMACEL HTHP		1.0	26	4.81×10^1	50	1.6	5	1000	–	20	Ø60/40
SCHUMALITH	3	0.5	700	2.70	25	2.1	5.5	1000	35	100	Ø70/40
	5	1.0	300	6.29	30	2.0	5.5	1000	35	80	Ø70/40
	10	2.0	30	6.29×10^1	35	2.0	5.5	1000	25	60	Ø70/40
	20	3.0	15	1.25×10^2	35	2.0	5.5	1000	20	60	Ø70/40
	30	5.0	7	2.70×10^2	35	2.0	5.5	1000	15	50	Ø70/40
	40	ca 10.0	5	3.77×10^2	35	2.0	5.5	1000	10	45	Ø70/40
	50	ca 15.0	2	9.38×10^2	45	1.8	5.5	1000	10	–	tile h=15
	100	ca 25.0	0.3	1.05×10^4	45	1.8	5.5	1000	8	–	tile h=25
SCHUMATHERM	10	1.5	100	1.89×10^1	35	1.6	5	600	9	40	Ø70/40
	20	2.0	40	4.71×10^1	40	1.5	5	600	8	30	Ø70/40
	30	4.0	25	7.55×10^1	40	1.5	5	600	7	20	Ø70/40
	40	8.0	10	3.15×10^2	40	1.5	5	600	6	20	Ø120/40
	60	ca 10.0	5	3.75×10^2	35	1.4	5	600	5	20	Ø70/40
THERMOLITH	20	2.0	40	4.71×10^1	40	1.5	5	1000	8	30	Ø70/40

[a] Ambient air, particle counter.

[b] Air @ 250 m/min.

[c] 1 Nanoperm (nPm)=0.1013 darcy.

[d] Pall Inc/Schumacher.

Table 7.18 Schumacher range of high density ceramic filter media[a]

Trade name	Description
Aerolith	A pure white mixture of crystalline and amorphous silicates. Thermally resistant to 400°C. Chemically resistant to hot and cold neutral and acidic liquids and gases. Suitable for wide range of applications.
Brandol	Quartz sand bonded with phenolic resin for use in fine bubble aeration or fluidization. Resistant to cold and warm neutral and acidic fluids.
Diapor	A mixture of alumina silicates with extremely fine porosity and highly resistant to acid. Ideal for diaphragms in electro-chemical processes.
Dia-Brandol Dia-Kermodur Dia-Schumalith	Schumacher's newest developments. Asymmetric open-pored support body with ceramic membrane surface. Used mainly for dust filtration up to 1000°C.
Durocel	Glass microfibres bonded with resin for use at up to 150°C to separate aerosols and fine particles from compressed air and vacuum pump exhausts. Chemically resistant to nearly all mineral and synthetic lubricating oils and to carbon tetrachloride.
Kermodur	Aluminium oxide assures high strength and high resistance to temperature changes. Resistant to acidic and alkaline environments. For high temperature processes (filtration of metals) up to 1000°C.
Schumacel HTHP	Silicon carbide and fibres of aluminium oxide bonded with silicon. For hot gas filtration, resistant to aggressively oxidizing or reducing atmospheres at temperatures above 1000°C.
Schumalith	Ceramic-bonded silicon carbide. Very good resistance to solutions of acids and acidic salts, saturated and superheated steam and to hot gases up to 1000°C. In grain size 3 can be used for sterile filtration of gases.
Schumatherm	A mixture of alumino silicates, stable to 600°C. Mainly used for filtration of liquids, as linings for nutsches and as support bodies for precoat filtration.
Thermolith	A mixture of ceramic-bonded fire-clay, stable at temperatures of 900°C. For filtration of liquids and process gases.

[a] See also Schumacher's carbon media in Table 7.27.

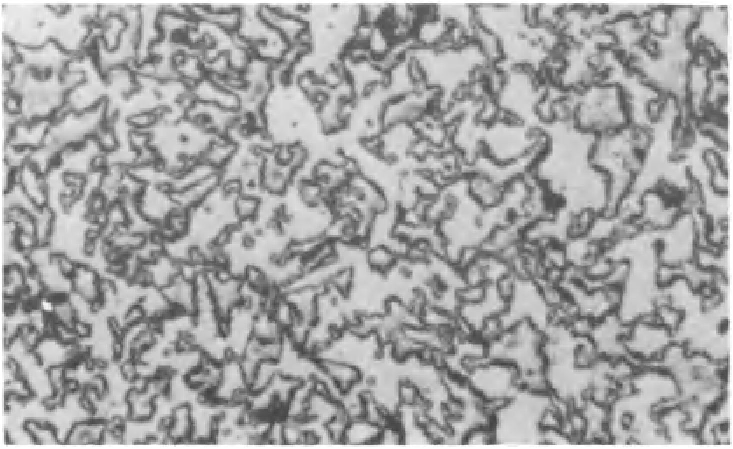

Figure 7.16. Photomicrograph (×32 magnification) of polished 'Pyrolith P8' with pores visible as darker areas.

The ceramic materials also vary as therefore do both the densities and maximum operating temperatures; some examples are given in Table 7.21.

Numerous advantages are claimed for these filter elements, as compared with traditional hard ceramics, including greater resistance to thermal and physical shock, lower pressure drop, less weight and lower cost. Care must, of course, be taken to ensure the absence of liquids in the use of ceramic filters[11], either as condensed vapours through operation below the dew point, or as molten droplets in the dirty gas, that might block the filter.

They achieve high levels of filtration efficiency with dust emissions less than 1 mg/m^3; as the data in Table 7.22 illustrate, the high efficiency of a virgin filter (which is dependent on the face velocity) increases after 'conditioning' by operation through

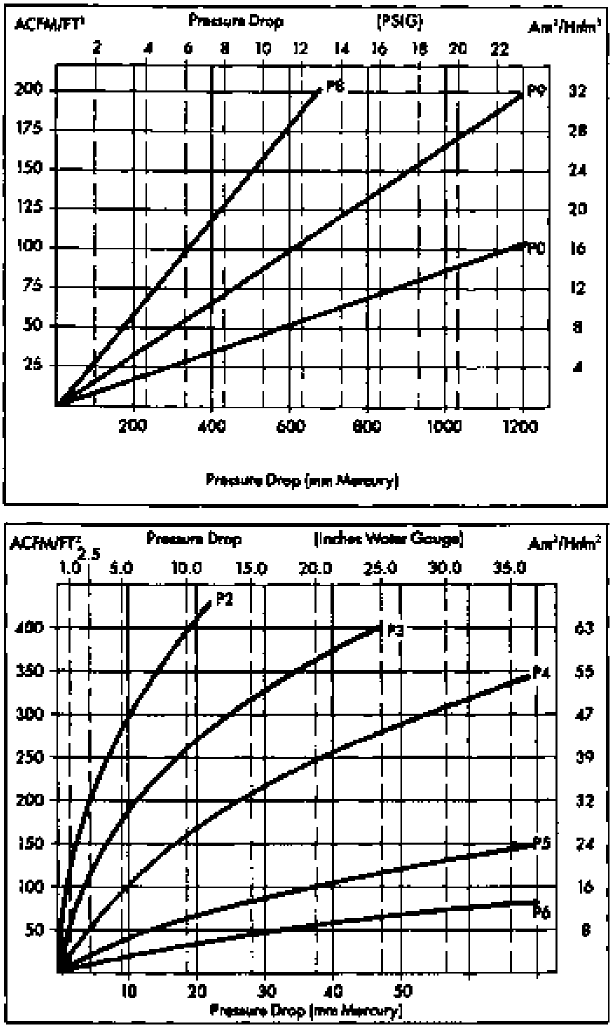

Figure 7.17. Typical clean air flow/pressure curves for 'Pyrolith' and 'Coralith' ceramic media.

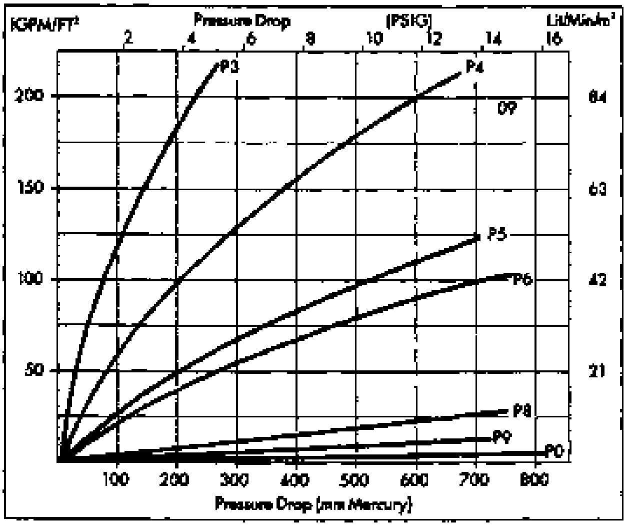

Figure 7.18. Typical clean water flow/pressure curves for 'Pyrolith' and 'Coralith' ceramic media.

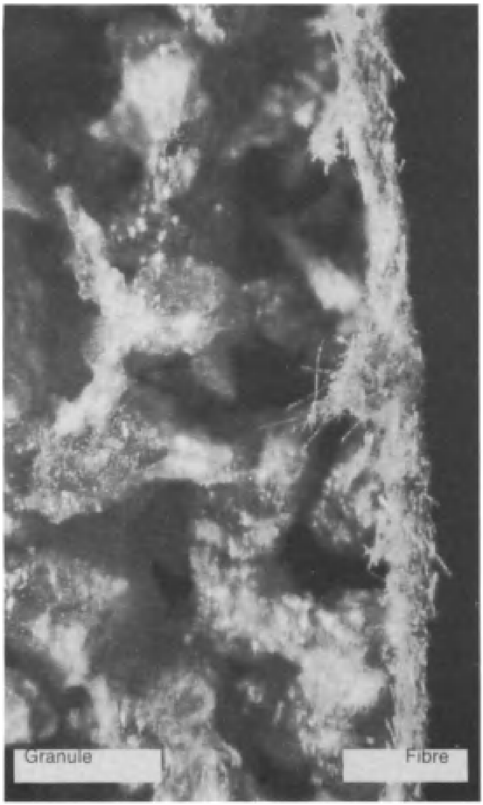

Figure 7.19. Microphotograph of a section through 'Dia-Brandol' showing the thin fibrous layer on a coarse granular substrate.

15–20 cleaning cycles, and becomes even higher during extended operation, because of the retention of a thin cake of dust particles on the surface[12].

A secondary effect of this residual cake of dust is that, under equilibrium operating conditions, the pressure drop is dependent on the nature of the dust as well as on the face velocity, as is illustrated in Figure 7.22.

Table 7.19 Properties and dimensions of 'Vitropore'[†] ceramic candles[a]

Gas removal rating[b] (μm)	2
Removal efficiency[c] (%)	99.9
Mean pore size (μm)	7–10
Average 1st bubble point pressure (mbar)	10.96
Average open bubble point pressure (mbar)	16.44
Permeability to clean air (bar/m^3/s/m^2)	0.0869
Dimensions	
Length (m)	0.5, 1.0, 1.5, 2.0
Inside diameter (mm)	40
Outside diameter (mm)	60
Bulk density (g/cm^3)	1.7
Weight, 1.5 m long (kg)	4
Porosity (%)	46
Maximum temperature (°C)	1000
Thermal expansion coefficient per °C	4.7×10^{-6}
Modulus of rupture[d] (bar)	110 minimum

[a] Pall Corporation.

[b] Particle count.

[c] Weight % based on AC FineTest dust in air, particles 1 μm and greater.

[d] Burst test subjects 2.54 cm long ring sample 60 mm o.d. × 40 cm i.d. to slowly increasing uniform internal pressure.

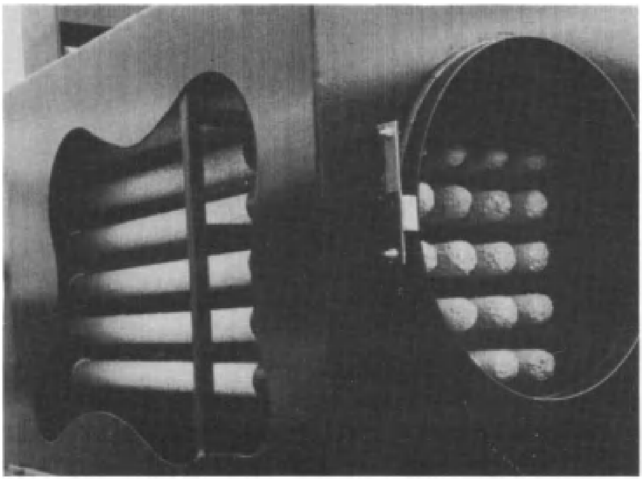

Figure 7.20. A multi-element ceramic candle filter. Dust collects on the outside surfaces.

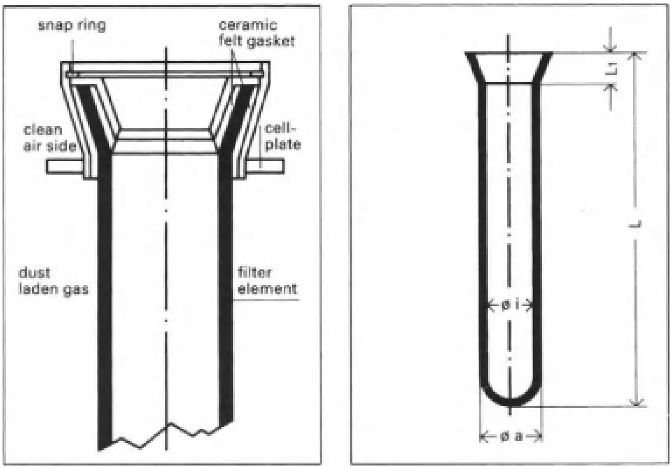

Figure 7.21. Typical form of candle filter element. See Table 7.20 for dimensions.

Table 7.20 Characteristics of 'Pyrotex' low density filter candles[a]

	KE85/60		KE85/150	KE85/200
Outside diameter Ø a (mm)	60	60	150	200
Inside diameter Ø i (mm)	42	42	110	160
Length of element L (mm)	985	1500	1530	1000
Length of collar L_1 (mm)	10	10	130	100
Weight (g/m^2)	1600	1600	35 000	3500
Weight/element (g)	300	450	2600	2400
Thickness, mm	9	9	20	20
Density (g/cm^3)	0.18	0.18	0.18	1.18
AP, l/dm^2.min at 200 Pa	120	120	60	60
Pore volume (%)	93	93	93	93
Surface area/element (m^2)	0.19	0.28	0.66	0.60

[a] BWF Textil GmbH & Co. KG.

Table 7.21 Temperature limits of low density ceramic candle filter

Manufacturer	Trade names	Material limit	Temperature (°C)	Density (gm/cm^3)	Porosity (%)
Madison	Cerafil S	Aluminosilicate	900	0.37	86
	Cerafil XS	Aluminosilicate	900	0.39	86
	Cerafil HS	Alumina	1200	0.61	–
Tenmat	Firefly	Various	1600	0.25–0.40	85–95
BWF Textil	Pyrotex KE85	Ceramic fibres	850	0.18	93

The low-density ceramic candles supplied by Brightcross[12] are available either in cylindrical form, or with a slight taper, which is claimed to reduce bridging between candles, and to increase ease of dust removal. Their temperature limits are dependent upon their material of construction:

Mineral fibre	Continuous: 700°C	Intermittent: 1000°C
Calcium silicate	1000°C	1500°C
Refractory ceramic	1200°C	1700°C

7.4.3 Ceramic membranes

Ceramic membranes are generally composites, with the membrane supported on a coarser ceramic substrate, which may be in the form of a flat plate or a tube. An important and growing variety utilizes metal as the substrate. Both types are discussed in Chapter 8.

Table 7.22 Filtration efficiencies of Cerafil S ceramic candles[a]

State of filter	Face velocity (cm/s)	Efficiency[b] (%)	Eurovent class (EU)
Virgin	1	99.6	12
	3	98.8	11
	4	97.6	11
Preconditioned	4	99.3	12
Used	4	99.9	12

[a] Madison Filter.

[b] Tested to BS 3928 using 0.6 μm NaCl particles.

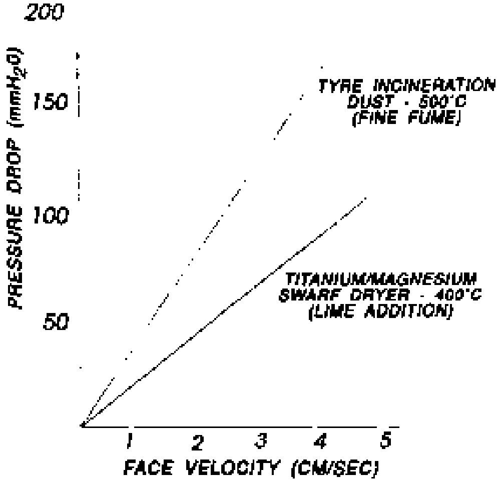

Figure 7.22. The pressure drop across a conditioned filter candle depends on both the face velocity and the nature of the dust being filtered.

These composites are primarily used for hot gas filtration of fine dusts in the form of tubular and star-shaped elements, for which typical data are given in Table 7.23. Because they function by surface filtration, composites are cleaned more thoroughly by an intermittent back pulse; this is demonstrated by Figure 7.23, which shows the typical relationship between pressure drop and the number of filtration cycles for several different media. Very much better performance is shown for the four grades of 'membrane' element, as compared to the standard elements.

7.4.4 Ceramic foams

This distinctive form of porous ceramic, used for many years in the foundry industry for gravity filtration of molten metal, is known as ceramic foam because of its very open structure, with porosities typically from 70 to 90% or more. One manufacturing process[13] involves impregnating polyurethane foam with an aqueous ceramic slurry and compressing it to expel excess slurry; the coated foam is then subjected to several stages of heat treatment, resulting in combustion of the organic polymer and sintering of the ceramic particles. The latter are typically mixtures of alumina and chromia, but may also be zirconia, magnesia, silica, etc.

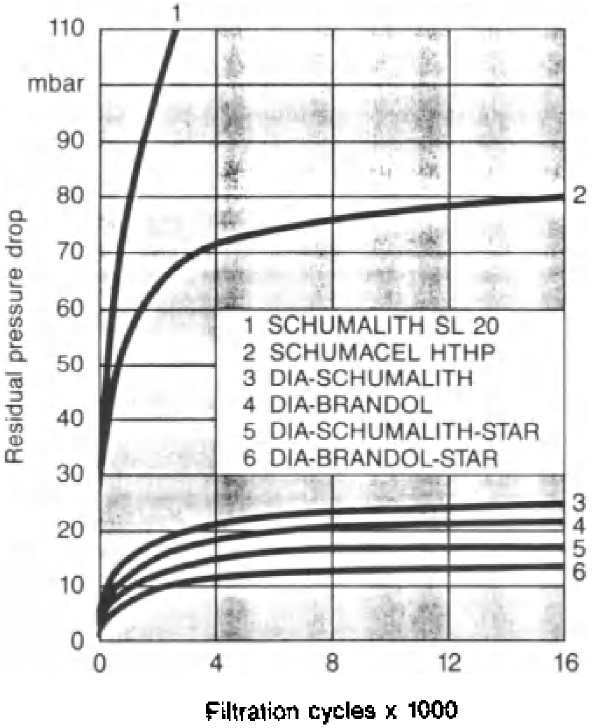

Figure 7.23. Example of the residual pressure drop of ceramic filter elements as a function of the number of filtration/cleaning cycles. Temperature 20°C; gas velocity 200 m/h; cycle time 6 min.

Table 7.23 Schumacher ceramic candle filter elements

	Schumalith 20 homogeneous granular	Schumacel HTHP heterogeneous granular/fibre	Dia-Schumalith asymmetric granular/fibre	Dia-Schumalith Star asymmetric, fluted granular/fibre	Dia-Brandol asymmetric granular/fibre	Dia-Brandol-Star asymmetric fluted granular/fibre
Maximum temperature (°C)	1000	1000	1000	1000	180	180
Granule/fibre diameter (μm)	120	120/3	300/3	300/3	500/1	500/1
Pore size (μm)	40	30/10	100/30	100/30	200/5	200/5
Outer element diameter (mm)	60	60	60	60	60	60
Inner element diameter (mm)	40	40	30	30	40	30
Wall thickness (mm)	10	10	15	15	10	15
Flange diameter (mm)	75	75	75	75	75	75
Flange thickness (mm)	15	15	15	15	15	15
Element length (mm)	1000/1500	1000/1500	1000/1500	1000/1500	1000/1500	1000/1500
Filtration area (m^2)	0.16/0.26	0.16/0.26	0.16/0.26	0.29/0.47	0.16/0.26	0.26/0.45
Weight (kg)	4.2/6.2	4.1/6.2	4.1/6.2	3.3/4.7	2.7/4.0	2.2/3.2

The structure of the ceramic foam thus effectively replicates the skeletal or reticulated form of the polyurethane foam discussed in Section 7.2.2. By selecting grades of polyurethane foam with pores of appropriate sizes (or combinations of sizes), and by forming it into the desired shape, a correspondingly wide variety of ceramic foam products may be produced, such as is shown in Figure 7.24.

Pore sizes are generally characterized in terms of the number per inch or centimetre, and can be controlled within the range 3–100 ppi. For example, there are three standard grades of Foseco's Sedex filters for cast iron alloys: the 10 ppi grade is for ductile and austenitic irons, the 20 ppi for grey iron and the 30 ppi for malleable iron. As indicated in Table 7.24, the capacity of these rectangular blocks depends both on their dimensions and on the alloy being filtered.

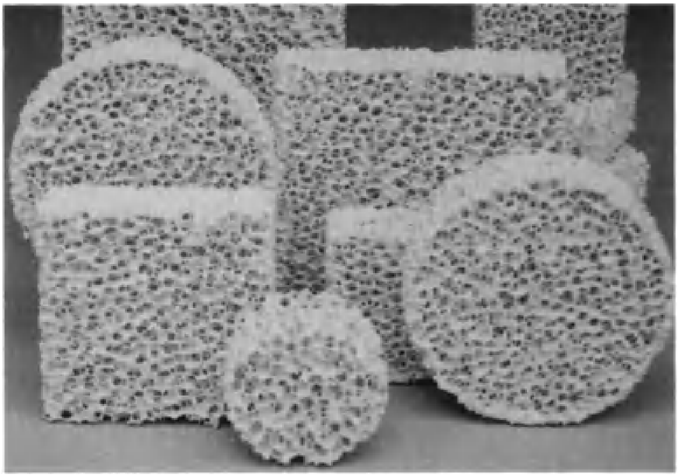

Figure 7.24. Examples of 'Stelex' ceramic foam filters for molten metals.

Table 7.24 Capacity of 'Sedex' ceramic foam blocks for filtering molten metal[a]

Block size (mm)	Surface area (cm^2)	Maximum capacity (kg)		
		Cast iron		Ni Resist/Inmold
		Grey iron	Spheroidal graphite	
35×35×22	12.5	50	25	12
35×50×22	17.5	70	–	–
50×50×22	25	100	50	25
50×75×22	37.5	150	75	37
50×100×22	50	200	100	50
75×75×22	56	200	100	50
100×100×22	100	400	200	–

[a] Foseco Ltd.

An approximate relationship between pore diameter and the number of pores is provided by Figure 7.25. An indication of air permeability as a function of the number of pores is given by the pressure drop curves at various face velocities in Figure 7.26. These figures relate to the ceramic foams produced by the Selee Corporation (now part of Porvair) from the variety of ceramic materials summarized in Table 7.25; comments on the applications of these foams are summarized in Table 7.26.

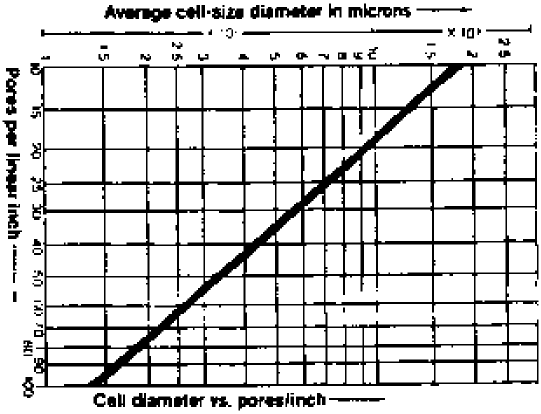

Figure 7.25. Relationship between pore diameter and pores per inch in ceramic foam.

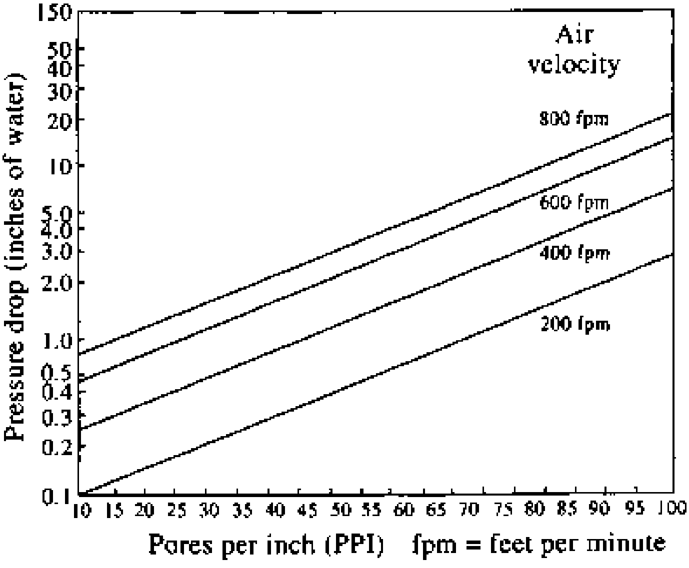

Figure 7.26. Relationship between pores per inch in ceramic foam and pressure with water flowing at various velocities.

Table 7.25 Typical properties of ceramic foams*

	Phosphate bonded alumina	Sintered alumina	Cordierite	Mullite	Partially stabilized zirconia	Zirconia alumina	Magnesia	Spinel	Silicon carbide
Chemical composition	Al_2O_3+ aluminium phosphate	99+%Al_2O_3	2 MgO 2 Al_2O_3 5 SiO_2	3 Al_2O_3 2 SiO_2	ZrO_2+CaO or MgO or Y_2O	65% partially stabilized ZrO_2 +35% Al_2O_3	MgO	MgO Al_2O_3	SiC
True density (g/cm^3)	3.9	4	2.5	3.2	5.4	5	3.6	3.6	3.2
Chemical resistance	Poor	Very good acids and bases	Fair	Good	Very good	Very good	Very good in bases	Good to very good	Very good
Max. use temperature °C (°F)	1430 (2600)	1650 (3000)	1100 (2000)	1540 (2800)	1760 (3200)	1700 (3100)	1650 (3000)	1650 (3000)	1540 (2800)
Thermal shock resistance	Fair	Fair to good	Excellent	Very good	Very good	Very good	Fair to poor	N/A	Very good to excellent
Compressive strength N/cm^2 (psi)	86 (125)	349 (506)	144 (209)	207 (300)	N/A	207 (300)	317 (460)	N/A	N/A
Bending strength N/cm^2 (psi)	35 (50)	86 (125)	64 (93)	69 (100)	N/A	69 (100)	86 (125)	N/A	N/A
Possible applications	1 Aluminium filtration	1 Ferrous, especially iron, filtration	1 Automotive catalyst substrates – catalytic converter and diesel particulate traps	1 Automotive substrates	1 Superalloy filtration	1 Ferrous filtration	1 Chemical industry	1 Magnesium filtration	1 High surface area heaters

Table 7.25 (*continued*)

	Phosphate bonded alumina	Sintered alumina	Cordierite	Mullite	Partially stabilized zirconia	Zirconia alumina	Magnesia	Spinel	Silicon carbide
	2 Non-ferrous filtration	2 High-melting non-ferrous filtration incl. reactive metals 3 Chemical industry filtration	2 High thermal shock applications	2 Chemical industry	2 Ferrous filtration 3 Chemical industry applications	2 Automotive substrates	2 Ferrous filtration 3 Magnesium filtration		2 Abrasives 3 High wear applications

[a] Selee Corporation.

7.5 Porous Carbon

Another range of coarse porous media may be formed either from elemental carbon, with its high chemical resistance and excellent thermal properties, or from activated carbon, the microporous structure of which provides

Table 7.26 Comments on applications of various ceramic foams[a]

Ceramic composition	Comments
Phosphate-bonded alumina and chromia/alumina	Used principally for the filtration of molten aluminium and its alloys. Usable to about 1400°C.
Sintered alumina	Direct bonding of high purity aluminium oxide grains by sintering results in a lower surface area than in phosphate-bonded material and low porosity. Very strong and resistant to high temperatures and chemical attack.
Cordierite	Especially well suited to severe thermal shock at temperatures below 1093°C, thanks to near-zero thermal expansion coefficient.
Mullite	Thermal expansion coefficient halfway between low level of cordierite and higher expansion of aluminas. Therefore reasonably good to thermal shock and can be used to much higher temperatures than cordierite.
Partially stabilized zirconia	An excellent combination of stability and resistance to both high temperature and thermal shock.
Zirconia-alumina	Far more thermally shock-resistant than alumina alone.
Magnesia	Advantages in non-acidic environments requiring a refractory body.
Spinal (magnesium aluminate)	Compatible with aggressive liquids, e.g. molten magnesium.
Silicon carbide	Relatively high thermal conductivity and electrical conductivity making them suitable for heating elements. Hard, highly abrasive and resistant to most acids and bases.

[a] Selee Corporation.

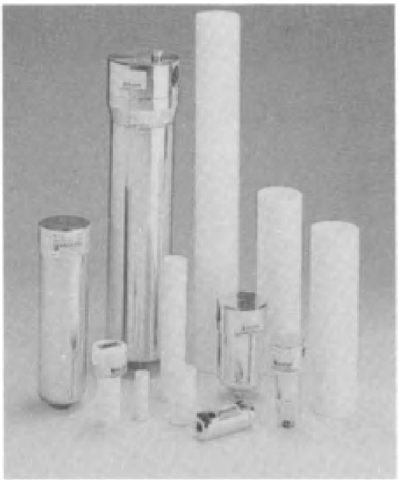

Figure 7.27. Balston filter tubes of glass microfibres.

Table 7.27 Properties of Schumacher carbon filter media[f]

Filter media		Filtration fineness (nominal) (µm)[a]	Pressure drop (mbar)[b]	Specific permeability (nPm)[c]	Porosity (%)	Density (%)	Linear expansion coefficient (10^{-6}·1/K)	Temperature resistance (°C)	Bending strength (Pa)	Bursting pressure (bar 10^5 Pa)	Test piece dimensions (mm) i.d./o.d.
Carbo	3	0.3	300	6.29	25	1.4	–	200[d], 1000[e]	7	60	Ø70/40
	5	0.5	200	9.43	30	1.35	–	200, 1000	7	60	Ø70/40
	10	1.5	80	2.34×10^1	40	1.2	–	200, 1000	6	17	Ø70/40
	20	2.5	40	4.69×10^1	40	1.15	–	200, 1000	4	12	Ø70/40
	30	3.5	20	9.44×10^1	40	1.1		200, 1000	3.5	10	Ø70/40
	40	ca 10.0	13	2.42×10^2	40	1.1	–	200, 1000	3	8	Ø120/70
Schumakat		–	40	6.29×10^1	60	0.7	–	180	–	–	Ø70/30
Schumasorb, AB, AC	5	0.5	2000	0.94×10^1	60	0.75	–	180	5.5	15	Ø70/40
	10	1.0	330	7.63	65	0.75	–	180	3.5	12	Ø70/30
	20	2.0	150	1.68×10^1	60	0.7	–	180	2.5	6	Ø70/30
Schumasorb AB	60	–	8	3.15×10^2	60	0.5	–	150	–	–	Ø70/30
Schumazin	20	2.0	150	1.68×10^1	60	0.7	–	180	2.5	6	Ø70/30

[a] Ambient air, particle counter.

[b] Air @ 250 m/min.

[c] 1 Nanoperm (nPm)=0.1013 darcy.

[d] Oxidizing atmosphere.

[e] Reducing atmosphere.

[f] Pall Inc/Schumacher.

exceptionally high surface areas. These two different types of media have very distinctive properties, as can be seen from examples summarized in Tables 7.27 and 7.28.

7.6 Glass Fibre Tubes

The final group of media involving inorganic materials is that employing glass. A distinctive use of the properties of glass microfibres is the range of Balston filter tubes (now supplied by Parker Hannifin). In essence, as shown in Figure 7.27,

Table 7.28 Schumacher range of carbon filter media

Trade name	Description
Carbo	Technically pure carbon and therefore very resistant to chemical reaction. Not attacked by hydrofluoric acid. Can be utilized over whole pH range 0–14. Stable in oxidizing atmospheres up to around 200°C and in reducing atmospheres to about 1000°C.
Schumakat	An open-pored sintered carbon element with low pressure loss, the support body is impregnated in catalytical substances. Used especially for catalytic reduction of hydrogen peroxide, e.g. in exhaust from packaging machines.
Schumasorb	Consists of highly porous activated carbon, stable over whole pH range 0–14.
Schumazin	Manufactured from chemically impregnated activated carbon. Its special value is for the removal of hydrazine from steam and water, together with the attendant neutralization of ammonia.

Table 7.29 Approximate dimensions of glass microfibre tubes[a]

Code	Outside diameter (mm)	Length (mm)
050-05	19	32
050-11	19	57
100-12	38	63
100-25	38	178
150-14	52	152
200-35	65	230
288-80	65	476
250-150	78	752

[a] Parker Hannifin Inc.

Table 7.30 Retention efficiencies of glass microfibre tubes[a]

Grade	Gas (retention of 0.1 µm) (%)	Water (98% retention of particle size) (µm)
D	93	25
C	98	8
B	99.99	2
A	99.9999+	0.9
AA	99.9999+	0.3

[a] Parker Hannifin Inc.

these are a simple form of cartridge, made from borosilicate glass microfibres, similar to those supplied by Whatman (the former owner of Balston) in its range of glass filter papers (see Chapter 4). Similar tubes are also produced from fibres of pure quartz, free of binders.

The borosilicate microfibres are bonded with either organic or inorganic binders to form tubes in five standard outside diameters (from 19 to 78 mm), with walls approximately 6 mm thick: lengths, as indicated in Table 7.29, range from 32 to 752 mm. Each is available in five standard grades, the filtration efficiencies of which are summarized in Table 7.30.

7.7 Selecting Coarse Porous Media

As the chapter's title implies, the media discussed here are not intended for the finest degrees of filtration, although some of them do achieve quite high filtration efficiencies. They find their main applications in preliminary filtration steps, or in the treatment of hot gases or of corrosive liquids.

In fact, temperature and corrosion are the guiding factors in choosing among these media: if the temperature of gas (or liquid) is above 120°C or so, or if the liquid (or gas) is at all corrosive, then the likelihood is that metal or ceramic will be used, rather than plastic, although PTFE materials are capable of resisting most corrosive liquids, and quite high temperatures.

A particular feature of some of these media is their use in the processing of molten materials, especially metals (for which ceramic foams are used) and polymers ahead of their being extruded or blown into film (for which sintered metal media are often used).

For the increasingly important process of cleaning hot dusty gases, the porous ceramic candle is really the only option available to the plant designer, and the fibre-based, low-density ceramic materials are developing fast to provide satisfactory process solutions.

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CHAPTER 8

Membranes

In filtration terms, membranes started as thin, flexible semi-permeable sheets of regenerated cellulose material, developed to separate species at the molecular and ionic level, their first main application being in the purification of salt and brackish waters by reverse osmosis. The word 'membrane' has stuck to a range of filter media that has expanded enormously from this early form, to embrace solid inflexible ceramic and sintered metal, and an ever-increasing group of polymeric materials, and to applications that now extend well into the microfiltration range. The existence of the membrane as a very effective filtration medium led to the development of the whole field of cross-flow filtration, which also now extends well beyond its reverse osmosis origins.

This chapter provides an introduction to the membrane as a filter medium, but makes no attempt to be a complete reference on membranes, even in filtration, let alone their wider uses. There is here a good deal of information about the ways in which membrane systems are used, but only enough to set the membrane media themselves in context. For a more complete reference to membranes of all kinds, the reader is directed to Keith Scott's *Handbook of Industrial Membranes*(1), on which the corresponding chapter of the first edition of this Handbook was largely based.

8.1 Introduction

The first edition of this Handbook defined membranes as follows:
'A membrane is a thin sheet of material which exhibits some degree of permeability to fluids thereby permitting phase or species separations to be affected for particles in the size range from a few microns down to molecules.'

Any attempt now to provide a succinct but comprehensive definition of a membrane is very much complicated by the immense and ever-growing diversity of membranes available, by the variety of mechanisms by which they function, and by the multiplicity of applications for which they are used. To many people, a membrane remains a thin flexible material, but in filtration terms the term now covers any medium that can achieve separations at 0.1 μm or below (down to molecular and ionic sizes), and which may be thick or thin, flexible or rigid, organic or inorganic. Many membranes are now employed in microfiltration applications at cut sizes well above 0.1 μm.

The membrane is essentially a surface filtration device, with little or no depth filtration involved in its use. In practice, many membranes are of asymmetric structure and effectively comprise two layers. The active, surface layer is a very thin skin, the permeability of which is of critical importance. The lower, thicker layer is of more open structure, its role being to serve as a mechanical support for the active layer.

This chapter looks firstly at the way membranes are used in filtration applications, and then at the nature of membrane media, and the ways in which they are made. A brief look at membrane characterization is followed by a review of some typical membrane media available on the market, and some guidance as to their selection. It is primarily concerned with the use of membranes in particulate separations, i.e. in microfiltration, but membrane media are now used in such a wide spectrum of applications, with considerable overlap among what were once clearly separate uses, that these other applications are covered here as well.

The membrane represents probably the fastest growing part of the filtration media market (especially if ceramic membranes for hot gas filtration are included). The most important of the changes in the membrane business since the first edition of this Handbook are:

- the extension of membrane media into microfiltration applications;
- the growth in importance of expanded PTFE as a membrane material;
- a corresponding growth of ceramic materials for membranes; and
- the development of techniques for the increase of stabilised fluid flux by the disturbance of boundary layers at the membrane surface.

8.2 Membrane Systems

In order to gain a good grasp of the nature and use of filtration membranes it is first necessary to look at the way in which membranes are used, both in process terms, and in their actual structural format. The fine surface structure of all membranes implies the need for significant pressure drops across the medium in order to achieve adequate fluid fluxes. As a result, membranes need to be contained in pressure-tight housings, and considerable ingenuity is required of the suppliers to achieve sound and efficient operation.

8.2.1 Membrane processes

Historically, membranes were first developed to work at the lowest size levels of separation, the removal of salts, i.e. ionic species, from water at quite high flow rates to produce water of drinkable quality. This application required high working pressures, but over the subsequent years the membranes have become 'looser', and the pressures required have become less, as the membrane has been used for separations at progressively higher sizes – because membranes have decreased in cost, and so become attractive for an increasingly wide range of applications. The broad spectrum of membrane processes is illustrated in Figure 8.1.

The highest levels of permeability correspond to membranes of relatively coarse microporous structure that permit the transmission of liquids that can be solutions of macromolecules; they reject fine suspended solids down to less than 0.1 μm by *microfiltration* at relatively low differential pressures (1–4 bar). Less permeable membranes, of finer microporous structure, allow passage of solutions of smaller molecules and ions; functioning by *ultrafiltration* at differential pressures up to about 10 bar, they reject finer particles and molecules of molecular weight above about 10 000. Membranes in these two categories (microfiltration and ultrafiltration) are the main theme of this chapter.

Contrasting with these are the semi-permeable membranes of *reverse osmosis* (or hyperfiltration), the asymmetric structure of which incorporates a thin non-porous homogeneous skin; under pressures of 30–60 bar, these membranes are capable of the finest possible level of separation, including the rejection of dissolved salts, and the complete removal of bacteria, pyrogens and organics from water. *Nanofiltration* is essentially a form of reverse osmosis operating at pressures in the range 20–40 bar, using a 'looser' membrane so as to restrict rejection to molecules in the molecular weight range 300–1000, and to larger ions (such as Ca^{2+} and Mg^{2+}), and the very finest particles.

These four specifically liquid filtration-related membrane processes are shown in Figure 8.2, with main applications for each. It should be noted that the separation size ranges overlap at each end.

Membranes incorporating thin layers of dense non-porous material utilize *gas permeation* to separate gases (such as hydrogen recovery from refinery exit streams, or the separation of oxygen and nitrogen from air), and *pervaporation* to separate miscible liquids, as an alternative to fractional distillation. Yet other mechanisms, utilizing electrically charged or ion exchange membranes, are involved in processes such as *electrodialysis*, and in fuel cells.

The full range of membrane processes is listed in Table 8.1, with typical membrane types, and associated driving forces and typical applications.

It should be noted that the use of the term 'non-porous' in the above definitions relates to the impossibility of the flow of fluids carrying particles through continuous open pores in the medium. Such materials are still permeable to molecular or ionic species by means of diffusion through the solid mass of the non-porous layer.

Because of the very fine nature of the membrane media, it is normal practice to employ a filter, ahead of the membrane unit, that is intended to remove any particulate material that might interfere with the membrane process. This is especially necessary where the flow passages are very narrow, such as in hollow fibre membranes. In fact, some membranes themselves are used as prefilters to membranes operating at a finer degree of separation. Thus there will normally be a microfilter ahead of an ultrafiltration or reverse osmosis membrane, but there may also be an ultrafiltration membrane ahead of a reverse osmosis step.

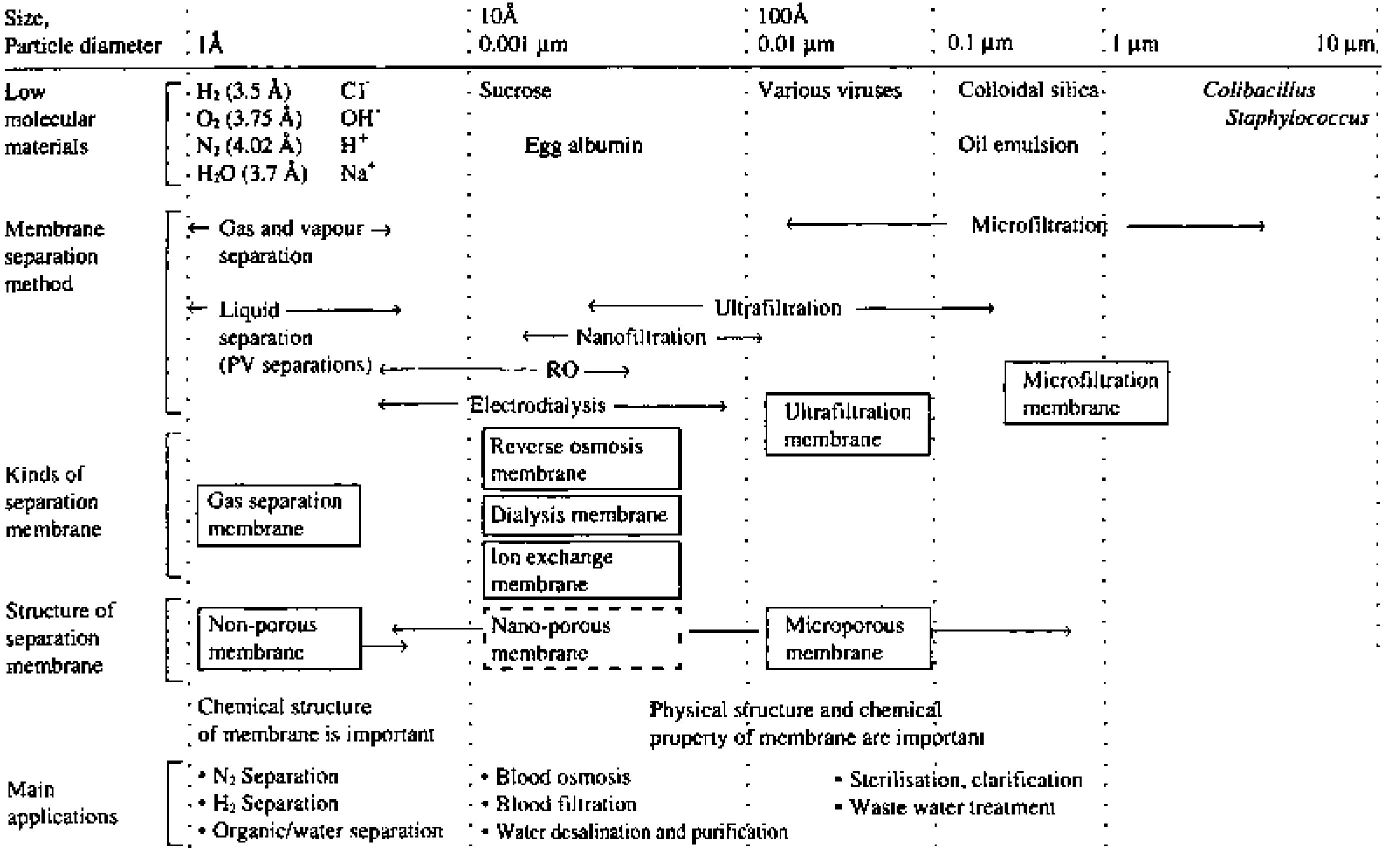
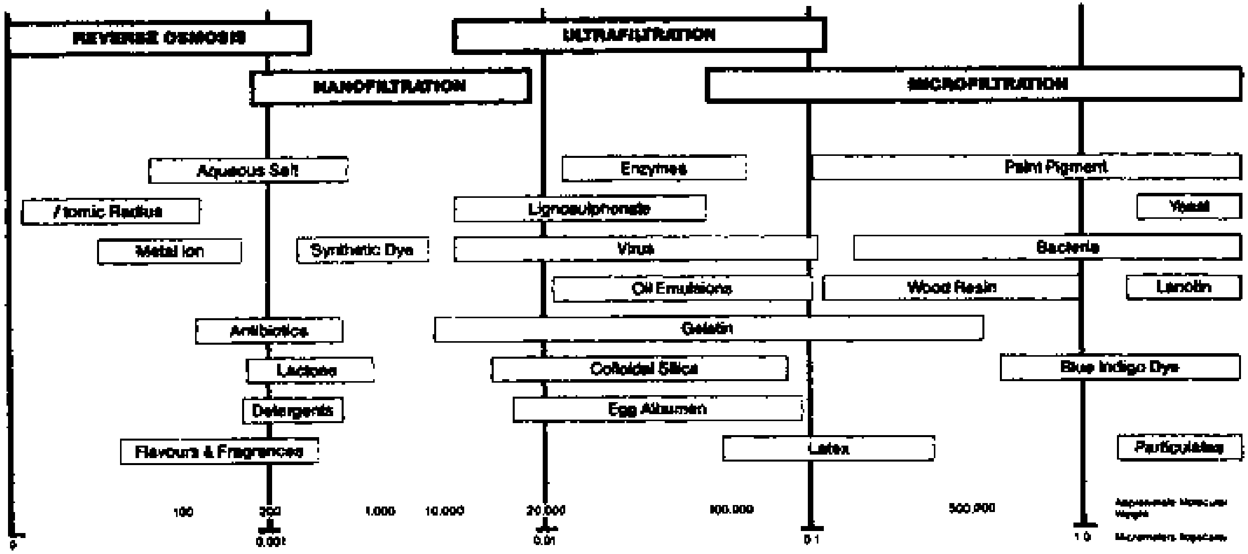


Figure 8.1. An overview of membrane separation technology.



Pressure, bar	30-60	20-40	5-10	1-4
Applications	demineralisation dewatering concentration	demineralisation dewatering concentration	fractionation sugar removal concentration clarification	clarification

Figure 8.2. Summary of membrane liquid filtration processes.

8.2.1.1 Operational modes

Two distinct modes of filtration are relevant to membrane media, as shown schematically in Figure 8.3. *Dead-end* (or through-flow) *filtration* is the conventional mode for all filtration, with the feed flow perpendicular to the membrane surface; essentially all of the fluid passes through the membrane whilst the separated particles accumulate on its surface as a layer of retained solids. This build-up of solid particles leads to a progressive increase in the resistance to filtration through the membrane, to the point where flow eventually stops.

Table 8.1 Membrane separations and materials

Membrane separation	Membrane type	Driving force	Applications
Microfiltration	Symmetric and asymmetric microporous	Hydrostatic pressure	Clarification, sterile filtration
Ultrafiltration	Asymmetric microporous	Hydrostatic pressure	Separation of macro-molecular solutions
Nanofiltration	Asymmetric	Hydrostatic pressure	Separation of small organic compounds and selected salts from solutions
Reverse osmosis or hyperfiltration	Asymmetric, composite with homogenous skin	Hydrostatic pressure	Separation of micro-solutes and salts from solutions
Gas permeation	Asymmetric or composite, homogenous or porous polymer	Hydrostatic pressure concentration gradient	Separation of gas mixtures
Dialysis	Symmetric microporous	Concentration gradient	Separation of micro-solutes and salts from macromolecular solutions
Pervaporation	Asymmetric, composite non-porous	Concentration gradient, vapour pressure	Separation of mixtures of volatile liquids
Vapour permeation	Composite non-porous	Concentration gradient	Separation of volatile vapours from gases and vapours
Membrane distillation	Microporous	Temperature	Separation of water from non-volatile solutes
Electrodialysis	Ion exchange, homogeneous or microporous polymer	Electrical potential	Separation of ions from water and non-ionic solutes
Electrofiltration	Microporous charged membrane	Electrical potential	Dewatering of solutions of suspended solids
Liquid membranes	Microporous, liquid carrier	Concentration, reaction	Separation of ions and solutes from aqueous solutions

The formation of this surface filter cake can be reduced or eliminated by the use of tangential or *cross-flow filtration*. Only part of the fluid now passes through the membrane as filtrate (or, more correctly, permeate, since some membrane processes operate by permeation rather than filtration); the retained part, or retentate, consequently becomes more concentrated in particulate or solute species. The extent to which cross-flow successfully prevents the surface of the membrane being fouled by deposited particles is dependent on a variety of factors, especially the cross-flow velocity. Chemical and/or mechanical procedures are usually required to clean (and sterilize) the membrane, which must be able to withstand the associated mechanical, chemical and thermal stresses. Whereas microfiltration utilizes both the dead-end and cross-flow filtration, cross-flow is the usual mode for the other membrane filtration processes, and has grown to its present level of importance from its beginnings in reverse osmosis.

8.2.1.2 Operational problems

The build-up of a 'fouling' layer on the surface of a membrane is one of the most serious problems in membrane processes. The term 'fouling', rather than the more familiar 'filter cake', arose from the origins of membrane processes in molecular separations, where macromolecular proteins would separate on to the membrane surface as a slimy, gel layer, which rapidly reduced the fluid flux through the membrane. Fouling layers have to be removed periodically by cleaning, as mentioned above, but much ingenuity is employed by membrane system designers to minimize fouling layer formation.

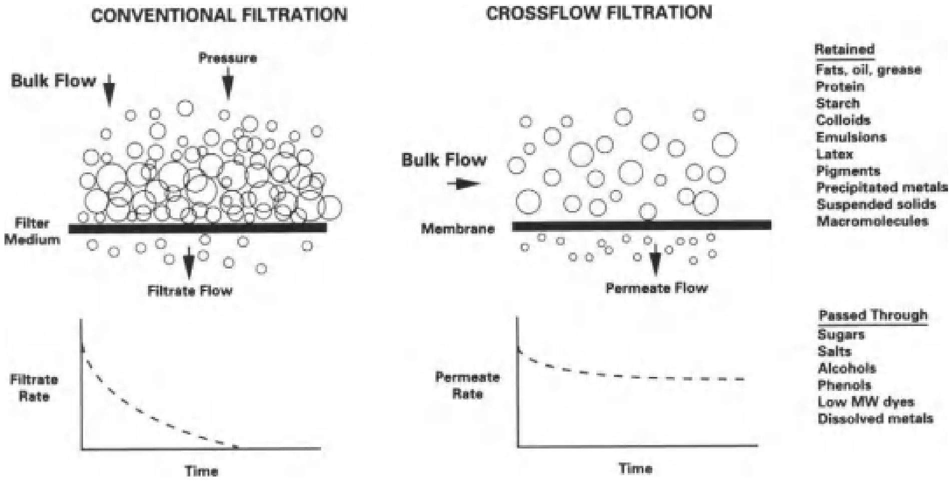


Figure 8.3. Comparing cross-flow filtration with conventional filtration.

Another operating problem, concentration polarization, affects the membrane processes dealing with suspended or dissolved species. The molecules to be separated (i.e. kept in the retentate) diffuse through the liquid close to the membrane surface and become much more concentrated at the surface, creating a different kind of barrier to liquid flow, and so reducing flux. In the same way, the particulate matter accumulates in the liquid as it approaches the boundary layer, creating a similar resistance to liquid flow.

There are basically three types of method employed to reduce fouling and/or concentration polarization, and so increase flux rates:

- changes in the surface characteristics of the membrane;
- conditioning of the feed slurry/solution; and
- modifications in the way the fluid/membrane is operated.

An example of the way in which the membrane material itself may be modified is given by Kalsep's Kalmem LF membrane[2]. This is basically a polyethersulphone (PES) material, with polymeric low-fouling additives incorporated into the PES. The chemically modified surface is permanently hydrophilic, and can be made with pore sizes in the microfiltration and ultrafiltration ranges.

The surface of the membrane needs to be as smooth as possible, and the slurry or solution as free as possible of material that will foul the surface. Operational modifications are generally designed to create some kind of shearing or scouring of the fouling layer. Some of these are mechanical, and are discussed in the next section, while the use of a two-phase (gas/liquid) flow[3] is growing in importance.

8.2.2 Membrane formats

Depending on the properties of the material used, membranes may be produced in the following geometrical forms:

- flat sheets – self-supporting or backed by a supporting substrate (and including the sheets when rolled up into a spiral-wound configuration);
- tubes – self-supporting or backed by a supporting substrate, typically 12–24 mm in internal diameter; and
- hollow fibres – typically 40 µm internal diameter × 80 µm outside diameter.

All of these forms are mostly utilized by being incorporated in filter cartridges, such as are described in Chapter 9. Some of the more robust types of membrane sheets can be used in industrial process filters such as filter presses. For laboratory duties, sheet membranes are available as discs in a range of standard diameters; appropriate grades are also supplied in roll form.

Because of the high fluid flow resistance of most membranes, they are usually operated in some kind of module, which allows the largest possible filtration area to be packed into the smallest possible equipment volume. There are six distinct styles of module in which membrane media are employed: flat sheet, pleated sheet, spiral wound sheet, tubes or tube bundles, perforated blocks and hollow fibre bundles. Polymeric membranes are used in almost all forms – except the perforated block, which is very largely restricted to inorganic materials.

Flat sheet modules are based on the principle of the plate-and-frame filter press, comprising an alternating stack of sheets of membrane media and separator plates through which the feed, retentate and permeate flow. These are the least compact of the different module formats, and are correspondingly the least used. Figures 8.4 and 8.5 show, respectively, a laboratory and a free-standing industrial flat sheet module of this type, which can be used for microfiltration or ultrafiltration. Most polymeric materials, and much of the inorganic materials are available as flat sheets or rolls, and can be used in this type of module, which finds most application in laboratory and pilot plant. For example, Tami Industries KaCeram media are available for microfiltration in the range 0.14–1.4 μm, and for ultrafiltration in the range 15–300 kD.

If the flat sheet medium is sufficiently flexible, then it can be pleated, just as can any other paper-like material. In this way, a membrane can be used for absolute air filtration, as in Chapter 5, as a filter bag for gas cleaning or as a cartridge filter, as described in Chapter 9. Pleating is possible for most polymeric media, for some metallic media, and even for some ceramics.

Membrane materials can also be made or cut into long, wide strips, which are then rolled up around a central former, with appropriate sheets of spacers and

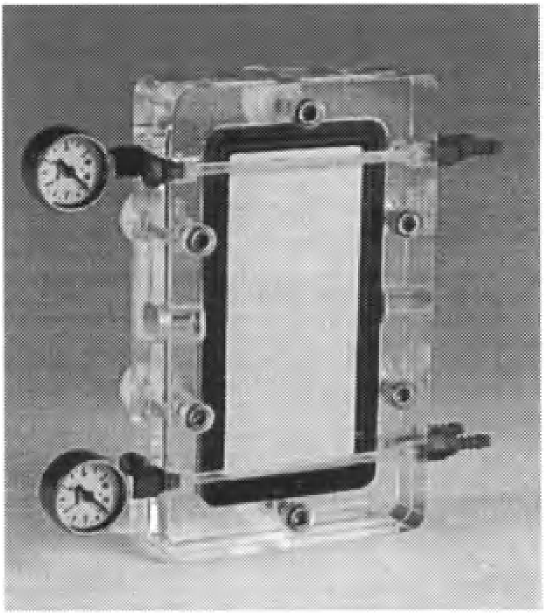


Figure 8.4. A laboratory scale 'Pleiade Rayflow 100' cross-flow filter with a membrane area of 100 cm². (Photograph: Ultra-Tech Services Ltd)

supports sandwiched between the membrane layers, to create a *spiral wound module*, as illustrated in Figure 8.6. Such a construction gives a very compact unit containing a large membrane area. For example, a module that is just 200 mm in diameter and 900 mm long may contain up to 23 m^2 of active membrane. Because the sandwich structure operates with very small clearances between the sheets, it is essential that adequate prefiltration is undertaken of the feed liquid. Spiral wound modules are used for microfiltration and ultrafiltration.

Simple tubes are feasible as membrane formats, but unlikely outside the laboratory, because of their small area. Much more likely, on the industrial scale, are *tubular modules*, with bundles of tubes constructed in the same form as a shell-and-tube heat exchanger, as shown in Figure 8.7. In the version illustrated, each replaceable 12.5 mm diameter membrane tube fits into a perforated stainless steel support tube. The membrane tubes, which can be several metres in length, are of composite construction, with, for example, a cellulose acetate membrane cast on to the internal surface of a synthetic fibre support tube.

An alternative approach is offered by the three options illustrated in Figure 8.8, all of these being disposable items. The single 25 mm i.d. tube version has an inside layer of PES membrane cast onto an epoxy resin reinforced fibreglass support, with an outside protective tube of PVC. The Ultra-cor VII tube is divided internally by a bundle of seven 12.5 mm membrane tubes, thereby increasing the available filtration are a per unit length; this concept is extended further in the Super-cor tube, with its array of 21 internal tubes.

The tubular formats are the ones most likely to be adopted for inorganic media, especially for ceramics, where the idea is further extended into the *perforated block* structure illustrated in Figure 8.9. A monolithic block, of very coarsely porous ceramic, shaped to fit into a containing tube, is perforated with a number of cylindrical channels parallel to its length. A ceramic membrane layer is then

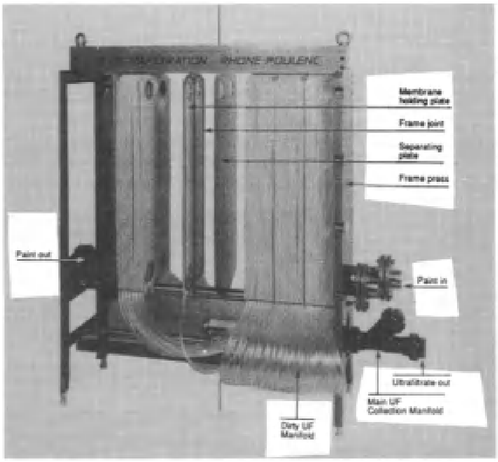


Figure 8.5. A 'Pleiade' UFP21 ultrafiltration filter, with a total membrane area up to 21 m^2 can be used on applications such as recovering paint from a car spraying unit.

laid down on the inner surface. A very wide range of channel number and shape is possible with this kind of construction – the range currently marketed by Tami Industries covers 14 different shapes, with up to 39 individual channels offering hydraulic diameters from 2 to 14 mm. These all have quite thin walls through which the permeate must pass.

Hollow fibre modules are also in the basic format of a shell-and-tube heat exchanger, but now the tubes are hollow fibres with outside diameters ranging from a few millimetres down to as fine as a human hair (about 80 μm). These fibres, which may be several hundreds in number, are assembled as a closely packed bundle, sealed at its ends into resin plugs, either at opposite ends of the containing shell, as in Figure 8.10, or with the bundle looped round and the ends sealed into the same plug, as in Figure 8.11. As indicated by these two figures,

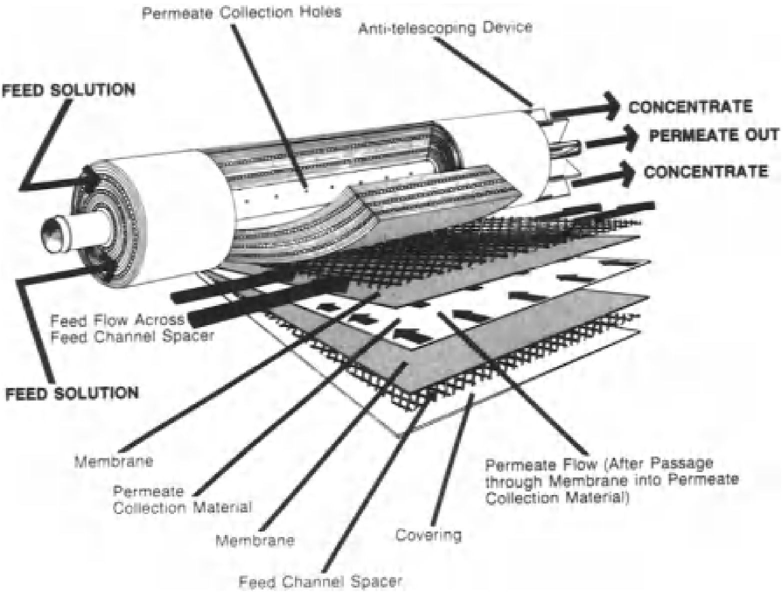


Figure 8.6. A spirally wound MF or UF module.

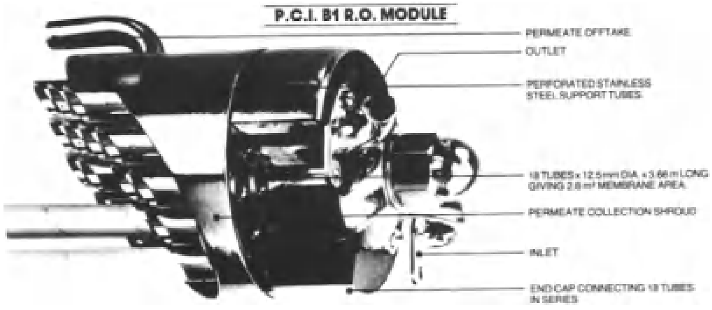


Figure 8.7. Part of a PCI tubular RO module.

the fluid to permeate flow direction can be either in-to-out or out-to-in for hollow fibre applications.

A great advantage of the hollow fibre module is its compactness in relation to its very large filtration area per unit volume, typically 8000 m^2/m^3. For example, with a Koch standard 1.09 m long, 0.127 m diameter module, the membrane area is 3.7 m^2 with 2.7 mm diameter fibres, and 12.3 m^2 with 0.5 mm fibres.

A general comparison of the main types of membrane module is provided in Table 8.2.

In all of the module designs discussed above the membrane medium is stationary, and the fluid flows across (or occasionally through) it. However, as stated earlier, the problems of fouling and concentration polarization can be at

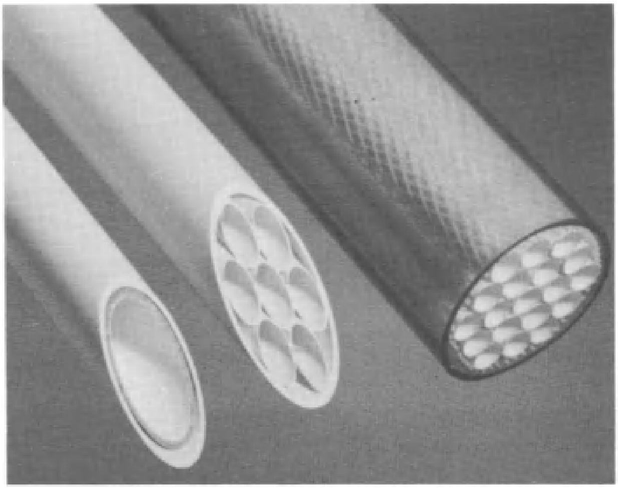


Figure 8.8. Tubular MF/UF/RO options: single tube, 'Ultra-cor VII' and 'Super-cor'.

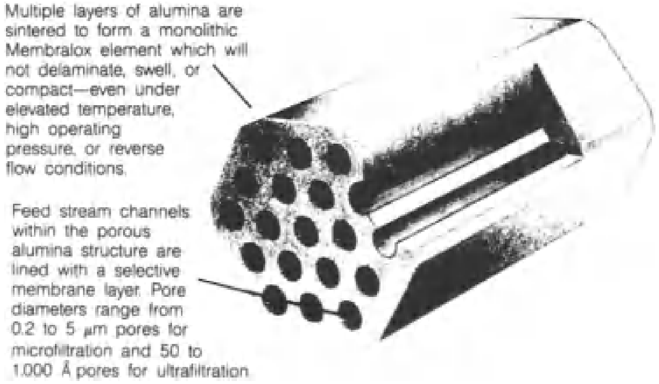


Figure 8.9. Sectional view of a 19-channel ceramic element. (Illustration: APV Membrantechnologie GmbH)

least partly reduced if an element of shear can be applied to the boundary layer at the membrane surface. This can be achieved either by causing the membrane to rotate or oscillate with relation to the fluid flow. Still very much in the development phase, the rotating moving membranes can be in the form of a disc(4) or a cylinder(5), while a stack of discs is caused to oscillate in another variant(6), which has reached commercial use. SpinTek Filtration Systems introduced a rotating ultrafiltration unit, using a ceramic membrane, into commercial use in mid-1999.

8.3 Membrane Materials

To be effective for separation, membranes should exhibit appropriate characteristics, such as good chemical resistance (to both feed and cleaning fluids), mechanical stability, thermal stability, high permeability, high selectivity and general stability in operation; for guidance on the chemical compatibility of membrane materials, see Table 8.3 (originating with Millipore Inc), or the more detailed Table 2.4 for fabrics in Chapter 2.

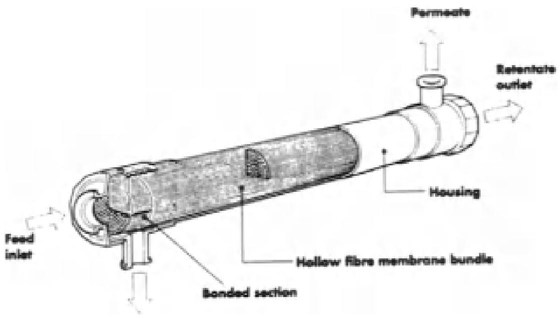


Figure 8.10. A hollow tube module with in-to-out flow.

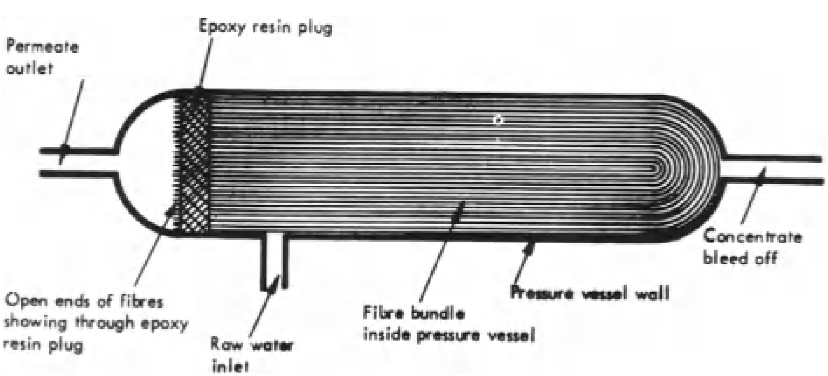


Figure 8.11. A hollow tube RO module with out-to-in flow.

Table 8.2 General comparison of characteristics of membranes

Tubular membranes

1. Tubular modules have relatively large channel diameters, and are capable of handling feed streams and slurries containing fairly large particles. The general rule of thumb is that the largest particle that can be processed in a membrane module should be less than one-tenth the channel height. Thus feed streams containing particles as large as 125 µm can be processed in 1.25 mm tubular units.
2. Tubular units of 1.25–2.5 cm diameters are operated under turbulent flow conditions with recommended velocities of 2–6 m per second. Flow rates are 15–60 l per minute per tube, depending on the tube diameter. Reynolds numbers are usually greater than 10 000.
3. Pressure drop averages 2–3 psi per 2.4–3.6 m tube. Thus, typical pressure drops for 12–25 mm tubes will be approximately 30–40 psig (2–2.5 bar) for UF units operating in parallel flow under these flow conditions. This combination of pressure drop and high flow rates gives high energy consumption.
4. The open tube design and the high Reynolds numbers make it easy to clean by standard clean-in-place techniques. It is also possible to insert scouring balls or rods to help clean the membrane.
5. Tubular units have the lowest surface area to volume ratio of all module configurations.
6. In certain modules the individual membranes can be replaced fairly easily in plant resulting in considerable savings in transportation costs and membrane costs.
7. Tubular module costs vary widely from about \$100 to 800/m^2 for replacement membranes of cellulose acetate, polysulphone or composites.

Hollow fibre modules

1. The recommended operating velocity in the UF hollow fibre system is around 0.5–2.5 m/s. This results in Reynolds numbers of 500–3000. Hollow fibres thus operate in the laminar flow region.
2. Shear rates are relatively high in hollow fibres due to the combination of thin channels and high velocity. Shear rates at the wall are 4000–14 000/s.
3. Hollow fibres have the highest surface area-to-volume ratio. Hold-up volume is low, typically 0.5 l in a typical 'short' cartridge of 1.4–1.7 m^2 membrane area.
4. Pressure drops are typically 0.3–1.3 bar depending on the flow rate. The combination of modest pressure drop and flow rates make hollow fibre modules very economic in energy consumption.
5. Hollow fibres have only a modest maximum pressure rating of about 1.8 bar. The short (30 cm) cartridge can withstand pressures up to about 2.4 bar at low temperatures (less than 30°C). Several process streams are dilute enough to permit UF operation at pressures much higher than the present 1.7 bar limiting transmembrane pressure. In addition, since the flow rate is proportional to pressure drop, flow rates are limited since the inlet pressure cannot exceed 1.7 bar. This can be problematic with highly viscous solutions, especially with long cartridges.
6. The small fibre diameters make them susceptible to plugging at the cartridge inlet. To prevent this the feed should be prefiltered to at least 10 µm.
7. Hollow fibres are suitable for 'back-flushing' because the fibres are self-supporting. This vastly improves performance due to cleaning *in situ* potential.
8. Replacement membrane costs are relatively high. Damage to one single fibre out of the 50–3000 in a bundle generally means the entire cartridge has to be replaced. However, it is possible to repair membrane fibres *in situ* in certain cases.
9. The cost is about \$700 per 7.5 cm industrial cartridge, regardless of surface area. Replacement cost is about \$230–350/m^2.

Plate

1. The typical plate channel height is between 0.5 and 1.0 mm. UF systems operate under laminar-flow, high shear conditions. The channel length (the distance between the inlet and outlet ports) is between 6 and 60 cm. The Grober equation agrees reasonably well with experiment in the Reynolds number range of 100–3000 for slits of channel height 0.4–1.0 mm.

Table 8.2 (continued)

2. The permeate from each pair of membranes can be visually observed in the plastic tubing coming from each support plate. This is convenient for several reasons, e.g. detection of leaks in a particular membrane pair, if samples need to be taken for analysis, or if flux measurement as a function of capacity needs to be made.
3. Replacement of membranes on site is relatively easy provided that care is taken when closing the stack of plates together. The previously embedded grooves of the unreplaced plates must match exactly as they were previously, or else leakage of feed can occur.
4. In horizontal modules, the flow is parallel through all channels at velocities of about 2 m/s. For a stack of plates, this can result in a pressure drop of about 10 bar. Plate-and-frame systems tend to be intermediate between spiral-wound and tubular systems in energy consumption for recirculation.
5. Membranes are currently about $120/m² for cellulose acetate, $230/m² for non-cellulosic RO membranes, and $140/m² for polysulphone membranes.
6. Surface area-to-volume ratio is fairly high, averaging about 600–1000 m²/m³.

Spiral wound

1. In spiral-wound modules the feed channel height is controlled essentially by the thickness of the mesh-like spacer in the feed channel. Spacers of 0.76 or 1.1 mm are most common. The advantage of a narrow channel height is that much more membrane area can be packed into a given pressure vessel.
2. A larger channel height, while reducing the surface area-to-volume ration slightly, may be more desirable to minimize pressure drops and reduce feed channel plugging. The general rule of prefiltering to one-tenth the channel height is modified for the spiral-wound unit due to the presence of the spacer which reduces the free volume in the channel. Prefiltration of the feed down to 5–25 μm is recommended for the 0.76 mm spacer-module, and 25–50 μm for the 1.1 mm channel.
3. Lengths of individual membrane assemblies vary from 1 to 6 feet (0.3–2 m). When calculating the surface area of a spiral-wound membrane, it is convenient to consider it as two flat-sheets, although the *effective* membrane area of spiral-wound modules must allow for gluing the membrane sandwich, for fixing the fourth side to the permeate collection tube and the outer periphery.
4. The hydrodynamics in the spiral-wound module is not too clear. The velocity in spiral-wound units ranges from 10 to 60 cm/s, being higher for the large mesh spacers. These are 'superficial' velocities, however, since the volume occupied by the mesh-like spacer in the feed channel is neglected. These velocities correspond to Reynolds numbers of 100–1300. Technically, this is in the laminar flow region, but the additional turbulence contributed by the spacers means that the flow is in the turbulent region.
5. Surface area-to-volume ratio is fairly high, averaging about 600–1000 m²/m³.
6. Pressure drops in the feed channel are relatively high due to the effect of the spacer. At a superficial velocity of 25 cm/s the pressure drop is around 1–1.4 bar. This high pressure drop can give rise to a 'telescoping' effect at high flow rates, i.e. the spiral pushes itself out in the direction of flow. This can damage the membrane and so anti-telescoping devices are used at the downstream end of the membrane element to prevent this.
7. The combination of the low flow rates, pressure drops and relatively high turbulence makes this an economic module in terms of power consumption. A problem with the mesh spacers is the creation of 'dead' spots directly behind the mesh in the flow path. This may cause particles to 'hang up' in the mesh network, resulting in cleaning problems. This makes it difficult to process feeds containing suspended particles, especially if it is a concentrated slurry and a high recovery of the particles is required. Spiral modules work best on relatively clean feed streams with a minimum of suspended matter.
8. Capital costs are quite low. The membrane element can be recovered from the pressure vessel and returned to the factory for reassembling new membranes. Replacement membranes are priced typically at $35–140/m² for cellulose acetate, polyvinylidenedifluoride, and polysulphone membranes.

Table 8.3 Chemical compatibility of membrane materials

	Cellulose acetate	Hydrophobic PVDF	Hydrophilic PVDF	MF-Millipore cellulose esters	Fluoropore PTFE	Mitex PTFE	Isopore PC polycarbonate	Isopore PET polycarbonate	AN and PP polypropylene
Acids									
Acetic acid, glacial	X	●	●	X	●	●	O	●	●
Acetic acid, 5%	●	●	●	●	●	●	●	●	●
Boric acid	●	●	●	●	●	●	●	–	●
Hydrochloric acid (conc.)	X	●	●	X	●	●	●	X	●
Hydrofluoric acid	X	●	●	X	●	●	●	X	O
Nitric acid (conc.)	X	O	X	X	O	●	●	X	O
Sulphuric acid (conc.)	X	●	X	X	O	●	X	X	●
Bases									
Ammonium hydroxide (6N)	X	●	X	X	●	●	X	O	●
Sodium hydroxide (conc.)	X	●	X	X	●	●	X	X	●
Solvents									
Acetone	X	X	X	X	●	●	O	●	●
Acetonitrile	X	●	O	X	●	●	–	–	O
Amyl acetate	X	●	●	X	●	●	●	●	X
Amyl alcohol	X	●	●	X	●	●	●	●	●
Benzene	X	●	●	●	O	●	O	●	O
Benzyl alcohol (1%)	O	●	●	●	●	●	●	●	
Brine (sea water)	●	●	●	●	●	●	●	●	●
Butyl alcohol	●	●	●	●	●	●	●	●	O
Carbon tetrachloride	X	●	●	●	O	●	O	●	X
Cellosolve (ethyl)	X	●	●	X	●	●	–	●	O
Chloroform	X	●	●	●	O	●	X	●	O
Cyclohexanone	X	●	●	X	●	●	●	●	X
Dimethylacetamide	X	X	X	X	●	●	–	–	O
Dimethylformamide	X	X	X	X	●	●	X	●	●
Dioxane	X	●	●	X	●	●	X	●	O
DMSO	X	●	●	X	●	●	X	●	●
Ethyl alcohol	●	●	●	O	●	●	●	●	●
Ethers	O	●	●	●	●	●	●	●	X
Ethyl acetate	X	●	●	X	●	●	O	●	●
Ethylene glycol	●	●	●	X	●	●	●	●	●
Formaldehyde	●	●	●	X	●	●	●	●	●
Freon TF or PCA	X	●	●	●	●	●	●	●	X
Gasoline	X	●	●	●	●	●	●	●	●
Glycerine (glycerol)	●	●	●	●	●	●	●	●	●
Hexane	X	●	●	●	●	●	●	●	●
Hydrogen peroxide (3%)	X	●	●	X	●	●	●	●	●
Hypo (photo)	–	●	●	●	●	●	–	●	●
Isobutyl alcohol	●	●	●	●	●	●	●	●	●
Isopropyl acetate	O	●	●	X	●	●	–	●	●
Isopropyl alcohol	●	●	●	X	●	●	●	●	●
Kerosene	X	●	●	●	●	●	●	●	

Table 8.3 (*continued*)

	Cellulose acetate	Hydrophobic PVDF	Hydrophilic PVDF	MF-Millipore cellulose esters	Fluoropore PTFE	Mitex PTFE	Isopore PC polycarbonate	Isopore PET polycarbonate	AN and PP polypropylene
Methyl alcohol	●	●	●	X	●	●	●	●	●
Methylene chloride	X	X	●	X	O	●	X	●	X
MEK	X	X	X	X	●	●	O	●	●
MIBK	X	●	X	X	●	●	–	–	●
Mineral spirits	X	●	●	●	●	●	●	●	●
Nitrobenzene	X	●	●	X	●	●	X	●	●
Paraldehyde	X	●	●	X	●	●	–	–	–
Ozone (10 ppm in water)	X	●	●	●	●	●	●	●	●
Pet base oils	X	●	●	●	●	●	●	–	–
Pentane	X	●	●	●	●	●	●	●	X
Perchloroethylene	X	●	●	●	O	●	●	●	X
Petroleum ether	X	●	●	●	●	●	●	●	X
Phenol (5.0%)	X	●	●	●	●	●	–	●	●
Pyridine	X	●	●	X	●	●	X	●	●
Silicon oils	X	●	●	●	●	●	●	●	●
Toluene	X	●	●	●	O	●	O	●	O
Trichloroethane	X	●	●	●	O	●	O	●	X
Trichloroethylene	X	●	●	●	O	●	X	●	X
TFA	X	●	O	X	●	●	–	–	●
THF	X	●	●	X	●	●	X	●	O
Xylene	X	●	●	●	O	●	●	●	O
Gases									
Helium	X	●	●	●	●	●	●	●	●
Hydrogen	X	●	●	●	●	●	●	●	●
Nitrogen	X	●	●	●	●	●	●	●	●
Ozone	X	X	X	X	X	●	●	O	O

Codes: ● = recommended; O=limited applications, testing prior to use is recommended;
X=not recommended.

Recommendations are based upon static soak for 72 h at 25°C and atmospheric pressure. Dynamic (operating) conditions at moderate (±10%) fluctuation will not change the recommendations, but high liquid temperature may do so in some cases.

8.3.1 Range of membrane materials

Originally, all membranes were based on natural materials or derivatives of natural cellulose. Whilst cellulosic media continue to play an important role in certain areas of application, the major source of membranes is now synthetic polymers, some of which are included in Table 8.4. There is an immense variety of polymeric materials available as filter media, including grades with specially

Table 8.4 Typical characteristics and applications of microfiltration membranes

Material	Characteristics	Typical applications
Polysulphone	An inherently hydrophilic polysulphone membrane with excellent flow rates, low extractables, broad chemical compatibility, high mechanical strength and temperature resistance.	Food and beverages Pharmaceuticals Semiconductor water Serum
Nylon	Hydrophilic membrane with high tensile strength. Very high flow rates, long life and low extractables. Offers excellent chemical compatibility.	Semiconductor water Chemicals Beverages
PTFE	Naturally hydrophobic membrane laminated to a polypropylene support for extra durability and strength. Superior chemical and temperature resistance.	Air and gases Pharmaceuticals Aggressive chemicals
Acrylic copolymer	Inherently hydrophilic copolymer with strong nonwoven polyester fabric support. Offers high flow rates, low differential pressures and low extractables.	Semiconductor water Pharmaceuticals Food and beverages
Polypropylene	Naturally hydrophobic membrane and chemically inert. Broad pH stability, high temperature resistance and high flow rates.	Chemicals Microelectronics Pharmaceuticals
Glass	Nominal 1.0 mm fine borosilicate glass fibre. High flow rates at moderate differential pressures. Good wet strength and high dirt-holding capacity.	Chemicals Serum Beverages
Polycarbonate	Hydrophilic membrane, unique pore structure and capture, strong, flexible, high flow rate, thermal stability, non-extractable.	Pharmaceuticals Air pollution Laboratory analysis
Cellulose	Hydrophilic membrane. General purpose, with limited thermal and mechanical stability. Some extractables.	Air pollution Microbiology Foods and pharmaceutical

developed properties: hydrophobic or hydrophilic, anionic or cationic, for specific filtration applications.

The range of synthetic polymers used for membrane media includes:

- acrylics
  - polyacrylonitrile (PAN)
  - acrylic copolymers
- amides and imides
  - nylons and aliphatic polyamides
  - polyaramids (aromatic amides)
  - polyimide and polyetherimide (PEI)

- esters
    polycarbonate (PC)
    polyethylene terephthalate (PET) and polybutylene terephthalate (PBT)
- fluoropolymers
    polyvinylidenedifluoride (PVDF)
    polytetrafluoroethylene (mostly as ePTFE)
- ketones and sulphones
    polyetherketone (PEK) and polyetheretherketone (PEEK)
    polysulphone, polyethersulphone (PES)
- olefins
    polyethylene (usually high density) (HDPE)
    polypropylene (PP).

Of these, PC, ePTFE and PES are among the fastest growing in importance. Most of these types of membrane material are reviewed in the next section.

During the last 20 years or so, inorganic materials such as ceramics and metals have become of increasing significance as membrane materials. The introduction of these, despite their being nearly an order of magnitude more expensive than their organic counterparts, has occurred because of their much-improved operating lifetimes, their robustness, their greater tolerance to extreme conditions of operation, such as higher temperature and aggressive chemicals, and the subsequent overall saving in lifetime costs.

Apart from the doped PES referred to above, in Section 8.2.1, for anti-fouling performance, most membranes have a single polymer (or copolymer) as the active layer. A quite different kind of membrane, the *affinity membrane*, is developing rapidly as a separation tool[7], able to separate molecular species by their chemical characteristics, rather than by size. These are based on the molecular recognition technology that won the 1987 Nobel Prize for Chemistry, and are marketed by 3M.

8.3.2 Membrane properties

The irregularity of the pores of most membranes, and the often irregular shape of the particles being filtered, results in there not being a sharp cut-off size during filtration. With symmetric membranes some degree of depth filtration could occur as smaller particles move through the tortuous flow path. To counteract this effect, asymmetric membranes, which have surface pore sizes much less than those in the bulk of the membrane material, are used to trap the particles almost exclusively at one surface (the membrane skin) whilst still offering low hydrodynamic resistance.

A membrane that is *hydrophobic* will have a greater tendency to being fouled, especially by proteins. Hydrophobic membranes require wetting, for example with alcohol, prior to filtration of water-based solutions; they are consequently good filtration media for gases. Three hydrophobic materials commonly used as microfiltration membranes are PTFE, PVDF (polyvinylidenedifluoride) and polypropylene. These all exhibit excellent to good chemical stability. PTFE is insoluble in most common solvents and is produced by solvent casting. PVDF is less stable than PTFE, and is soluble in aprotic solvents such as dimethylformamide, and can be produced by solvent casting. Polypropylene is the least stable of the three and can be produced by stretching and phase inversion.

Many polymer membrane materials exhibit detrimental adsorption characteristics. Solute adsorption has the effect of reducing flux, and can lead to difficulties in membrane cleaning. *Hydrophilic* membranes are consequently widely used because of their reduced adsorption behaviour. The best-known hydrophilic materials are based on cellulose, such as cellulose ester (acetate, triacetate, nitrate and mixed esters). Cellulose is a polysaccharide, derived from plants, and is quite crystalline; the polymer is very hydrophilic but is not water soluble. Cellulose acetate is a relatively inexpensive hydrophilic material that has good resistance to fouling in many applications, especially with proteins; however, it has a limited pH operating range (3–7), and its operating temperatures need to be below 35°C, while the polymer is very susceptible to biological degradation. Other hydrophilic membranes commonly used are polycarbonate, polysulphone, polyethersulphone and nylon. More recently, ceramic membranes (mainly alumina and zirconia) have become routinely used in more demanding applications. Membranes made from glass, carbon and metals (including silver, aluminium and stainless steel) are used for special applications.

Polysulphone is an engineering polymer used for both microfiltration and ultrafiltration membranes. The ultrafiltration versions are available with a nominal molecular weight cut-off (MWCO) in the range 2–100 kD. Polysulphone exhibits quite good chemical and temperature stability (up to 80°C) and can function in the pH range 1.5–12 for short periods of cleaning. It exhibits some resistance to oxidizing agents (e.g. chlorine) but on prolonged exposure to such materials it will lose its separation characteristics.

PVDF has similar, if not better, pH and temperature tolerances than polysulphone and has a superior tolerance to oxidizing agents and many solvents. It thus can be cleaned with more aggressive agents for substantially longer periods. It is available as an anisotropic membrane, produced by phase inversion.

Polyacrylonitrile is used either alone or as a copolymer, with for example PVC or methyl methacrylate added to increase its hydrophilicity, for ultrafiltration. It offers a tolerance to a wide range of organic solvents.

Semi-crystalline aromatic polyetherketones form an extremely useful range of high-performance engineering polymers, with a unique combination of mechanical toughness, high modulus, hydrolytic stability, resistance to oxidative degradation, the retention of physical properties at moderately high temperatures (up to 250°C), and the ability to withstand organic solvents such as toluene and tetrachloroethylene; these materials are steam sterilizable.

Polyamides are another important class of membranes with good chemical, thermal and mechanical stability. Aliphatic polyamides, such as Nylon-6, Nylon 6-6 and Nylon 4-6, are used as microfiltration and ultrafiltration membranes.

8.4 Membrane Manufacture

Factors that have a profound influence on the structure or morphology of a particular membrane are the nature of the process by which it is manufactured and the form of the raw material used. The various manufacturing processes, which are discussed in this section, can be broadly summarized as:

- sintering of fine graded particles;
- solvent casting or phase inversion, involving the stage-wise evaporation of a solution of polymer in a mixture of solvents;
- irradiation and etching of an impervious film; and
- stretching an impervious film to cause multiple ruptures.

Figures 8.12 and 8.13 respectively provide schematic and photographic representations of the resultant variety of morphologies – strictly speaking for microfiltration membranes only, but actually applying to all kinds.

he manufacturing processes for membranes are actually quite numerous, as shown in Table 8.5. In presenting a brief description of these processes, it is appropriate to distinguish between polymeric membranes, which formerly dominated the whole field, and the increasingly important membranes based on inorganic materials.

8.4.1 Manufacture of polymeric membranes

Polymeric membranes for microfiltration are manufactured by several processes, including stretching, phase inversion (solvent casting) and track etching, as well as sintering. In the case of ultrafiltration membranes, the usual method of preparation is phase inversion, as it is for reverse osmosis and nanofiltration media; ultrafiltration membranes are sometimes used as supports for the production of composite membranes for reverse osmosis and gas permeation.

8.4.1.1 Sintering

The production of membranes by sintering involves the compressing of a powder of particles of carefully graded size, and then heating to an elevated temperature. With the correct temperature of sintering for the specific material, the interface between the particles disappears to produce a porous structure. The pore size produced depends on the particle size and size distribution, but is limited to sizes of 0.1 μm or more. Porosity of the membrane is relatively low, typically in the range 10–20% for polymers (but up to 80% for metal membranes). The method is also used to produce membranes of ceramic, carbon and glass.

8.4.1.2 Stretching

The patented stretching process invented by W L Gore Inc converts impervious PTFE film into a range of membranes. The essence of the process is to subject the hot film to an extremely rapid unidirectional stretching action at about 320°C,

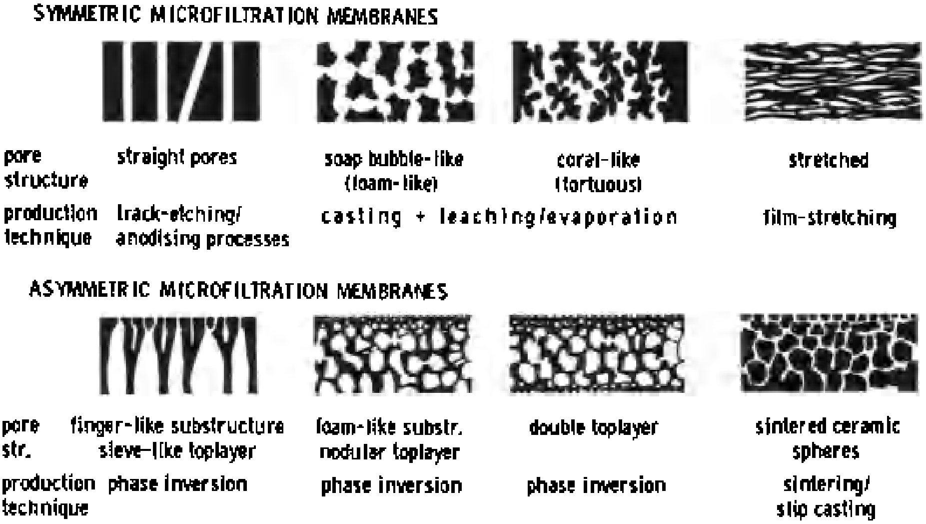
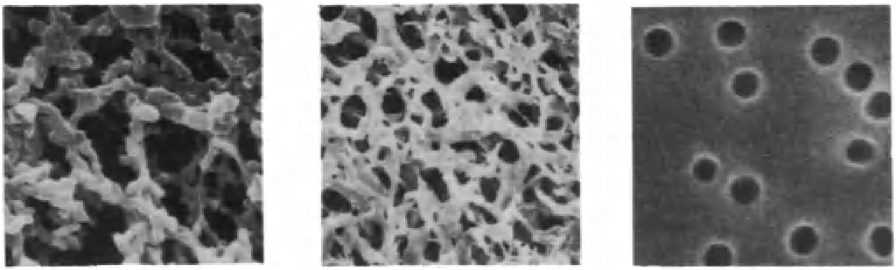


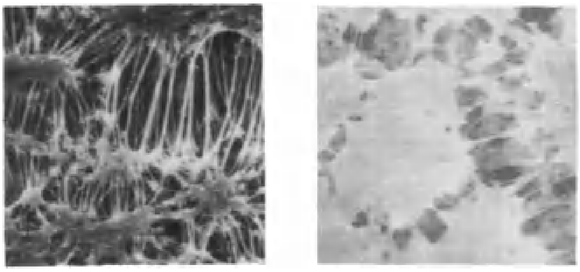
Figure 8.12. Morphologies of microfiltration membranes.



Mixed esters of cellulose membrane.

Durapore polyvinylidene difluoride membrane.

Isopore track-etched polycarbonate membrane.



Fluoropore PTFE membrane.

Solvex polypropylene membrane.

Figure 8.13. Electromicrographs of the surfaces of MF membranes. (Photographs: Millipore Corporation)

Table 8.5 Summary of membrane materials and manufacturing processes

Nominal pore size (μm)	Membrane/ support	Manufacturing process	Module configuration	Mechanical, thermal and chemical stability	Degree of asymmetry
0.1–5	Polysulphone	Immersion precipitation	Hollow fibre	+	++
0.1–0.65	Polypropylene	Thermal precipitation	Hollow fibre/ tubular	++	–
0.1–0.4	Nylon-6		Hollow fibre/ tubular	++	–
0.1	Polysulphone Cellulose acetate Fluoropolymer	Several phase inversion techniques	Hollow fibre/ flat sheet	+	+
			Flat sheet	–	±
			Flat sheet	++	±
2–5	Polyethylene	Phase inversion technique	Tubular	+	–
0.02–0.4	Polypropylene	Stretching	Hollow fibre	++	–
0.1–5	Polysulphone	Immersion precipitation	Flat sheet	+	++
0.1–5	Fluoropolymer		Flat sheet	++	++
0.2–10	Nylon	Evaporation precipitation	Flat sheet cartridge	++	–
0.1–5	Polysulphone	Immersion precipitation	Spiral wound/ tubular	+	+
0.01–0.5	Polyvinylalcohol	Immersion precipitation	Hollow fibre	–	
0.2	Polysulphone/ Fluoropolymer	Phase inversion technique	Flat sheet (rotary module)		
0.2	Polyolefine	Phase inversion technique	Hollow fibre	++	
0.1–0.65	Cellulose nitrate Fluoropolymer	Evaporation/ immersion	Flat sheet	–	±
		Precipitation	Flat sheet	++	±
0.1–1.2	Polysulphone	Immersion precipitation	Spiral wound	+	
	Fluoropolymer		Spiral wound	++	
0.1–1.5	Fluoropolymer	Immersion precipitation	Flat sheet	++	+
0.2–5	Fluoropolymer	Evaporation/ immersion	Flat sheet	++	±
0.6–0.8	Nylon	Precipitation	Flat sheet	++	±
0.05–1	Poly(ether)imide	Immersion precipitation	Hollow fibre/ flat sheet	+	+
0.05-1	Polysulphone		Hollow fibre/ flat sheet	+	+
0.2	Polycarbonate	Track etching	Flat sheet		
0.025–0.2	γ-Al_2O_3	Anodic oxidation	Flat structure	±	–
0.2–5	α-Al_2O_3	Sintering/slip casting	Tubular	+++	++
0.1	ZrO_2/α-Al_2O_3		Tubular	+++	

Table 8.5 *(continued)*

Nominal pore size (μm)	Membrane/ support	Manufacturing process	Module configuration	Mechanical, thermal and chemical stability	Degree of asymmetry
0.2–3	Glass	Leaching of soluble phase	Tubular		
0.1	ZrO_2/C	Dynamically formed from suspension	Tubular	+	++
0.15–8	SiC	Sintering/slip casting	Tubular	+++	++
0.2–1	Carbon	–	Tubular	+++	++
0.2–1	α-Al_2O_3	Sintering/slip casting	Tubular	+++	++
0.2	SiC	Sintering/slip casting	Tubular	+++	++
0.6–0.14	ZrO_2/C	Dynamically formed from suspension	Tubular	++	++
0.05–0.3	Glass	Leaching of soluble phase	Hollow fibre	±	–

followed by a period of heat treatment at a somewhat higher temperature. The first stage generates a structure of small nodes (from less than 1 μm up to 400 μm) connected by a mass of fine fibrils, as shown schematically in Figure 8.14. The heat treatment step results in a change in the crystalline structure, giving what is termed 'amorphous locking', with a major increase in mechanical strength. A highly magnified view of a sample of this type of membrane is shown in Figure 8.15.

Whilst the process as summarized permits the direct manufacture of a range of membranes, all of high porosity and strength, their extreme thinness (12–75 μm) presents considerable handling problems. It is essential to combine them with a suitable substrate, so as to give a product that is handleable and robust enough to use. Depending on the intended application, substrates range from lightweight spunbonded polypropylene or polyester, to substantial fabrics, such as thick needlefelts. Figure 8.16 shows a Goretex membrane coating a 500 g/m^2 needlefelt, at the still higher magnification of ×900. The delicate structure of the membrane is clearly visible, as are the spherical particles of fly ash, their sizes ranging from 3 to 15 μm, trapped on the surface.

8.4.1.3 Track-etching

Track-etched membranes are the closest membrane analogues to a sieve, the membranes being essentially dense polymer films punctuated by cylindrical holes. Figure 8.17 shows the surface of a track-etched membrane, in which the holes are about 0.2 mm in diameter. These membranes are manufactured by a process divided into two steps: tracking and etching. During the tracking phase, a thin polymer film is unrolled at high speed while exposed to a fast-moving beam of accelerated argon ions. The highly energetic ions pierce the polymer film and break the polymer chains, leaving 'tracks' that are then etched in baths of aggressive chemical agents (such as caustic soda) to convert them into clean, cylindrical pores of a defined uniform character.

The pore density of the membrane is controlled during the tracking step, by modifying the speed of the film, while the pore diameter is controlled during the etching step, by varying the immersion time in the etchant bath. The use of a highly energetic argon ion beam during the tracking step allows the piercing of thicker films than was possible in older processes. The beam of argon ions, accelerated in a cyclotron during the manufacturing, avoids radioactive

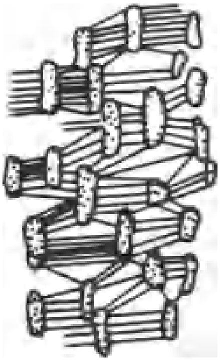


Figure 8.14. Schematic representation of the structure of Goretex membrane (from US Patent 3,953,566)

Figure 8.15. A microphotograph of expanded PTFE membrane. (Photograph: Tetratec Corporation)

contamination, and enables the etching to be performed immediately after the tracking step, reducing manufacturing time and improving quality control of the final product.

It has only proved possible to manufacture track-etched membranes with pore sizes in the microfiltration range (0.03–8 μm). Because these membranes are symmetric, their resistance to the flow of water is proportional to the membrane thickness, and they are therefore made thinner than asymmetric microporous membranes, in order to have comparable fluxes. The usual material that is track

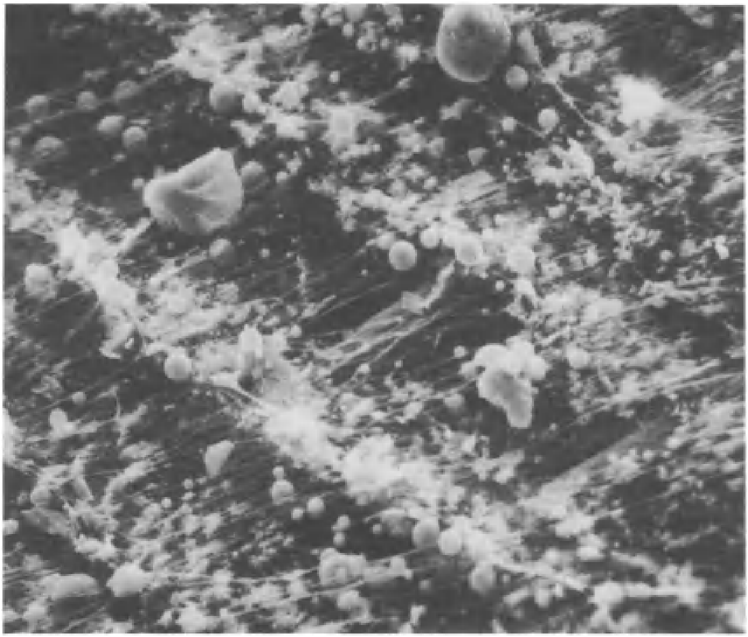


Figure 8.16. Fly ash particles on the Gore-Tex laminated surface of needlefelt.

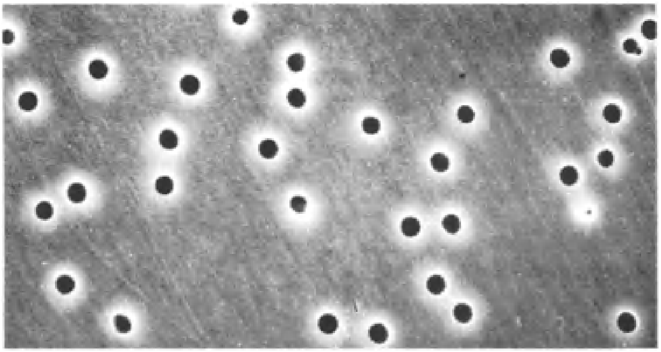


Figure 8.17. Surface of track-etched membrane showing regular hole size and distribution.

etched is polycarbonate, resultant porosities being of the order of 10%, depending on the radiation time.

8.4.1.4 Solvent casting or phase inversion

The majority of polymeric membranes can be produced by a method known variously as solvent casting or phase inversion, whereby a polymer solution inverts into a swollen three-dimensional macromolecular complex or gel. Porous membranes are produced from a two- or three- (or even four-) component dope mixture containing polymer, solvent and non-solvent (and salt in some cases).

The first step is to prepare a casting solution by dissolving polymer in a solvent, which may contain certain additives. To form flat membrane sheets, the casting solution is spread directly onto a suitable support by using a casting knife. The support may be a glass plate or other inert support, from which the membrane is then removed, or a support for the membrane itself (such as a non-woven polyester) to which the membrane remains fixed.

The casting thickness can typically vary from 50 to 500 μm. The cast film is then transferred to a non-solvent (gelation) bath, where exchange occurs between solvent and non-solvent (typically water), which leads to precipitation of the polymer from the solvent.

A typical example of the phase inversion manufacturing process, for cellulose acetate ultrafiltration membranes, is by dissolving the polymer in a mixture of acetone, dioxan and formamide. After precipitation has occurred, a thin skin of polymer forms on the surface of the cast film. The microstructure of the bulk of the membrane is determined in the gelation stage, although the process of gelation is strongly influenced by the properties of the skin at the surface of the membrane exposed to the air.

The invention of this basic process is attributed to Loeb and Sourirajan, an interesting account of whose pioneering work was provided in the opening paper(8) presented by Loeb to a four-day symposium of the American Chemical Society in 1980. This event was held specifically to mark the 20th anniversary of their development of the first modified asymmetric membranes with commercial potential for reverse osmosis.

Three types of membrane are typically produced in this way:

1. if the skin layer is dense, and has a very high resistance to the gelation medium and the outward transfer of the solvents, the rate of polymer precipitation can be limited by the rate of transfer across the skin, and a uniform porous structure is produced;
2. if the resistance of the skin is such that the rate of diffusion across the bulk of the membrane is more important, a gradation in pore size away from the skin surface is likely to occur, giving an asymmetric sponge-like structure;
3. membranes with finger-like voids are formed if the precipitation of polymer occurs rapidly, i.e. where solvents with little affinity for the polymer are used or where the gelation bath has a high salinity.

The performance characteristics (chiefly flux and selectivity) of phase inversion membranes depend upon many parameters, including polymer concentration, evaporation time before immersion, humidity, temperature, composition of casting solution, and the composition and condition of the coagulation bath.

Hollow fibre membranes are produced by a different procedure, using various spinning processes (wet spinning, dry–wet spinning, melt spinning and dry spinning). The casting solution is pumped through a spinneret, which is a nozzle with a solid inner annular section that enables the solution to be extruded in a cylindrical form; this spinneret is used for the wet and wet–dry spinning processes. The hollow fibres are self-supporting and demixing occurs both outside and inside the fibre; after spending some time in the air, or in a controlled atmosphere, the fibre is then immersed in a non-solvent coagulation bath.

Tubular polymer membranes require a different procedure since they are not self-supporting. The casting has to be carried out on a supporting tubular material, such as non-woven polyester or carbon.

A variety of other methods for forming membranes by phase inversion are summarized in Table 8.6. Certain polymer membranes cannot be produced by conventional solvent casting because their crystallinity makes them insoluble in conventional solvents at ambient temperatures. This problem can be overcome by thermal phase inversion, in which a polymer is dissolved in a solvent at a high temperature, the solution then being cooled to precipitate the polymer as a formed membrane from which the solvent is removed. Polymeric materials made into membranes in this way include polyethylene, polypropylene, polycarbonate and PVC.

An alternative thermal phase inversion process permits the production of ultrafiltration and microfiltration membranes from aromatic polymers containing in-chain ether or thioether and ketone linkages. Suitable materials are homopolymers such as polyetherketone (PEK) and polyetheretherketone (PEEK), or copolymers such as PEK/PEEK and PEEK/PES (polyethersulphone). The first step is to dissolve the polymer in a 'latent' solvent, which is a compound

Table 8.6 Phase inversion membrane preparation

Precipitation method	Principle
Solvent evaporation	Evaporation on inert support or porous substrate in an inert atmosphere. Produces dense membranes (homogenous).
Vapour phase	Casting of film into a vapour phase of solvent and non-solvent. Membrane formation is due to penetration of non-solvent into cast film, producing a porous membrane with no top layer.
Controlled evaporation	Polymer is dissolved in a solvent/non-solvent mixture. Evaporation of solvent during evaporation shifts the composition to a higher non-solvent and polymer content. This leads to polymer precipitation and the formation of a skin on the membrane.
Thermal precipitation	A polymer and solvent solution is cooled to enable phase separation. Evaporation of solvent can allow the formation of a skinned membrane. Frequently used to prepare microfiltration membranes.
Immersion	A solution of polymer plus solvent is cast (on a support) and immersed in a coagulation bath. Precipitation occurs by the exchange of solvent and non-solvent in the coagulation bath.

in which the polymer is soluble at high temperatures, typically only 5°C below the polymer melting point of 320–340°C, while, at low temperatures, below 100°C, the polymer is only poorly soluble in the chosen solvent. Examples of suitable solvents, with a plurality of aromatic rings, are tetraphenyls, hexaphenyls or polar polyaromatic compounds. The initial concentration of the polymer in the solvent is 10–50 wt.% (preferably 20%); a pore-forming agent (e.g. an inorganic salt or soluble polymer) can be added to the solution. With pore diameters in the range 0.001–1 μm, the membranes manufactured in this way may be asymmetric or isotropic, and either unsupported or supported (e.g. on PTFE, carbon fibre or stainless steel).

Alternative solvents for these otherwise intractable polymers are certain very strong mineral acids, such as liquid hydrogen fluoride, trifluoromethane sulphonic acid and sulphuric acid. Casting solutions can be formed containing, for example, 7–14 wt.% of PEK in 98% sulphuric acid, to produce both flat sheet and hollow fibre membranes for ultrafiltration.

8.4.2 Manufacture of inorganic membranes

There is growing interest in the use of inorganic membranes because of their robustness, their tolerance to extreme conditions of operation, such as higher temperature and aggressive chemicals, and the resultant long life, which offsets their higher initial cost as compared with polymeric membranes. The materials include ceramics, metals, carbon and glass. Some examples are listed in Table 8.7. Inorganic membranes may be homogeneous, asymmetric or composites.

8.4.2.1 Ceramic membranes

Almost all ceramic membranes are made by the sintering of a layer of carefully sized particles. A layer so made would be far too brittle to survive separate use, so

Table 8.7 Range of available porous inorganic membranes

Membrane material	Support material	Membrane pore diameter (nm)	Geometry of membrane element
Ni, Au		> 500	Tube
Ag, Pt			
Ag/Pd		0	Tube
ZrO_2	C	4	Tube
ZrO_2	C	4–14	Tube
ZrO_2	Metal	Dynamic	Tube
ZrO_2	Al_2O_3	10	Tube
SiC	SiC	150–8000	Tube
SiO_2 (glass)		4–120	Tube capillary
Al_2O_3	Al_2O_3	4–5000	Monolith/tube
Al_2O_3	Al_2O_3	200–5000	Tube
Al_2O_3	Al_2O_3	200–5000	Tube
Al_2O_3	Al_2O_3	200	Tube
Al_2O_3	Al_2O_3	25–200	Disk

all ceramic membranes are manufactured as a composite structure, with the membrane layer laid down on a porous substrate before sintering.

Composites require a support of open structure, and they may be of ceramics or carbon. For ceramics these supports are typically tubes or monolithic elements with several channels, as in Figure 8.9, fabricated by ceramic shaping methods such as slip-casting, extruding, etc. Carbon supports are typically produced by pyrolysis of a polymeric precursor, or by the pressing of carbon powders or fibres. The supports typically have pore sizes in the range 5–15 μm and porosities of 40–50%, or greater for carbon supports.

Typical use of these supports is to produce microfiltration membranes, which have deposited layers 10–50 μm thick, with pores 0.2–1 μm in size, and 40–50% porosity. The membranes are prepared by film coating the porous support with a suspension of the ceramic powder. The thickness of the coated layer is adjusted by changing the viscosity of the suspension, for example by changing its solids content. In preparation, pinholes in the deposited layer are avoided by suppressing the capillary force effect in the pores. The membrane layer is then formed by sintering at high temperatures, e.g. 1200–1450°C for alumina, the temperature used depending upon material, powder particle size and required pore structure.

The suspensions used in the process are prepared either by milling the powders or, for finer suspensions, by hydrolysis of salts or alkoxides (e.g. those of aluminium, zirconium and silicon). Overall the method is used to apply layers having pore sizes from 0.05 to 0.5 μm and, in the case of zirconia, suspensions on carbon of 0.01 μm pore size. The use of colloidal suspensions is applied in the 'sol–gel' process, which uses the capillary forces in the support to improve adherence between membrane layer and support. The method produces a sharp pore size distribution, with rapid production of layers to 0.01 μm in thickness. In practice the support quality has to be very good and the pore size in the top of the support should be 1 μm or less, otherwise the capillary forces are too weak at the start of the cake filtration/slip casting process. The method can be used to produce membranes with multiple layers, the top layer being the thinnest and with the smallest pore size. Final pore sizes of the order of 0.003 μm can be produced in this way (see Figure 8.18).

The production of crack-free membrane layers requires careful control of the drying, calcining and sintering stages. Drying control agents and organic additives, to adjust viscosity, are frequently employed to adjust the pore size distribution. During calcination and sintering the additives are burnt out. Membranes produced by these methods include alumina and titania layers on ceramics and glass, zirconia on carbon and alumina, and silica on alumina.

Classical slip-casting of slurries or sols on ceramic supports is a common procedure for the preparation of commercial microfiltration and ultrafiltration materials. These materials are manufactured by association of various granular layers. Each ceramic layer is characterized by its thickness, porosity and mean pore diameter, and these parameters are controlled by the particle size and synthesis method. However, the experimental hydraulic resistance of an inorganic composite membrane can be much larger than that obtained by summing the individual resistances of all the layers. This is explained by the existence of a transition boundary layer between two porous media having drastically different pore sizes.

Non-infiltrated ceramic membranes can provide the expected water permeabilities. To prepare non-infiltrated membranes a new step is introduced, this being pretreatment of the support by impregnating the top of the support material with an aqueous solution of methyl cellulose. After the resulting polymer film has dried, the ceramic suspension is poured into the tube, which is then evacuated for 10 minutes, during which the polymeric dense film prevents any penetration into the pores of the support. The subsequent firing operation destroys the polymeric film and leaves a non-infiltrated membrane. The final temperature and time of firing control the mean pore size and size distribution of the membrane. This process is well suited to the production of titania membranes.

8.4.2.2 Carbon membranes

Carbon membranes, as shown in Figure 8.19, are produced from a thin porous layer of carbon (approximately 0.01 μm thick) applied to the internal surface of a narrow diameter support tube made from a carbon fibre/carbon matrix. The active layer pore size is in a range of 0.1–1 μm. Carbon membranes are particularly useful for operation at very low pH and they can function at temperatures of 165°C and at pressures up to 40 bar. They are suitable for conditions when many cleaning cycles are required either by backflushing or chemically.

8.4.2.3 Porous glass

A technique for preparing porous glass membranes combines leaching with the thermal phase inversion process used for the production of certain types of polymeric membrane. A three-component mixture of the oxides of sodium, boron

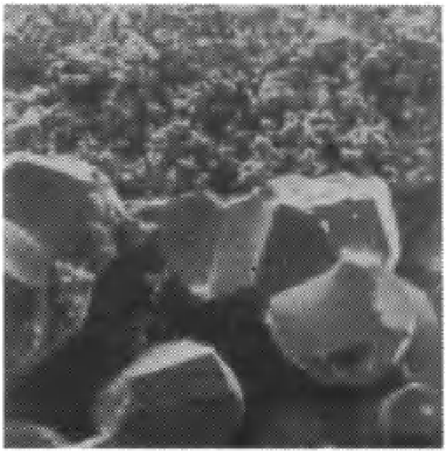


Figure 8.18. Scanning electron micrograph of a ceramic membrane. (Photograph: APV Membrantechnologie GmbH).

and silicon is converted into a homogeneous melt. When this is cooled it separates into two phases. One phase consists mainly of insoluble silica, while the other phase is soluble. After solidification, the soluble phase is leached out by acid to produce a porous structure.

8.4.2.4 Metal membranes

There is a very indistinct boundary line in any classification of membrane media between ceramic and metal media. Most 'metal' membranes are actually a substrate of metal, with the oxide of that metal, i.e. a ceramic, forming the actual active layer at the surface of the membrane. However, it is customary to regard media that are mainly metal as metal membranes, and they are so discussed here, although there are one or two media that are all metal.

The first of these all metal media is the range of pure metallic *silver membrane* discs available from Osmonics Inc. These are in the form of discs of eight different diameters between 13 and 293 mm, and with particle retention ratings extending from 0.2 to 5 μm. Originally produced by the sintering of silver granules, these membranes are now formed by a reaction bonding mechanism that transforms a suspension of amorphous silver into a strong homogeneous crystalline network of porous silver. The membranes are 50 μm in thickness, with a 60% open area. They are claimed to be usually more economical than disposable filters because they can be reused several times after chemical or ignition cleaning.

Membrane media are also made from *anodized aluminium*. An asymmetric structure that can be formed by anodizing aluminium is shown schematically and photographically in Figure 8.20. The top-side pores have a size of approximately 0.025 μm, while the support pores are of the order of 0.2 μm.

During anodic oxidation, several metals develop coherent porous oxide coatings that adhere strongly to the metal substrate, limiting the direct use of the porous layer as a membrane. For example, anodizing aluminium in electrolytes of oxalic, phosphoric or sulphuric acid, generates a porous structure inwards from the outer surface only as far as an imperforate barrier layer. However, if the voltage of the anodizing cell is varied, say by reducing the starting potential from 25 V to zero in steps of 0.5 V, the resultant pore structure is altered; the single

Figure 8.19. Photomicrograph of a carbon composite membrane showing the fine upper layer and the carbon fibre/composite support. (Photograph: Le Carbone Lorraine)

pores that normally form instead branch into numerous small pores that weaken the film near the substrate metal. Collectively, the branched pore system introduces a weakened stratum into the metal oxide film, thus enabling it to be quite easily separated from the substrate.

The barrier layer is very thin in this process and is generally left on the metal substrate. The detached oxide film is therefore porous on both sides. However, before it is detached from the metal substrate, a perforated supporting layer can be attached to the other side of the film by heat sealing or glue.

An inorganic membrane in the form of an *etched aluminium foil*, as shown in Figure 8.21, may be made from aluminium foil by an etching process that generates a capillary pore structure with a pore size of 0.5–8 μm. Recrystallized aluminium foil is etched, either on both sides to produce a symmetrical pore structure, or on one side to produce an asymmetric structure. The membrane has also been made with a silicon rubber coating, and also with a finer pore size, down to 0.002 μm, produced by coating the pore walls with alumina.

The following typical flow rates for the membrane are reported:

- air – 7000 $m^3/m^2/h$ bar;
- water – 1000–2000 $l/m^2/h$ bar;
- methanol – 2000–3000 $l/m^2/h$ bar.

Advantages claimed for aluminium foil membranes as compared with polymeric or ceramic membranes are:

1. the foil is easily formed; a laser-welded tubular format has been used for standard microfiltration tests;
2. it has excellent resistance to organic solvents, even at elevated temperatures, and to radiation;
3. it is stable in aqueous solution and withstands cleaning by bleaching with oxidizing agents;
4. it is electrically conducting, a property that has been used to obtain flux enhancement in microfiltration, and can facilitate cleaning; and

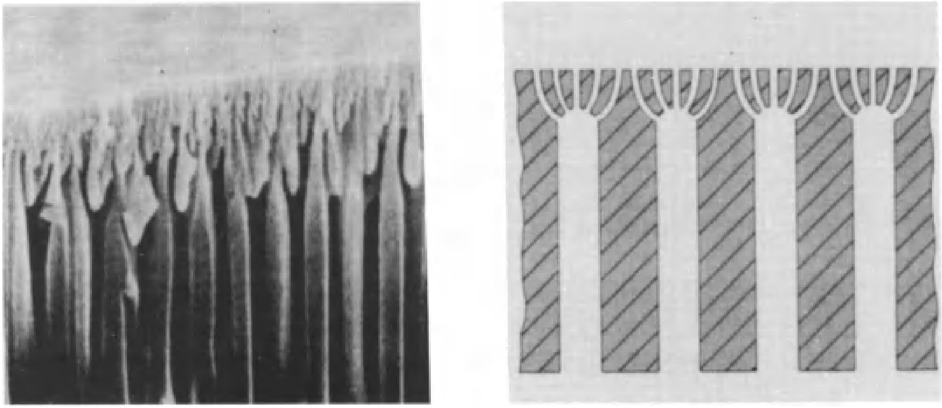


Figure 8.20. Anodized aluminium membrane with asymmetric support. (Photographs: Alcan Int. Ltd)

5. it is tough, withstanding pressures up to 20 bar: this also allows increased filtration rates.

The main metal membrane, however, is that made from *sintered metal*, usually supported on a layer of sintered wire mesh. A simple example of this is Pall's Supramesh Z, data for which are included in Table 6.18 of Chapter 6. It combines a layer of sintered mesh, with a layer of powder or fibre sinter-bonded to the upper surface.

A sophisticated variant of this type of composite metal medium provides the basis for the Pall range of PMM metal membranes. These incorporate a thin sintered matrix of stainless steel or other metal powder within the pore structure of sintered woven wire mesh, as can be seen in the microphotograph of Figure 8.22. These thin, strong and ductile media can be pleated into high specific area packs, while the smooth and highly uniform surface functions as a high-performance medium for filtration down to 2 µm absolute with liquids and 0.4 µm with gases. Some relevant data are given in Table 8.8.

These PMM membrane media are also effective support layers in the highly robust multilayer elements used for filtering molten polymers, where the process conditions combine viscosities up to 4000 poise, temperatures of 250–350°C, and pressure differentials as high as 300 bar.

8.4.2.5 Organo-mineral membranes

Zirfon is a novel form of membrane material described by Leysen[9], which combines mineral particles with conventional polymeric materials. For example, zirconia particles are combined with polysulphone by dispersing them in the polymer solution used to cast membranes by immersion precipitation in a water bath. The resulting membrane structure consists of a porous polymer network

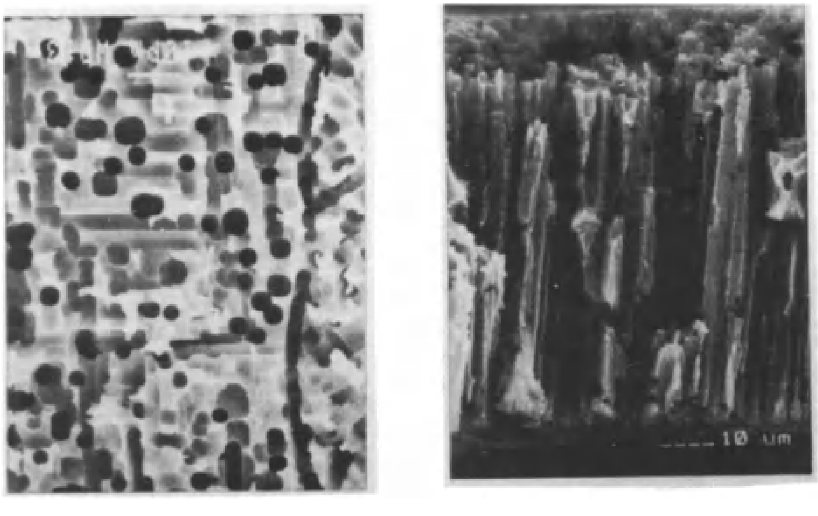


Figure 8.21. Etched aluminium foil membrane: (left) double-sided etched foil: (right) cross-section of the same double-sided etched foil.

incorporating the mineral grains, their presence significantly modifying the resulting membrane structure and the properties of the membrane surface in a very favourable manner. An increase in the weight percentage of zirconia in the casting solution significantly increases the membrane permeability and hence flux; the cut-off values of the membranes are around 25 kD, thus confirming that there are no significant changes in skin pore size.

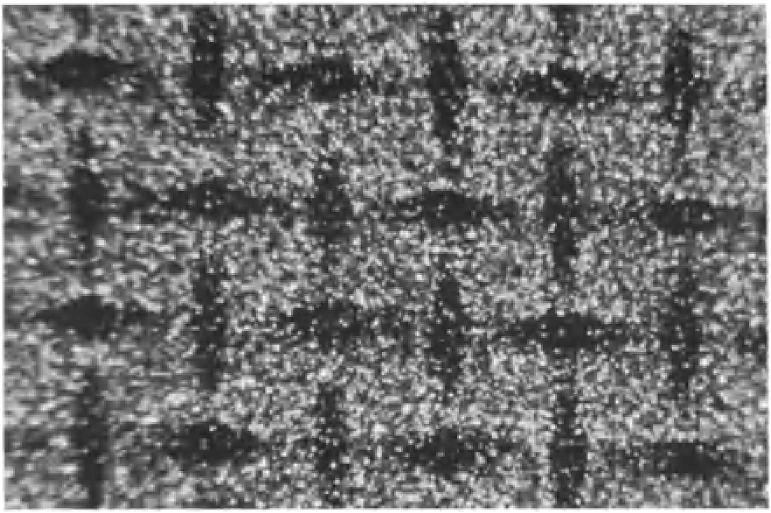


Figure 8.22. Pall 'PMM' filter medium is a sintered composite of mesh and powder.

Table 8.8 Pall PMM sintered mesh and powder media

Media grade	Micron removal rating					Nominal standard thickness (mm)	Permeability[c]	
	Liquid service[a]			Gas service[b]				
	90%	99%	100%	Wt.% removed	100%		to air	to water
M020	0.1	0.5	2	> 99.99	0.4	0.14	4.7	0.07
M050	0.6	2	5	99.99	0.6	0.14	7.6	0.12
M100	2	5	10	99.97	1.3	0.13	10	0.21
M150	5	9	15	99.96	2.5	0.15	31.8	0.35
M200	8	13	20	99.93	4.0	0.23	38.8	0.84
M250	10	16	25	99.90	9.0	0.23	152	2.95

[a] Using AC dusts in water, efficiency measured by particle count.

[b] Based on AC Fine Test Dust in air. Absolute retention rating based on particle count data.

[c] $l/dm^2/min$ @ 10 mbar pressure drop.

The technology is employed by the Dutch company X-Flow to manufacture hollow fibre membranes for the filtration of potable water and wine. Flat sheet membranes for battery separators are also available.

8.5 Characterization of Membranes

Characterization methods for porous membranes can be divided into two groups of parameters: structure related and permeation related. Certain tests are also used to establish the integrity of membranes in specific applications. The direct measurement of pore statistics is routinely carried out by electron microscopy, as is seen in the various typical SEM (scanning electron microscopy) photographs of membrane structures in this chapter.

Table 8.9 summarizes various test procedures used for microfiltration and ultrafiltration membranes or for filters incorporating these membranes. It should be noted that the asymmetric structure of most ultrafiltration membranes, with top layer pore sizes in the range of 20–1000 Å, means that many of the methods of characterization of microfiltration membranes cannot be applied. Bubble point and mercury intrusion methods require high pressures that would damage or destroy the membrane structure; SEM is generally not possible and TEM (transmission electron microscopy) is not always applicable. The methods that can be used with ultrafiltration membranes include permeation experiments and methods such as gas adsorption–desorption, thermoporometry, permporometry and rejection measurements. The appropriate test methods are discussed in Chapter 11.

Table 8.9 Tests for characterizing membranes or membrane filters

Principle of test	Medium	Characteristic
Microfiltration membranes		
Air diffusion	Air	Integrity
Bubble point test	Air	Pore size
Cartridge retention test	Water	Filtration efficiency
Flow rate vs differential pressure	Water	
Particle shredding test	Water	
TOC tests	Water	
Resistivity test	Water	
Bacteria passage test	*Pseudomonas diminuta*	Sterility
Mercury intrusion test	Hg	Pore size and pore distribution
Latex sphere test	Latex sphere dispersion	Integrity
Water penetration test	Water	Integrity
Electron microscopy (SEM, TEM)		Pore size, shape, distribution, density
Permeation measurements		Water flux for pore size and distribution.
Ultrafiltration membranes		
Gas adsorption–desorption	N_2	Pore size and distribution
Thermoporometry	Water	Pore size and distribution
Permporometry	Gas	Pore size and distribution
Solute rejection	Various solutes	MWCO

8.6 Commercial Membranes

The performance of a membrane is defined in terms of two factors, fluid flux and selectivity. Ideally a membrane is required to combine high selectivity with high permeability, but typically attempts to maximize one factor often result in a reduction in the other. Membrane performance characteristics vary considerably from manufacturer to manufacturer, even where comparisons are between nominally identical materials. What follows here is a selection from the very wide range of membrane media available, the selection being made to highlight particular features of the membrane as a filter medium. The emphasis is primarily on microfiltration and ultrafiltration media, with reference to nanofiltration and reverse osmosis membranes only as necessary for completeness.

This part of the first edition's coverage of typical membrane media was divided into separate treatment of micro- and ultrafiltration. These two areas have merged significantly in the time since that edition was prepared, so the coverage now is very largely by material rather than membrane process.

8.6.1 Polymeric membranes

The specifications of Millipore's range of membrane microfilters, with pore sizes in the range 0.025–12 μm, are given in Table 8.10, while their contrasting surfaces are shown in the SEM photographs of Figure 8.13. Within this range it is possible to obtain variants of the basic materials. For example, Durapore PVDF is available as hydrophilic, hydrophobic or super hydrophobic membranes, with radically different protein binding characteristics. The track-etched Isopore polycarbonate membranes are also available in polyethylene terephthalate (PET), which is more resistant to organic solvents.

Certain of these membranes are supplied bonded to a suitable support. The Fluoropore PTFE membranes are laminated to high-density polyethylene to improve handling; however, certain pore grades are available as unsupported materials, where there is a risk of degradation of the support. These are recommended for the filtration of gases and non-aqueous liquids, although a hydrophilic material is available for the filtration of aqueous solutions. Membranes made from polypropylene (for sterilization applications) and PVC (for air monitoring) are also available.

Dead-end microfiltration is primarily carried out with flat sheet membranes, either as discs or rectangular sheets, or in the form of pleated cartridges that can incorporate several square metres of filtration area. Table 8.11 gives specifications for the sheet membranes Millipore provides for use in cross-flow modules of the type illustrated in Figure 8.23. Membranes are available in two materials, Durapore PVDF and Ceraflow, which is a ceramic of α-alumina: each material is available in two grades, a hydrophilic grade for microfiltration and a hydrophobic grade with finer pores for ultrafiltration.

A complete spectrum of membrane media, covering microfiltration to reverse osmosis is supplied by Osmonics, in a catalogue approaching 1000 pages (for

Table 8.10 Specifications of Millipore membranes

Specifications									
Filter type	Mean pore size (μm)	Typical flow rate[a], water[b]	Typical flow rate[a], air[c]	Typical porosity (%)	Typical refractive index	Minimum bubble point[d] (bar)	Minimum bubble point[d] (psi)	Autoclavable	Mean thickness (μm)
Durapore (polyvinylidene difluoride)									
SVLP	5.0	288	–	70	1.42	0.21	3	Yes	125
DVPP	0.65	69	–	70	1.42	0.98	14	Yes	125
HVHP	0.45	35	6	75	1.42	0.56	8	Yes	125
HVLP	0.45	29	–	70	1.42	1.55	22	Yes	125
GVHP	0.22	15	3	75	1.42	1.20	17	Yes	125
GVWP	0.22	6.9	–	70	1.42	3.1	45	Yes	125
VVLP	0.10	2.5	–	70	1.42	4.9	70	Yes	125
MF-Millipore (mixed cellulose acetate and nitrate)									
SC	8.0	620	65	84	1.515	0.42	6	Yes	135
SM	5.0	580	32	84	1.495	0.42	6	Yes	135
SS	3.0	320	30	83	1.495	0.70	10	Yes	150
RA	1.2	270	20	82	1.512	0.77	11	Yes	150
AA	0.80	190	16	82	1.510	0.98	14	Yes	150
(black)		190	16	82	–	1.12	16	No	150
DA	0.65	140	9	81	1.510	1.20	17	Yes	150
HA	0.45	60	4	79	1.510	2.11	30	Yes	150
(black)		60	4	79	–	2.32	33	No	180
PH	0.30	32	3	77	1.510	2.46	35	Yes	150
GS	0.22	18	2	75	1.510	3.52	50	Yes	150
VC	0.10	1.5	0.4	74	1.500	14.1	200	Yes	105
VM	0.05	0.74	0.2	72	1.500	17.6	250	Yes	105
VS	0.025	0.15	0.15	70	1.500	21.1	300	Yes	105
Fluoropore (PTFE)									
FS	3.0	286	20	85	[e]	0.05	0.7	Yes	200
FA	1.0	90	16	85	[e]	0.21	3	Yes	145
FH	0.5	40	8	85	[e]	0.49	7	Yes	175
FG	0.2	15	3	70	[e]	0.91	13	Yes	175
Miltex (PTFE)									
LC	10.0	126	14	68	–	0.04	0.5	Yes	125
LS	5.0	51.9	9	60	–	0.06	0.9	Yes	125
Isopore (polycarbonate film)									
TM	5.0	2000	50	–	1.6	0.21	3	Yes	10
TS	3.0	1500	50	–	1.6	0.42	5	Yes	9
TT	2.0	350	22	–	1.6	0.63	9	Yes	10
RT	1.2	250	20	–	1.6	0.77	11	Yes	11

Table 8.10 (*continued*)

Specifications

Filter type	Mean pore size (μm)	Typical flow rate[a], water[b]	Typical flow rate[a], air[c]	Typical porosity (%)	Typical refractive index	Minimum bubble point[d] (bar)	Minimum bubble point[d] (psi)	Autoclavable	Mean thickness (μm)
AT	0.8	215	20	–	1.6	1.3	18	Yes	9
DT	0.6	115	10	–	1.6	1.7	24	Yes	10
FT	0.4	70	10	–	1.6	2.5	35	Yes	10
GT	0.2	7	1	–	1.6	5.3	75	Yes	10

[a] Flow rates listed are based on measurements with clean water and air, and represent initial flow rates for a liquid of 1 centipoise viscosity at the start of filtration, before filter plugging is detectable. Actual initial flow rates may vary from the average values given here.

[b] Water flow rates are millilitres per minute per cm^2 of filtration area, at 200°C with a differential pressure of 0.7 bar (10 psi). Flow rates for Fluoropore, Durapore hydrophobic and Miltex filters are based on methanol instead of water.

[c] Air flow rates are litres per minute per cm^2 of filtration area, at 20°C with a differential pressure of 0.7 bar (10 psi) and exit pressure of 1 atmosphere (14.7 psia).

[d] Bubble point pressure is the differential pressure required to force air through the pores of a water-wet filter (except methanol-wet for Fluoropore, hydrophobic Durapore and Miltex filters).

[e] Crystalline and amorphous regions of Fluoropore filters have differing refractive indices, and it is therefore not possible to obtain uniform clearing.

Additional notes: Flow rate correction for viscosity: For a liquid having a viscosity significantly different from that of water (1 cps), divide the water flow rate by the viscosity of the liquid in centipoises to obtain the approximate initial flow rate for the liquid in question (viscosity of methanol is 0.6 cps at 20°C).

Water Extractables: Water extractables measure 5% or less for most filter types, except for Durapore membranes, which measure 0.5%.

systems as well as elements and components). The microfiltration media are marketed under the Desal brand name, as spiral wound units, in three ranges, all safe up to 50°C:

- E500 Series: cut-off size 0.04 μm, made from polysulphone.

EW4026F	5.6 m^2 filter area	24.6 m^3/day flow at 207 kPa & 25°C
EW4040F	8.4 m^2	41.6 m^3/day
EW8040F	32.5 m^2	136.1 m^3/day

- J Series: cut-off size 0.3 μm, made from PVDF.

JX4040F	8.4 m^2 filter area	45.4 m^3/day flow at 207 kPa & 25°C
JX8040F	32.5 m^2	151.0 m^3/day

- K Series: cut-off sizes 0.1, 0.2, 0.5, 1.0 and 3.0 μm, made from PTFE.

K2540	1.2 m^2 filter area
K4040	4.7 m^2
K8040	18.6 m^2

Table 8.11 Millipore membranes for MF and UF cross-flow filtration

Specification	Durapore	Ceraflo	PZHK	Ceraflo-UF
Material	Hydrophilic PVDF	α-Alumina with Teflon end seal	Hydrophobic PVDF	α-Alumina with Teflon end seal
Pore sizes (μm)	0.10 0.22 0.45	0.20 0.45 1.00	0.04 (approx.)	0.02 (approx.)
NMWL (kDalton)			200	50
Tested by	Bubble point	Bubble point	Dextran retention	Dextran retention
Properties				
Temperature	4–135°C	−100–150°C	4–135°C	−100–150°C
Max. pressure (25°C)	6 bar	10 bar	6 bar	10 bar
Continuous	2–10	0–14	2–12	4–10 (> 50°C)
Intermittent	1–13	0–14	1–13	4–10 (> 50°C)
Organic solvent compatibility	Limited	Broad	Limited	Broad
Protein binding	Very low	High	Medium	High
Biocompatibility USP test	Pass	n/a	Pass	n/a
Abrasion resistance	Poor	Excellent	Poor	Excellent

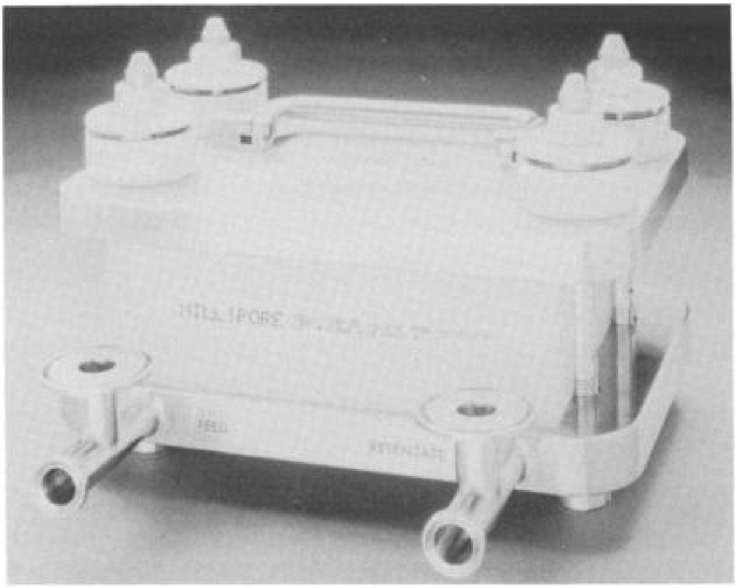


Figure 8.23. A 'Pellicon' cassette holder for cross-flow filtration. (Photograph: Millipore Corporation)

Whatman's ranges of track-etched microfiltration media are sold under the Nuclepore and Cyclopore brand names. Cyclopore in polycarbonate and polyester, Nuclepore in polycarbonate and mixed cellulose esters (CA and CN). Typical flux data and other values are given in Table 8.12 for the Nuclepore media. Cyclopore has a similar range of pore sizes (0.1–12 μm) and is slightly thicker (8–20 μm). Values of flux decrease with pore size and there is a corresponding increase in the bubble point pressures.

Common polymeric materials used for ultrafiltration membranes are regenerated cellulose and polysulphone or polyethersulphone, which are available in a range of molecular weight cut-off values, as illustrated by Millipore's media in Table 8.13.

Membrane area data for ultrafiltration hollow fibre cartridge units with polysulphone membranes are given in Table 8.14. These membranes have internal diameters between 0.5 and 1.5 μm and are free from macrovoids. For pure water, the cross-flow velocity will have little, if any, effect on flux. However, this is not the case with real process fluids, where the build-up of solutes at the membrane surface induces concentration polarization that reduces the flux.

The performance of an ultrafiltration membrane is defined in terms of its ability to retain molecules of a specific size, i.e. a rejection factor R, which is expressed as a number between 0 and 1 (or sometimes as a percentage). Values of rejection are not absolute values for any single membrane or solution, but depend upon conditions of operation, the concentration of the feed solution, the

Table 8.12 Track etched 'Nuclepore' microfiltration membranes[d]

Rated pore size (μm)	Rated pore density (pores/cm²)	Nominal wt. (mg/cm²)	Nominal thickness (μm)	Bubble point[c]		Typical flow rates	
				psi	bar	Water[a] (ml/min/cm²)	Air (l/min/cm²)
12.0	1×10^5	1.0	8	< 1	> 0.07	3000	85[b]
10.0	1×10^5	1.0	10	> 1	> 0.07	2500	65[b]
8.0	1×10^5	1.0	7	3	0.21	2000	40[b]
5.0	4×10^5	1.0	10	3	0.21	2000	55[b]
3.0	2×10^6	1.0	9	7	0.48	1500	50[b]
2.0	2×10^6	1.0	10	9	0.62	350	22
1.0	2×10^7	1.0	11	14	0.96	250	25
0.8	3×10^7	1.0	9	18	1.24	215	24
0.6	3×10^7	1.0	10	29	2.00	115	10
0.4	1×10^8	1.0	10	42	2.90	70	11
0.2	3×10^8	1.0	10	82	2.65	20	4.0
0.1	3×10^8	0.6	6	> 100	> 6.90	4.0	1.5
0.05	6×10^8	0.6	6	> 100	> 6.90	0.7	0.70
0.015	6×10^8	0.6	6	> 100	> 6.90	< 0.01	0.024

[a] Typical flow rate using water or air at 10 psi (0.7 bar).

[b] 5 psi (0.35 bar).

[c] Water bubble point.

[d] Whatman International Ltd.

flow rate and the extent of concentration polarization at the membrane surface. Rejection coefficients vary with the molar mass of the solute, as shown in Figure 8.24 for the ultrafiltration of dextran and with the membranes of Table 8.13. The use of polydisperse dextran solutions is claimed to be a better retention test marker than single-protein solutions, to ensure quality control of the rejection performance.

The tubular membranes illustrated in Figure 8.7 are the basis for PCI Memtech's range of RO, NF and UF separation systems, which have now been extended to cover microfiltration, while the types supplied now include spiral wound modules as well as ceramic tubes. There are 22 items in the tubular membrane range, covering reverse osmosis, nano- and ultrafiltration, and 9 items in the spiral wound list.

An ultrafiltration specialist, Koch Membrane Systems, has, for just industrial water and wastewater treatment, 10 different systems, all covering cut-off figures of 50–120 kD. There are three tubular formats, in PVDF, four hollow fibre formats, variously in PAN and polysulphone, and three spiral wound, also in PVDF.

A/G Technology is a hollow fibre specialist, providing membranes and membrane systems for microfiltration and ultrafiltration. The microfiltration cartridges have pore cut-off sizes of 0.1, 0.2, 0.45 and 0.65 μm, while the ultrafiltration cartridges have nominal molecular weight cut-off (NMWC) values of 1000–750 000. Membrane areas run from less than 0.01–28 m^2.

Table 8.13 Millipore membranes for ultrafiltration[b]

Specifications	PL series	PT series
Material	Regenerated cellulose on polypropylene	Polyethersulphone on polypropylene
	NMWL (kD)	1 PLAC
	3 PLBC	
	5 PLCC	10 PTGC
	10 PLGC	30 PTTK
	30 PLTK	50 PTQK
	100 PLHK	100 PTHK
	300 PLMK	300 PTMK
Retention specifications	See Figure 8.24	See Figure 8.24
Properties		
Temperature	4–50°C	4–50°C
Maximum pressure	7 bar	7 bar
pH range (25°C)		
Continuous	2–12	1–14
Intermittent (e.g. cleaning)	2–13	1–14
Organic solvent compatibility	Broad[a]	Limited
Protein binding	Very low	High
Susceptibility to antifoam fouling	Low	High

[a] In Prostak-UF modules only.

[b] Millipore Corporation.

Table 8.14 Membrane area values for UF polysulphone membranes

Membrane area as a function of housing and fibre/tubule internal diameter

Cartridge housing identifier	Fibre/tubule internal diameter code	Fibre/tubule internal diameter (mm)	Cartridge membrane area	
			sq. ft	sq. m
3	C	0.5	0.16	0.015
	D	0.75	0.10	0.009
	E	1	0.08	0.007
4	C	0.5	0.70	0.065
	D	0.75	0.50	0.046
	E	1	0.35	0.032
4X2TC	H	2	0.8	0.073
	K	3	0.5	0.046
5	C	0.5	3	0.28
	D	0.75	2	0.19
	E	1	1.5	0.14
6	C	0.5	6	0.56
	D	0.75	4	0.37
	E	1	3	0.28
	H	2	2.4	0.22
	K	3	1.6	0.15
8	C	0.5	6.7	0.62
	D	0.75	5	0.46
	E	1	3.75	0.35
9	C	0.5	15	1.4
	D	0.75	10	0.93
	E	1	7.5	0.7
	H	2	6	0.55
	K	3	4.9	0.45
10	H	2	12.1	1.1
	K	3	8.8	0.82
35, 35A 35STM	C	0.5	14	1.3
	D	0.75	11	1
	E	1	8.5	0.8
55, 55A 55R, 55STM	C	0.5	36	3.4
	D	0.75	27	2.5
	E	1	23	2.1
	H	2	14	1.3
	K	3	10.6	1
75, 75R	C	0.5	65	6
	E	1	40	3.7
	H	2	27	2.5
	K	3	20	2

Aided by the well-known non-stick properties of PTFE, the membranes made from ePTFE have proved to be highly successful, especially for use in fabric dust filters, using all kinds of cleaning mechanism: shaker, reverse flow or pulse jet. Versions are available utilizing a variety of substrate materials to suit different operating temperatures, as illustrated by the Tetratex media of Tables 8.15 and 8.16.

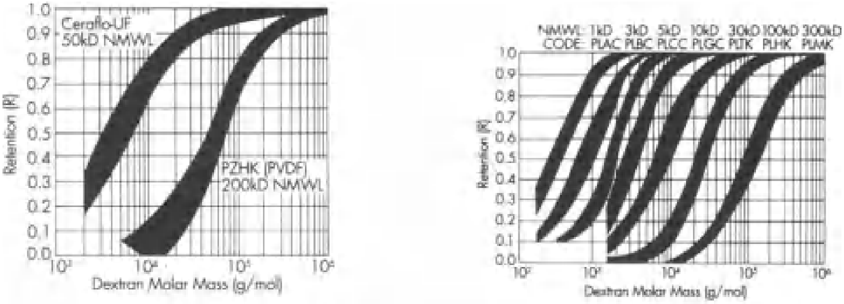
The use of ePTFE laminated fabrics in dust filters is beneficial by comparison with conventional fabrics in terms of air/cloth ratio (flow per unit area), pressure drop, bag life, and lower dust emission values. Several case histories are summarized in Table 8.17.

W L Gore, the originators of ePTFE, has recently introduced a new form of Gore-Tex ePTFE membrane, which, laid on a polyester needlefelt, is being marketed as a High Durability filter bag. The company also has a membrane medium offering catalytic destruction of dioxins and furans, and has established the Pristyne brand name for a series of filter bags using ePTFE membranes on substrates made from seven different fibres, as felts, wovens or spunbonds.

Dow is one of the largest membrane material makers in the world, largely for the reverse osmosis market, under the Filmtec brand name. Data for water treatment using these polyamide membranes are given in Table 8.18.

8.6.2 Inorganic membranes

In high-temperature processes with hot aggressive fluids, filtration requirements can only be met by a limited number of materials. Carbon is one such material well known for its corrosion resistance. Membranes made from carbon are typically a composite structure of a very thin layer of porous carbon applied to the internal surface of a narrow diameter carbon fibre/composite support tube. The membrane tubes are assembled in monolithic joint-free bundles (see Figure 8.25) using a carbon composite tube sheet. The bundles are then mounted in a shell made from an appropriate compatible material such as PTFE-lined steel or stainless steel. The carbon tubes are 6 mm internal diameter and 1.5 mm thick, giving good mechanical resistance, i.e. bursting pressures of 40 bar.



- *Dextran Retention Profile of Ceraflo and Durapore UF Membranes*

Dextran Retention Profile of Regenerated Cellulose UF Membranes

Figure 8.24. Rejection characteristics of the UF membranes in Tables 8.11 and 8.13.

Table 8.15 'Tetratex' PTFE membrane/needle felt laminates[a]

Product code	6202	6211	6212	6222	6272	6232	6242	6262
Fibre	PE	PE	PE	PP	$PE_{Epitropic}$	P-84	Nomex	Ryton
Scrim	PE	None	PE	PP	PE	P-84	Nomex	Ryton
Weight (g/m^2)	400–490	510–590	510–590	490–560	440–520	440–520	440–520	510–560
Thickness (mm ± 0.25)	1.1	1.5	1.5	1.8	1.3	2.3	1.4	1.5
Width (mm ± 12.5)	1690	1690	1690	1690	1690	1730	1730	1690
Air permeability (l/dm^2/min @ 20 mm WG)	39–54	39–54	39–54	39–54	39–54	39–54	39–54	39–54
Continuous service temperature (°C)	135	135	135	120	135	245	205	190
Minimum Mullen burst pressure (kg/cm^2)	25	32	32	35	32	25	28	28
Minimum breaking strength (kg/5 cm)								
Machine direction	27	34	34	36	34	67	54	45
Across machine	54	67	67	45	67	101	76	45
Maximum elongation (% @ 23 kg/5 cm)								
Machine direction	10	8	8	8	10	n/a	n/a	8
Across machine	10	8	8	8	10	n/a	n/a	8
Maximum % unrestricted shrinkage in 24 h.	3	3	3	3	3	1.5	2	3
dry heat @ specified °C	177	177	177	105	177	1 h @ 245	1 h @ 230	1 h @ 205

[a] Donaldson Tetratec.

This carbon tube module has a great tolerance to the many thousands of back flushing operations at 8–12 bar typically used to clean the membrane of fouling layers *in situ*. Sealing of the bundles into the end plates ensures no bypass problems. The membranes are tolerant to strong acids at all concentrations, hot organic solvents and alkaline baths, but not to strong oxidizing agents. Carbon is a fully biocompatible material, recommended for alimentary and other biological fluids.

In recent years, there has been substantial development of ceramic membranes, with specific features of heat resistance, a high degree of resistance to organic solvents, good cleaning potential, high mechanical strength, applicable in a wide pH range, a long life cycle and a good price/performance ratio. Modules are supplied in a wide range of sizes to meet most applications of microfiltration with a pore size of 0.1–5 μm. The filtration systems are constructed as cylinders equipped with ceramic filtration tubes. The disadvantages of ceramic membranes compared to polymeric membranes are that they are brittle, the surface area/volume ratio is lower and the cost is relatively high.

Typical characteristics of ceramic membranes are shown in Table 8.19. Ceramic ultrafiltration membranes can be constructed in several layers, by successively depositing finer layers of α- and γ-alumina onto a ceramics support tube of high porosity. The top layer is the real membrane layer and is responsible for the separation; it needs to be very thin to achieve a high flux. Sizes start from a membrane area of 0.05 m^2 with typical filtration flows of 3–9 dm^3/h, up to a membrane area of 4 m^2 at filtration flows of 175–500 dm^3/h. The configuration is based on a porous hexagonal log into which a series of 4 mm diameter channels are introduced. The elements are either single- or 19-channel design, with the latter giving a 0.2 m^2 internal filtration surface for a 900 mm long, 25 mm diameter unit. The operating range of pH is 1–11 at 700°C and 1–14 at 250°C. For microfiltration the pore size cut-off sizes can vary from 0.05 to 10 μm. Typical water fluxes are shown in Figure 8.26 for microfiltration membranes.

Table 8.16 'Tetratex' PTFE membrane/woven glass laminates[a]

Product code	6254	6253	6252	6255
Average weight (g/m^2)	305	475	543	760
Actual weight (g/m^2)	322–373	458–526	543–627	712–814
Width (mm ± 12.5)	978	978	1650	1650
BGF style no.	427	454	448	477
Finish style no.	615	615	615	615
JPS style no.	3602	631	648	7577
Finish style no.	Teflon B	Teflon B	Teflon B	Teflon B
Air permeability (l/dm^2/min @ 20 mm WG)	34–44	29–39	24–34	29–39
Continuous service temperature (°C)	260	260	260	260
Minimum Mullen burst pressure (kg/cm)^2	35	42	42	63
Minimum tensile strength (kg/5 cm)				
Machine direction	260	450	270	450
Across machine	144	225	225	315

[a] Donaldson Tetratec.

Table 8.17 Case histories demonstrating benefits of PTFE laminates for dust filters[a]

Dust:	PVC		Lead oxide		Sugar		Boiler flyash		Cement	
System:	Spray dryer		Processing		Silo exhaust		Exhaust gases		Crusher venting	
Filter type:	Reverse air		Shaker		Pulse jet		Shaker		Reverse air + shaker	
Filter media:	Acrylic	GoreTex	Dacron	GoreTex	Egg-shell polyester	GoreTex	Silicone cotton	GoreTex	Polyester felt	GoreTex
Air/cloth ratio	2/1	3.6/1	1.5/1	3/1	10/1	10/1	7/1	7/1	5/1	5/1
Gas flow (m^3/min)	840	1540	616	1232	NA	22	NA	294	NA	266
Pressure loss (mm WG)	279	51	76	76	254	25	203	102	178	64
Bag life (months)	6	24	12	26	1/2	12	3	15	6	17
Comments		[b]	[c]				Visible plume	No plume visible		5 µm dust

[a] W.L. Gore & Associates, Inc.

[b] Up to 75% increase in production rate (kg/h).

[c] At A/C ratio of 3/1, pressure loss > 300 mm WG.

The LCI Corporation sells what is basically a stainless steel tubular microfiltration system, which has a fine sintered TiO_2 membrane on a stainless steel support. For ultrafiltration, a ceramic membrane is laid on top of the titania, and for nanofiltration, a synthetic polymer membrane is laid on top of the ceramic one. The resultant separations achieved run from 1 µm down to 0.001 µm.

A fully metallic membrane is offered by GKN Sinter Metal Filters, in the form of its SIKA-R. . .AS medium. This involves powder metal technology to produce a base of coarse metal powder, and a thin layer (200 µm) of the same alloy diffusion bonded to it, during the sintering process. Operation up to 900°C in an oxidizing atmosphere is possible^(10), with efficient removal of dust particles in the 0/5–10 µm range.

8.7 Guidance on Membrane Selection

The performance and selection of a membrane is affected by a multiplicity of factors associated with the membrane medium, the particulate material, the fluid carrier phase, the conditions of operation, and the interactions among all these

Table 8.18 Filmtec nanofiltration membranes[e]

Grade	Diameter[a]	Area[b]	Flow[c]	Rejection[d]
NF90-2540	61	2.6	2.3	99.0 ($MgSO_4$)
NF90-4040	99	7.6	7.0	99.0 ($MgSO_4$)
NF90-400	201	37.2	28.4	85–95 (NaCl)
NF200-400	201	37.2	30.3	35–50 ($CaCl_2$)
NF270-400	201	37.2	55.6	40–60 ($CaCl_2$)
NF270-2540	61	2.6	3.2	99.0 ($MgSO_4$)
NF270-4040	99	7.6	9.5	99.0 ($MgSO_4$)
NF400	201	37.2	25.7	98.0 ($MgSO_4$)

[a] Element diameter (mm) for 1016 mm length.
[b] Separation area (m^2).
[c] Water flow (m^3/day).
[d] Stabilized flow rejection (%).
[e] The Dow Chemical Company.

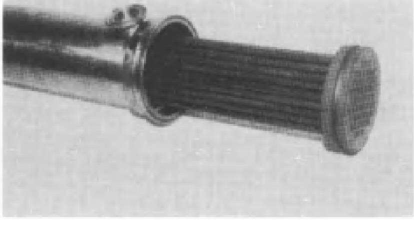


Figure 8.25. Carbon fibre cross-flow filtration module.

Table 8.19 Characteristics of ceramic membranes

Product characteristics	Microfilter	Ultrafilter	Ultrafilter
Membrane composition	Alpha Alumina	Gamma Alumina	Zirconia Alumina
Available pore size	0.2–5 µm	50–1000 A	200–1000 A
Burst pressure	Limited by the maximum housing operating pressure		
Maximum operating pressure	120 psig (standard, higher pressures optional)	120psig (standard, higher pressures optional)	120psig (standard, higher pressures optional)
Water permeability 20°C			
0.2 µm pore Ø	2000 l/h m^2 bar		
40 A° pore Ø		10 l/h m^2 bar	
500 A° pore Ø			850 l/h m^2 bar
Resistance to corrosion	Can be washed with NaOCl 2% NaOH 2% HNO_3	Limited	Same as Microfilter
Steam sterilizable*	Yes	Yes	Yes

* The Membralox Steam Sterilization Procedure must be followed.

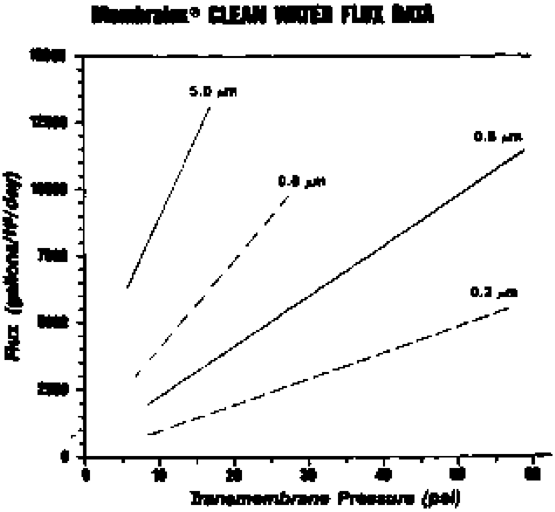


Figure 8.26. Typical clean water flux/pressure curves for ceramic membranes.

factors. Of particular importance are those that relate to the particulate material (size, shape, concentration, distribution, zeta potential, and whether it is inert or viable), the membrane structure (pore size, rating, asymmetry), the stability of the membrane (chemical, mechanical, thermal, hydrolytic, extractables, shedding), and the retention mechanisms (absorption, adsorption, impingement, cake retention).

The selection of an optimum (or at least an appropriate) membrane and system will usually require a trade-off between various possible alternatives. Table 8.20 summarizes the typical information required to permit a systematic analysis of the available options.

The important performance indicator in microfiltration is the volumetric flow through the membrane, which is directly proportional to the applied pressure difference across it. For most membranes, values of fluid flux are quoted for particular conditions of temperature and applied pressure, with specific fluids, which typically are water, air and methanol.

From the data normally available for membranes, it is possible to calculate the permeability constant for the membrane for a particular fluid. In principle, this should be independent of the fluid if there are no interactions between the membrane and the feed slurry. The important factor in microfiltration is not the flux of clean fluid but the performance during actual filtration. Performance is potentially affected by several solute-related parameters and specifically by concentration polarization and fouling.

A good general review of microfiltration is given in Table 8.21. This was produced originally by Costar, but is still generally applicable.

Microfiltration membranes are routinely used in a range of analytical procedures to determine particulate contamination in a wide range of gases and liquids. The procedures include the detection of micro-organisms in a variety of waters and process fluids (foods, beverages, pharmaceuticals) where the membrane traps the micro-organism and is subsequently used as the culture medium, in passive cell growth studies and in so-called blotting applications. A range of different types of membrane is used, including:

1. mixed cellulose esters – e.g. biologically inert mixtures of cellulose acetate and cellulose nitrate; suitable for a wide range of analytical procedures, including gravimetric analysis by the ashing technique and light microscopy;
2. PTFE – either unlaminated or laminated to a support of high-density polyethylene or polypropylene; for applications with gases and non-aqueous fluids, with acids and alkalis, and for higher temperature operation;
3. silver – ideal collection medium for analysis of crystalline silica by X-ray diffusion and for the analysis of organics;
4. PVDF – suitable for aqueous or organic samples; and
5. track-etched polycarbonate – recommended for scanning and transmission electron microscopy.

Commercial polymeric ultrafiltration membranes are designed to give the requirement of high permeability and high permselectivity. An extensive range of membrane materials is used including polysulphone, polyethersulphone, PAN, polyimide, cellulose acetate, aliphatic polyamides, the oxides of zirconium

Table 8.20 Membrane filtration selection criteria

Criteria	Characteristics
Fluid properties	What liquid or gas is being filtered? What are the fluid properties (pH, viscosity, temperature, surface tension, stability, etc.)? What are the important chemical components and their concentrations? What pretreatment has been given to fluid? What is the desired minimum and maximum flow rate? What is the product batch size?
Pressure characteristics	What is the maximum inlet pressure? What is the maximum allowable differential pressure? Is there a required initial differential pressure? What is the source of pressure (centrifugal/positive displacement pump, gravity, vacuum, compressed gas, etc.)?
Sterilization/sanitization	Will the filtration system be steamed or autoclaved? Will the system be sanitized with chemicals or hot water? How many times will the system be sterilized or sanitized? What are the sterilized/sanitized conditions?
Hardware	Is there a restriction on the material for the housing? Is there a recommended housing surface finish? What are the inlet and outlet plumbing connections? Is there a size or weight restriction?
Filter	What is the size of particles to be retained? Will the filter be integrity tested; if so, how? Will this be a sterilizing filtration? Is there a minimum acceptable level of particle removal? Is there a recommended filter change frequency?
Temperature	What is the temperature of the fluid? Temperature affects the viscosity of liquids, the volume of gases and the compatibility of the filtration system.
Configuration	How will the filtration systems be configured – in series or in parallel? *Parallel flow arrangement*: uses several filters of equal pore size simultaneously to either increase flow rates, extend filter service life or lower differential pressure. It also permits filter changeout without system shutdown. The total flow rate and differential pressure is equally distributed across each filter. For any given flow rate, the differential pressure can be reduced by increasing the number of filters in parallel. *Series flow arrangement*: uses a group of filters of descending pore sizes to protect the final filter when the contaminant size distribution indicates a wide range or a high level of particulates that are larger than the final pore size. You can also use additional filters of the same pore size in series to improve particle removal efficiency, to protect against the possible failure of a unit within the system, and to add an extra measure of safety in any application.

Table 8.21 Guidance on membrane applications

Application	Recommended filter media			References/comments
	Description	Pore size (μm)	Diameter (mm)	
Air pollution analysis				
Asbestos, airborne	Mixed esters of cellulose	0.45, 0.8, 1.2	25	NIOSH Methods 7400 and 7402: EPA-CFR763-Fed Reg. 1987, pp. 41826–41905.
Cadmium	Mixed-esters of cellulose	0.8	37	NIOSH Method 7048
Carbon black	PVC	5.0	37	NIOSH Method 5000
Cyanides	Mixed-esters of cellulose	0.8	37	NIOSH Method 7904
Lead	Mixed-esters of cellulose	0.8	37	NIOSH Method 7082
Lead sulphide	PVC	5.0	37	NIOSH Method 7505
Nuisance dust	PVC	5.0	37	NIOSH Methods 0500 and 0600
Quartz in coal dust	Mixed-esters of cellulose	0.8	37	NIOSH Method 7602
Silica, crystalline	PVC	5.0	37	NIOSH Method 7601
Welding and brazing fume	Mixed-esters of cellulose	0.8	37	NIOSH Method 7200
Zinc oxide	PVC	0.8	25	NIOSH Method 7502
Trace elements	Polycarbonate aerosol-type	0.2–8.0	25–47, 8 × 10 in	Low trace metal contamination (Br, Pb, Zn, etc.) with aerosol holders
Bacterial Analysis				
Total coliform count	Mixed-esters of cellulose	0.45	47	*Standard Methods/Water & Wastewater*, 17th Ed., 9222B
Fecal coliform	Mixed-esters of cellulose	0.7	47	*Standard Methods/Water & Wastewater* 17th Ed., 9221
Legionella	Polycarbonate	0.2	37, 47	
Heterotrophic plate count (HPC) (formally known as standard plate count)	Mixed-esters of cellulose	0.45	47	*Standard Methods/Water & Wastewater*, 17th Ed., 9215D
Direct total microbial count	Polycarbonate, Mixed-esters of cellulose	0.2 5.0	25 25	*Standard Methods/Water & Wastewater*, 17th Ed., 9216B
Escherichia coli	Mixed-esters of cellulose	0.45	85	For *E. coli*, use REC-85® food micro membrane, direct plating technique in petri dish
Yeast and moulds	Mixed-esters of cellulose	0.65–1.2	13–47	
	Polycarbonate	0.6, 0.8	13–47	

Table 8.21 *(continued)*

Application	Recommended filter media			References/comments
	Description	Pore size (μm)	Diameter (mm)	
Sterility testing	Mixed-esters of cellulose	0.22, 0.45	47	For sterility testing, use gridded, sterile hydrophobic edge membranes (see *Code of Federal Regulations*, Title 21 #436)
Blood filtration				
RBC deformability	Polycarbonate Hema-Fil	4.7–5.0	13, 25	
Plasmapheresis	Polycarbonate	0.6–1.0	90	Use fluid cross-flow, thin channel technique
Cell culture	Polycarbonate	0.4–3.0	13–47	Fit membrane to petri dish or culture plate
Chemotaxis				
Epithelial, fibroblasts, neutrophils, polymorphonuclear leukocytes	Polycarbonate (chemotaxis membrane, PVP-free)	2.0–8.0	13	For chemotaxis, use blind well or modified Boyden chambers
Macrophage	Polycarbonate (chemotaxis membrane)	2.0–8.0	13	
Cytology				
Cytopreparative and cyto-diagnostic methods	Polycarbonate, mixed-esters of cellulose	2.0–8.0	25, 47	Use with Swin-Lok holder or vacuum filtration
		3.0—5.0	19×42	
EPA testing				
EPA toxicity characteristic leaching procedure (TCLP)	Glass fibre	0.7	90, 142	EPA Ref. 40CFR Part 268 Fed. Reg. 53:18795 May 24, 1988
Fuel testing	Mixed-esters of cellulose	0.45, 0.8	47	ASTM D2276
	Fuel monitor	0.8	37	
General filtration				
General clarification or prefiltration	Mixed-esters of cellulose	0.8–5.0	13–293	
	Glass fibre	D49, D59, D79	13–293	
Beverage stabilization	Mixed-esters of cellulose	0.45–1.2	47–293	
Particulate removal	Polycarbonate	0.1–5.0	13–293	
	Mixed esters of cellulose	0.1–5.0	13–293	
	Glass fibre (D49, D59, D79, 0.7 nominal)		10–293	

Table 8.21 *(continued)*

Application	Recommended filter media			References/comments
	Description	Pore size (µm)	Diameter (mm)	
Fine aqueous clarification	Polycarbonate	0.6–1.0	13–293	
	Mixed-esters of cellulose	0.65–1.2	13–293	
Bacterial removal	Mixed-esters of cellulose	0.22–0.45	13–293	
Adsorbable organic halogens (AOX)	Polycarbonate	AOX®	25, 47	
Alkaline elution, DNA	Polycarbonate	0.8, 2.0	25, 47	PORETRAITS® (NUCLEPORE®) Winter 1988
Forensic analysis	Polycarbonate	0.4	13	Sample collection for S.E.M.
Liposome extrusion	Polycarbonate	0.1–0.4	25–76	Use with high-pressure holder
HPLC solvent purification				
Samples, aqueous	Mixed-esters of cellulose	0.45	13, 25	
Samples, organic	PTFE	0.45	4–25	
Solvents	PTFE	0.45	47	
Parasitology				
Microfilariae (*Dirofilaria immitis*)	Polycarbonate	5.0	2.5	Use Swin-Lok holder or stainless steel syringe holder
Schistosoma haematobium	Polycarbonate	12.0	13	
Pharmaceuticals (human or veterinary)				
Small volume parenterals	Syrfil®-MF	0.22	25	
Prefiltration	Glass fibre	D49–D79	10–293	Parenteral processing must conform with FDA GMPs: 21 CFR 210 and 211
Sterilization	Mixed-esters of cellulose	0.22	13–293	
Protein or virus assay and purification				
Fractionation or collection	Polycarbonate	0.015–0.1	25–293	For protein or virus filtration, use Stirred Cell Series – S25, S43, S76 Swin-Lock® holders, or stainless steel holders
Purification	Polycarbonate	0.015–0.4	25–293	
Colony hybridization	Mixed-esters of cellulose	0.45	25, 85	
Low binding	Polycarbonate	0.4	25	
Serum filtration				
Prefiltration	Glass fibre	D49–D79	10–293	
	Mixed-esters of cellulose	0.3–1.2	13–293	

Table 8.21 (*continued*)

Application	Recommended filter media			References/comments
	Description	Pore size (μm)	Diameter (mm)	
Bacterial removal	Mixed-esters of cellulose	0.1–0.22, 0.45	13–293	
Mycoplasma removal	Mixed-esters of cellulose	0.1	13–293	
Sterilizing filtration				
Air venting	Syrfil®-FN (PTFE)	0.2	25, 50	
Fluids-aqueous	Mixed-esters of cellulose	0.22, 0.45	90–293	
Air or gas	PTFE	0.2	25–293	
Tissue culture media filtration				
Prefiltration	Glass fibre	D49	47–293	
	Mixed-esters of cellulose	0.1	4–293	
Bacterial removal	Mixed-esters of cellulose	0.22	90–293	
Mycoplasma removal	Mixed-esters of cellulose	0.1	90–293	
Water microbiology				
Escherichia coli	Mixed-esters of cellulose	0.45	47	*Standard Methods/Water and Wastewater*, 17th Ed., 9260F
Fecal coliform	Mixed-esters of cellulose	0.7	47	*Standard Methods/Water and Wastewater*, 17th Ed., 9222D
Fecal streptococcus	Mixed-esters of cellulose	0.45	47	*Standard Methods/Water and Wastewater*, 17th Ed., 9230C
Fine particles	Mixed-esters of cellulose	0.45	47	
Giardia lamblia	Polycarbonate	5.0	293	Cyst Concentration and Analysis, EPA 600/S2-85/027 Sem. 1985
Leptospires	Mixed-esters of cellulose	0.45	13, 25	*Standard Methods/Water and Wastewater*, 17th Ed., 9260I
Phytoplankton	Mixed-esters of cellulose	1.2–5.0	47	*Standard Methods/Water and Wastewater*, 17th Ed., 10200C
Heterotrophic plate count (HPC) – formerly standard	Mixed-esters of cellulose	0.45	47	*Standard Methods/Water and Wastewater*, 17th Ed.,
Salmonella	Mixed-esters of cellulose	0.45 0.45	142 47	*Standard Methods/Water and Wastewater*, 17th Ed., 9260B

Table 8.21 (*continued*)

Application	Recommended filter media			References/comments
	Description	Pore size (µm)	Diameter (mm)	
Suspended particulates	Mixed-esters of cellulose	1.2–5.0	47	
	Polycarbonate	1.0–5.0	47	
	Glass fibre	0.7 nom	47	
Direct total microbial count	Polycarbonate	0.2	25	*Standard Methods/Water and Wastewater*, 17th Ed., 9216B
	Mixed-esters of cellulose	5.0	25	
Total coliform count	Mixed-esters of cellulose	0.45	47	*Standard Methods/Water and Wastewater*, 17th Ed., 9222B
Vibrio cholerae	Mixed-esters of cellulose	0.45	142	*Standard Methods/Water and Wastewater*, 17th Ed., 9260H
Virus concentration	Mixed-esters of cellulose	0.45	47, 90	*Standard Methods. Water and Wastewater*, 17th Ed., 9510B
	Glass fibre, D49		142	

and aluminium, and other ceramics. Membranes are produced as flat sheets, also used as spiral wound modules, and in tubular or hollow fibre forms.

The flux of the liquid through ultrafiltration membranes is much smaller than through microfiltration membranes, in the general range of 0.1–10 m^3/day, the actual figure depending upon many structural parameters. For pure water (or other liquids) there is a linear correspondence between flux and transmembrane pressure. With solutions there is a tendency for the flux to reach an asymptotic value with increasing pressure. This is a result of several factors, including concentration polarization, gelation, fouling and osmotic effects.

The selection of a membrane for ultrafiltration will require determining the molar mass of the species to be separated and selecting a membrane with a limiting rejection ($R \approx 1.0$) under anticipated conditions of operation. Small-scale application tests will generally need to be performed. Ultrafiltration membranes are rated in terms of their nominal molecular weight cut-off (NMWC). There are no industry-wide standards for this rating, hence manufacturers use different criteria for assigning ultrafiltration pore sizes. For example, for the concentration of protein, the protein should be larger than the NMWC of the membrane by a factor of 2–5. The greater the difference (i.e. the tighter the membrane pore size), the higher the protein yield. The protein shape, in addition to its molecular weight, plays a role in determining its retention by the membrane. The more globular the protein, the greater its retention, while linear

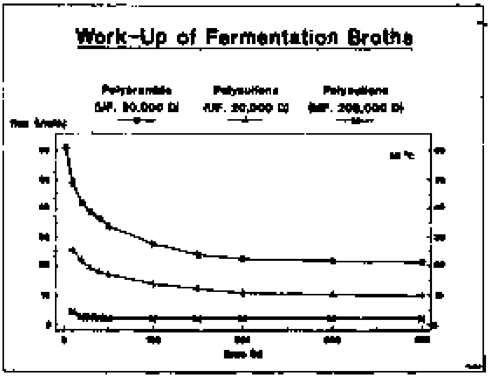


Figure 8.27. Variation of UF flux with conversion of a fermentation broth.

proteins may require a tighter membrane for high recoveries. Moreover, protein shape may be affected by solution pH or salinity.

Figure 8.27 shows the typical effect of time on the concentration of a fermentation broth with two types of ultrafiltration membrane, respectively hydrophilic polysulphone and polyaramid. Typically, the initial loss of flux is relatively rapid, whilst for longer times the decline in flux is less severe. The difference in the membrane flux behaviour is due to the greater tolerance of the very hydrophilic polyaramid membrane to fouling.

Although the separation mechanism of ultrafiltration is broadly considered to be one of sieving, in practice the effect of concentration polarization limits the flux, due to a build-up of solute in the concentration boundary layer on the feed side of the membrane. At sufficiently high pressures, gelation of the macromolecules can occur, resulting in the formation of a thin gel layer on the surface; this can act as a secondary membrane. Increasing the feed stream circulation rate will generally reduce the thickness of the gel layer and increase the flux. Operation within the turbulent flow regime may significantly enhance permeation by reducing the thickness of both the gel and fouling layers, by transferring solids from the membrane surface back into the bulk stream. As with microfiltration, factors of chemical compatibility of materials with the solution will need to be addressed.

8.8 References

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CHAPTER 9

Replaceable Filter Elements

To provide an effective filter, the filter medium has to be held in some kind of housing that provides a complete seal between upstream and downstream sides of the medium, and to provide inlet for the feed and exit for the filtrate or permeate. It is convenient in many types of filter to mount the medium on some kind of support structure, which enables it to be taken out of its housing to be cleaned or replaced. It is this replaceable structure, or filter element, that is the subject of this chapter.

9.1 Introduction

Replaceable filter elements may be almost entirely composed of the filter medium, as with the sheets in a sheet filter, or they may be a complex assembly of supporting core, pleated medium (itself perhaps made of several layers, including support and retaining cover), and an outer shield. So long as an element can be changed, whether to discard the old one, or to clean it, then it is covered in this chapter. Some of these elements are made from media that have been discussed in earlier chapters, while others are specially fabricated to achieve a filtration task, without the use of what could be recognized as filter media.

Although the term 'cartridge' has a specific meaning smaller in scope than that of this chapter, it is convenient to use the word as shorthand for 'replaceable filter element'. A filter cartridge in this broader sense is thus any component of a filter that includes the filter medium, and that can be removed from the filter as an integral unit, either for servicing or for replacement by a new, but identical component.

There are two reasons for including a chapter on cartridges in a book overtly devoted to filter media. One is that the immense diversity of commercially available cartridges forms a uniquely important and versatile category of equipment, which collectively utilizes almost the entire range of media described in the preceding chapters. The other is that there are yet further types of filter media that exist only because of the structure of specially fabricated cartridges; a good example is the popular yarn-wound cartridge.

Cartridges provide a very convenient, versatile and often economic way to filter either liquids or gases, provided the concentration of solid or liquid contaminant is low; as a general guide, the concentration of particulates in a liquid should be less than say 0.01% by weight, with the particle size ranging downwards from about 40 μm to submicrometre sizes. If the solids concentration is much larger than this figure, then, unless the medium has a high dirt-holding capability, the service life of the cartridge will be inconveniently short.

In application, cartridges may be used for general clarification, polishing or sterilization. For liquids, most such duties are typically on a small or medium scale, but multiple cartridge units are used for substantial flows in some special applications, such as coalescer filters for aircraft refuelling. Cartridges play a major role in gas filtration at all scales of operation.

9.1.1 Types of cartridge

An important characteristic of a cartridge filter is the type of cleaning action to be taken, manually or automatically, when it becomes fully loaded with collected contaminant, as typically indicated by either an increase in back pressure or decrease of flow rate. In this regard, four categories of cartridge may be distinguished:

- the 'throwaway' or 'disposable' cartridge, which cannot be cleaned and is therefore replaced;
- the 'cleanable-in-place' cartridge, which can readily be cleaned (e.g. by intermittent reverse flow as part of the operating cycle) and reused several or many times, even if eventually it may need to be replaced;
- the 'service-cleanable' cartridge, which must be removed from the filter and subjected to specialized cleaning (e.g. in an ultrasonic bath), either on site or by returning to the manufacturer or to a service company; and
- the 'reclaimable' cartridge, which must be returned to the manufacturer who strips it down and rebuilds it after replacing the filter medium.

To a large extent, the differences between these cartridges result from the nature of the filter medium involved and the filtration mechanism by which it functions. For example, media functioning exclusively by surface straining and/or cake filtration can be easily cleaned. By contrast, depth filtration inevitably involves the trapping of particles within the depth of the medium, whence their removal is likely to be difficult or impossible; on the other hand, depth filtration can provide a relatively large dirt-holding capacity. Equally important, however, may be the exact conditions under which the filter is to be used, as well as the detailed design and construction both of the cartridge and of the filter housing.

So far as the chemical and processing industries are concerned, it is generally only the first two categories that are of practical importance. Examples of the application areas of the other categories are service-cleanable cartridges for the manufacture and processing of polymers and reclaimable cartridges for filters used in high-pressure hydraulic systems.

As cartridges are used to remove solid or liquid contaminants from a fluid flow, it goes almost without saying that they will eventually become too dirty for continued use and must then be cleaned or removed, for which purpose the process fluid flow must be stopped. Where only one filter is in use, such stoppage could cause inconvenience to the process operation. To achieve continuity of flow, therefore, *duplex* filter housings are used, in which two identical cartridge units are mounted side-by-side, so that the fluid flow can be switched from the dirty unit to the clean one, with almost no impact on fluid flow, and the dirty unit then cleaned, ready to take up its duty when required.

Where more than one cartridge is used, then the cleaning process can be operated in rotation, with a reverse flow pulse, for example, applied to individual cartridges, or small groups of them, in turn.

9.1.2 Element disposal

A feature of replaceable elements that is of growing importance is the nature of the materials of construction or, more particularly, the range of materials. Some elements are intended for once-only use, followed by disposal, and all elements eventually reach a point where they can no longer be reused and have to be discarded. Disposal practice increasingly requires material recycle, or disposal by controlled incineration. In either case, the nature of the discarded element could be critical to its ease of disposal, and, in general, the fewer the number of component materials the easier will be the disposal.

Ideally, an element should only have one material of construction, from which all parts of it are made: filter medium, supporting core, end caps, retaining screens, protective covers – everything. This is not easy, especially where a filter medium is a multi-layer material, with different layers doing different jobs, and, therefore, possibly needing to be made from different materials, but all manufacturers are now trying to make single-material elements.

9.2 Cartridges with Conventional Media

The replaceable elements in filters that are made from the media, woven and non-woven, paper, screen and membrane, discussed in preceding chapters, are of three major types:

- the panel (or cassette) used for air conditioning;
- the simple filter bag or pocket; and
- the cylindrically shaped cartridge, made in a variety of structures.

To these should be added the special modular cartridges employed for membrane media.

An essential feature of all of these types of cartridge is the need to maximize operating lifetime, i.e. to maximize the ability of the cartridge to hold the dirt removed from suspension. Especially in the case of surface filtration media, this need results in maximizing the filter surface area packed into a specific filter volume.

9.2.1 Ventilation filters

The media involved in the replaceable panels used in air conditioning systems are described in detail in Chapter 5. The underlying principles common to the evolution of many commercially available filter cartridges can be illustrated by following the developments in ventilation air filters from the very basic panel illustrated in Figure 9.1. This comprises a flat square sheet of filter medium, usually with retaining screens front and back, mounted within a cardboard frame so that the cartridge can be inserted into a metal support frame. In practice, the filtering material is typically of multi-layered construction, such as an active thick inner layer of synthetic polymer or glass microfibres sandwiched between protective outer coverings of open spunbonded fabric.

So as to increase the available filtering area and thereby to permit a correspondingly larger flow, a logical step from this elementary format is to pleat the filter medium, to give the form shown in Figure 9.2. Deeper and more closely packed pleats, with spacers to maintain a gap between adjacent pleats, as in Figure 9.3, provide yet higher active area for the same superficial face area of a cartridge. Another construction that involves even deeper pleats is the multi-pocket or bag filter shown in Figure 9.4. The types of media utilized in these various constructions are discussed in Chapter 5.

9.2.2 Filter bags

An extremely simple form of cartridge for liquid filtration is a fabric bag in the open filtration system illustrated in Figure 9.5; more usually, these bags are used as inserts in mesh baskets housed in an enclosed vessel, as in Figure 9.6, for operation at differential pressures up to 20 bar or more. Alternatively, the bags may be fitted as sleeves over a supporting cage of mesh or welded rods. The interest in bags for liquid filtration faded when higher efficiencies were

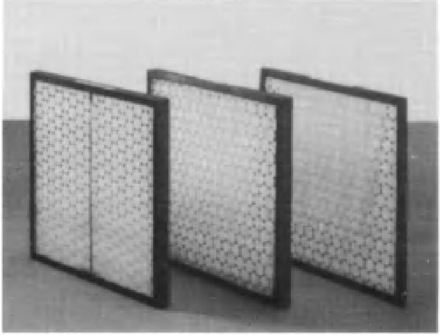


Figure 9.1. Flat panel air ventilation filter cartridges.

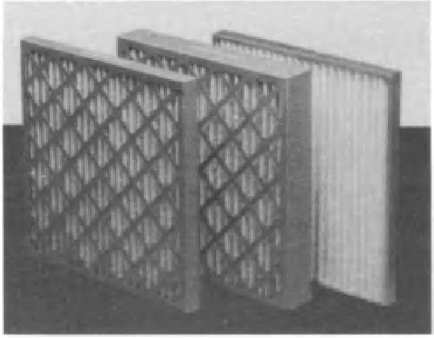


Figure 9.2. Pleated panel air ventilation filter cartridges.

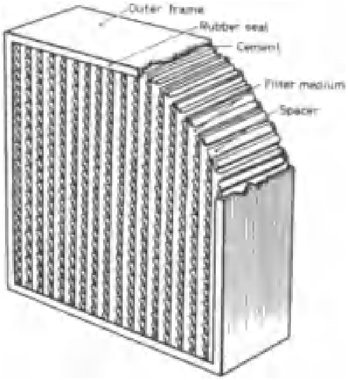


Figure 9.3. A typical high efficiency (HEPA) air filter.

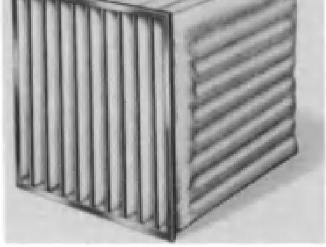


Figure 9.4. Multi-pocket or bag air filter.

demanded because the structure of the bag with a sown longitudinal seam allowed passage of larger particles. Now that manufacturers are able to offer seamless bags, the interest in such elements has returned.

The range of filter bags for liquid filtration offered by the Hayward group is very extensive, now that it includes the old GAF and Loeffler ranges. The products include needlefelt media, multi- and monofilament meshes, and meltblown polypropylene, the last as high efficiency, layered construction, capable of filtration down to 1 µm.

Bags may be of one or more layers, an extreme example of multi-layered construction being 3M's Series 500 bags, which contain 35 seamless layers; these comprise bypass layers with holes in them, transport layers between the

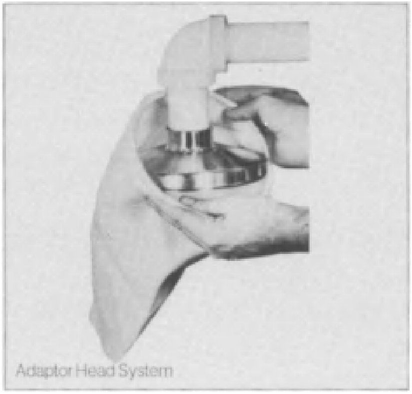


Figure 9.5. Fitting a bag filter to an adaptor head for open filtration.

Figure 9.6. Fitting a bag filter into an enclosed housing.

bypass layers, and finally 15 layers of meltblown microfibres, to achieve high flow rates and dirt-holding capacity at low pressure drops.

The filter bag for gas filtration is mentioned in Chapter 5 as the active element in fabric filters. The BHA Group, one of the world's largest suppliers to the air pollution control sector, supplies filter bags for air and gas filtration, made from polyester, polypropylene, acrylics, glass fibre, Nomex, Ryton, P84, and fluoropolymers. The range includes bags covered in ePTFE (the BHA-TEX range), with a microporous coating of ePTFE on felts or other non-wovens, providing efficiencies of 99.99% or more; the coating can be on the inside or the outside depending upon the direction of gas flow. Bags are made from all of these materials for fabric filters operating with reverse air or shaker mechanisms for dust cake removal, where the dust-laden air flows into the inside of the bag, with dirt collected on the inside, or with pulse jet or plenum pulse removal, where the air flow is from outside-to-in, and dirt collects on the outside of the bag.

A novel form of filter bag is sold by Albany International as its Star-Bag configuration. This uses a fabric bag supported on a cage so made as to allow the bag to take up a pleated shape, offering 1.7–2.4 times the filter area of a normal cylindrical bag. Star-Bags are available in polyester, homopolymer acrylic, polyphenylene sulphide, aramid, polyimide, glass fibre, polypropylene, and PTFE, as needlefelt or woven materials.

9.2.3 Cylindrical cartridges

Contrasting with the rectangular geometry of ventilation filters is the cylindrical form usual for the major family of cartridges both for liquids, and for compressed gases and for the air intakes of engines. Cartridges are also of increasing importance in general gas cleaning applications.

The simplest form of a cylindrical cartridge filter comprises a cylindrical vessel containing a tubular filtering element or cartridge. This may be either sealed at one end or open at both ends but suitably locked within the housing to produce the same results, as shown in Figures 9.7 and 9.8; flow is generally inwards through the wall of the element.

A Y-type or basket in-line strainer, as in Figure 9.9, conforms with this general description, the strainer element typically being formed from relatively coarse woven metal or plastic mesh, or perforated sheet. Strainers are, as their name implies, used for the removal of relatively coarse particles from a liquid stream, especially as prefiltration units ahead of some other more delicate filter or piece of machinery.

The cartridge may be formed of a single layer of medium if the material is sufficiently rigid to be self-supporting, such as sintered metal or wire-wound, or porous ceramic or plastic, of which two examples are shown in Figures 9.7 and 9.10. Media of this kind are discussed more fully in Chapter 7.

Frequently, the cartridge comprises a rigid porous core supporting one or more layers of media, such as woven or non-woven textiles, as in Figure 9.11. Various types of support cores are used, including perforated metal and Netlon-type extruded polymers (Figures 9.12 and 9.13).

9.2.4 Pleated cylinders

The active filtration area in a cartridge can be greatly increased by using a tubular core to support pleated media, which can be single or multiple layers of media such as cellulose paper, non-wovens and membranes; the multi-layer assemblies may provide a graded pore structure (e.g. including a prefiltration stage), as well as incorporating layers to aid drainage, support more fragile

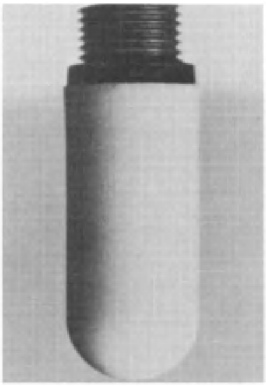


Figure 9.7. A porous plastic filter cartridge, open at one end.

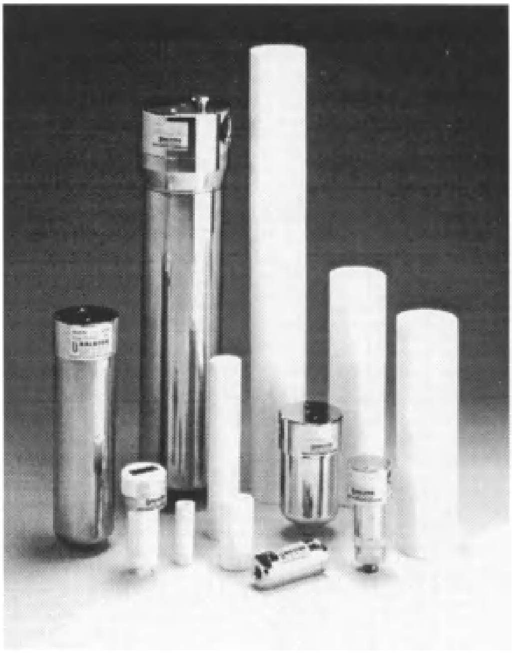


Figure 9.8. Balston glass fibre tubes, both ends open.

media, and act as a protective covering. Pleated cylindrical cartridges are used for both gas and liquid filtration.

A typical design is that supplied by Freudenberg in its TFP 60 range. This is a depth filtration cartridge, using a graded felt of synthetic fibres, the fibres being finer and more densely laid in the direction of gas flow. The TFP 60 P66 P2 is 660 mm long, 327 mm in outside diameter, with its pleats held on a plastic mesh core. The resultant filtration area is 3 m^2, the initial pressure drop at 1000 m^3/h being 150 Pa, the recommended final pressure drop being 800 Pa, at which point the dust capacity (AC Fine) is 1.2 kg.

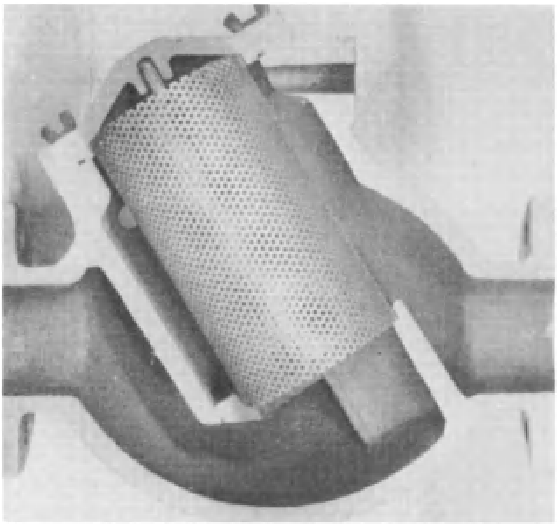


Figure 9.9. A typical pipeline Y-strainer

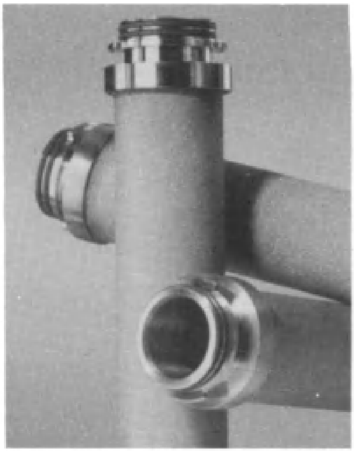


Figure 9.10. Sintered stainless steel filter cartridges.

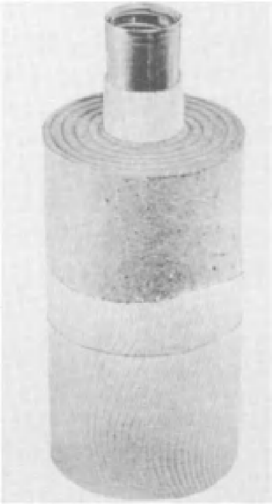


Figure 9.11. Cartridge formed by winding layers of felt around a metal former.

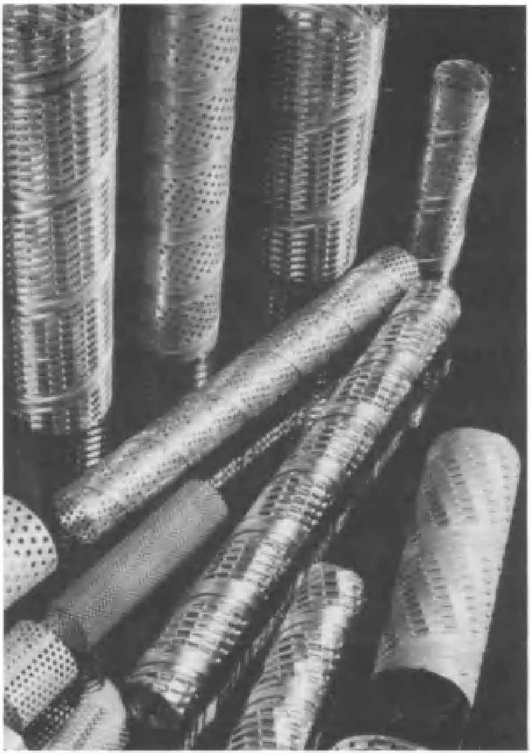


Figure 9.12. Perforated metal tubes as cores for filter cartridges.

9.2.4.1 Pleated cartridges for liquids

Typical examples of liquid filtration cartridges are the fuel and lubricating oil felt filter in Figure 9.14, and the all-propylene, hot melt bonded, general-purpose multi-layered cartridge in Figure 9.15; versions of this latter incorporate various types of media, including membranes of polypropylene, nylon and PTFE, sandwiched between protective layers of spunbonded media.

Cartridges of the type illustrated in Figure 9.15 are sold in a series of standard sizes, with manufacturers of replaceable elements competing with the original suppliers for the replacement market.

Cuno has recently introduced its Betafine XL range of pleated cartridges for liquid filtration, employing its Advanced Pleat Technology. APT produces a staggered pleat, of different depths, mixing 'W' pleats among the standard 'V' shapes, especially so that the pleats are not too pinched at their bases, thereby not losing valuable surface area for filtration. Betafine XL cartridges, made from polypropylene microfibres, are available in absolute ratings from 0.2 to 70 μm.

The more complex structure of the coalescer cartridge in Figure 9.16 results from the multiplicity of filtration stages that it combines. Contaminated fuel or oil entering the centre of the cartridge encounters first the pleated needlefelt of synthetic fibres that acts as a particulate filter and protects the outer coalescer layers. These comprise glass fibres pressed to a controlled density and thickness.

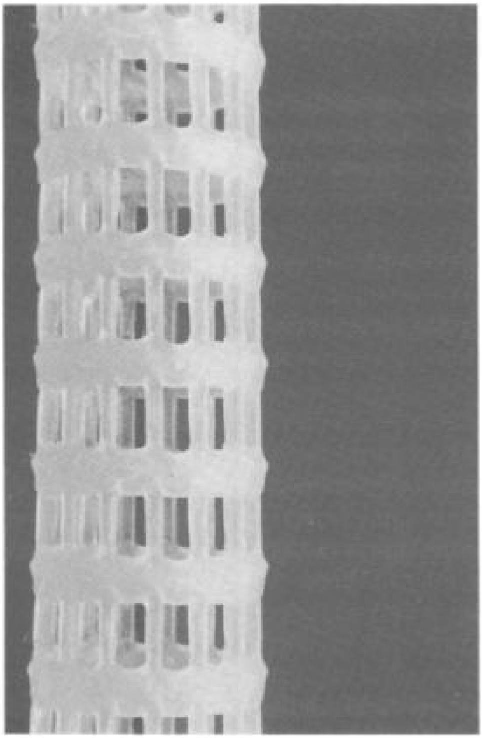


Figure 9.13. A Netlon plastic mesh core for a filter cartridge.

within which finally dispersed water coalesces into droplets large enough to separate from the fuel or oil by gravity settling.

The pleated cartridge in Figure 9.17 utilizes a single layer of sintered stainless steel fibres, sandwiched between layers of coarse mesh. These sophisticated cartridges are used for high-pressure and high-temperature applications, such as the filtration of molten polymers.

An unusual style of pleating is used by Lucas Industries in the resin-impregnated paper cartridges for their FS diesel fuel filter, which is designed to collect solid particles and also to serve as a coalescer and remove water. The cartridge comprises a thick roll of specially pleated creped paper in the form of a spiral around a central core, as shown in Figure 9.18. When inserted in the filter housing as in Figure 9.19, flow is downwards, parallel to the axis of the cartridge. Although the paper is wound closely together, the creping allows continuous flow between all the adjacent turns; evidence of this is the collected dirt visible in Figure 9.20.

A variant on the pleated paper cartridge is shown in Figure 9.21, as applied to the filtration of hydraulic oil under high pressure. This version is limited to 170 bar, while Figure 9.22 shows a more expensive version, suitable for operating pressures up to 375 bar and pressure differentials up to 17 bar. This is now an example of a reclaimable cartridge, which must be returned to the manufacturer for replacement of the used filter medium. The cartridge comprises multiple layers of graded papers interleaved with wire discs. These discs provide mechanical support and also act as fluid distributors between adjacent sets of papers, thereby ensuring simultaneous parallel flow of fluid through all the sets.

Another unusual style of pleating is featured in the novel Series 700B cartridges developed by 3M and incorporated in the High Flow Liquid Filter. As shown schematically in Figure 9.23, the meltblown polypropylene microfibre filter medium is pleated radially, as opposed to the conventional longitudinal pleating, thereby effectively forming a stack of lenticular discs. This orientation evidently allows the use of much deeper pleats, resulting in a cartridge of

Figure 9.14. Fuel and lubricating oil filter.

relatively large diameter, as in Figure 9.24, and greatly increased filtration area, with corresponding benefits in respect of dirt-holding capacity and life. The latest version of this cartridge is the 750 KF filter, also made of meltblown polypropylene.

The pleated cellulose paper cartridge has been the mainstay of engine fluid filtration for many years. However, the demands of modern industry and commerce are such that extended service intervals are becoming normal[1], and filters are having to change to accept higher dirt loadings, and to achieve higher efficiencies. New types of cartridge are being developed to meet this need, while

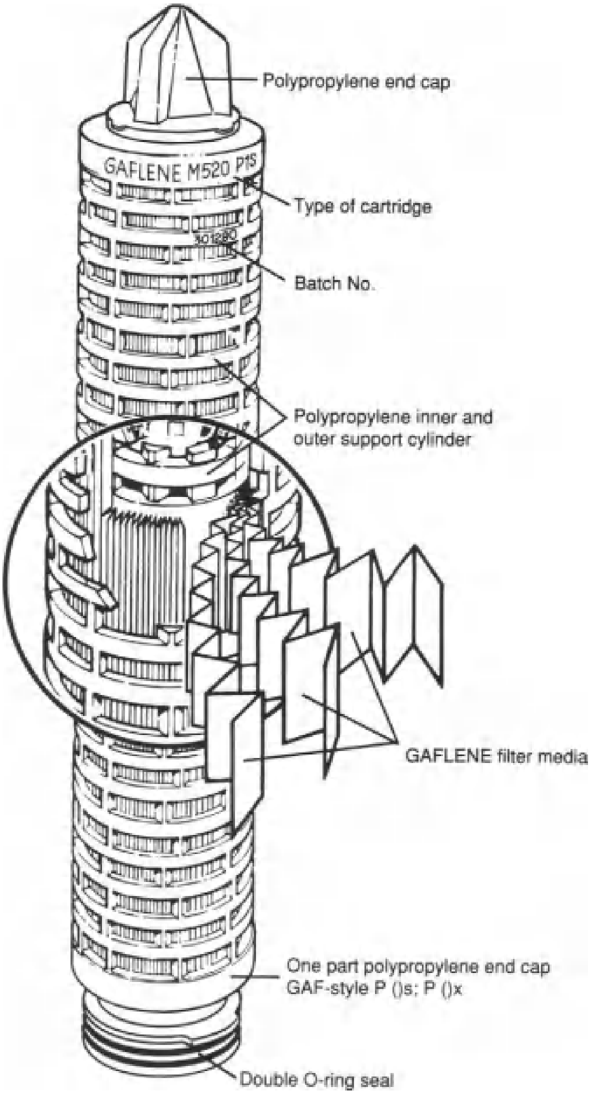


Figure 9.15. All-polypropylene multilayer general purpose filter cartridge.

small disc-stack centrifuges are also being employed. Engine oil filtration in heavy-duty engines is often effected by means of two filters in parallel – one, the full-flow filter, accepts the full liquid flow and removes particles down to 10–20 µm, while the other, the bypass filter, works on about 5–10% of the oil, and achieves very fine filtration. A new venturi combination filter replaces both full-flow and bypass filters with one unit. This has a pleated synthetic medium

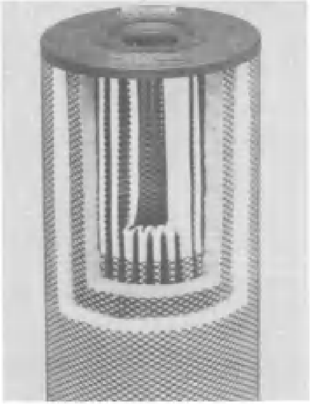


Figure 9.16. A coalescer cartridge.

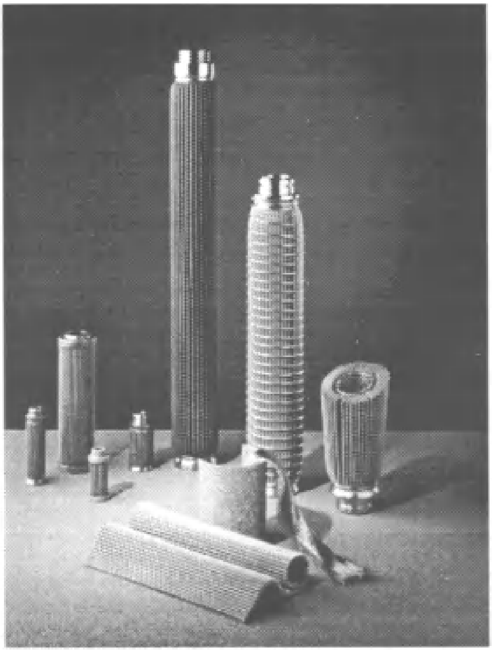


Figure 9.17. Pleated sintered metal fibre cartridges.

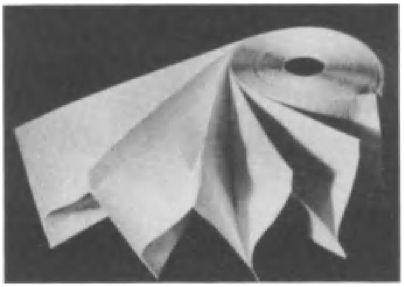


Figure 9.18. The pleated and spiral formation of paper cartridge for the FS diesel fuel filter.

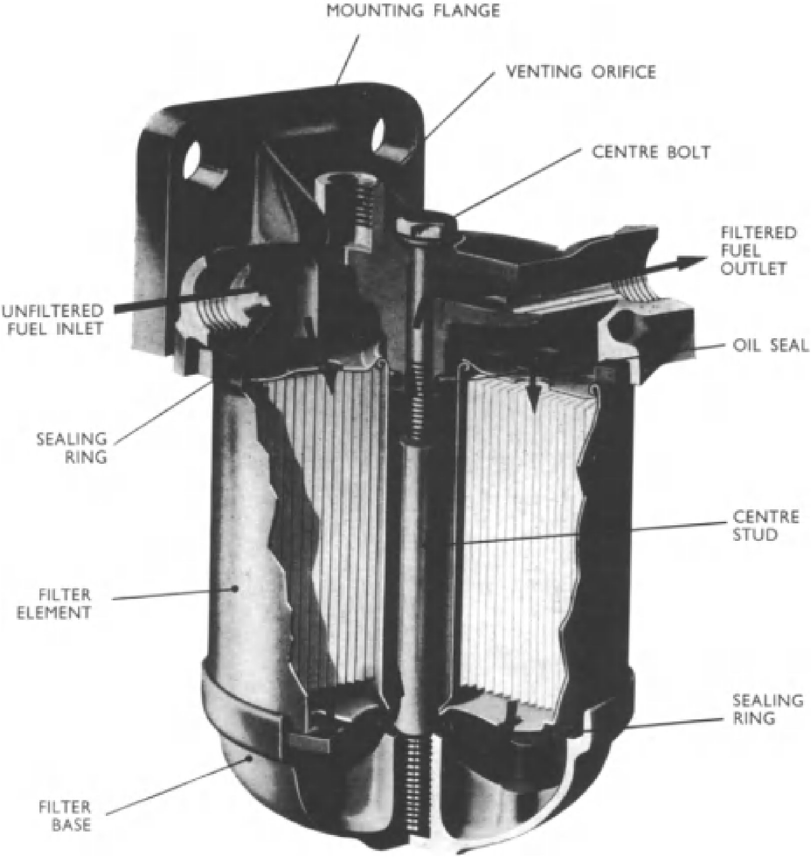


Figure 9.19. The FS diesel fuel filter.

section, connected to a stacked disc of cellulose medium by a venturi that increases the flow through the stacked discs.

Other new designs for engine oil filters are the modular incinerable cartridge (in which all parts of the disposable element are made from incinerable materials), and the in-place cleanable oil filter, which has an element that can be cleaned by back-flushing with compressed air.

9.2.4.2 Pleated cartridges for gas filtration

For the greater part of its life, the fabric filter used for the filtration of large volumes of inlet air or exhaust gas streams has employed filter bags for its medium. While bags are still an important part of the fabric filter scene, made largely of non-woven media, there has been a rapid influx of pleated media cartridges into gas filtration, triggered by the need for higher filtration efficiencies. The ePTFE membrane media discussed in Chapter 8 have been

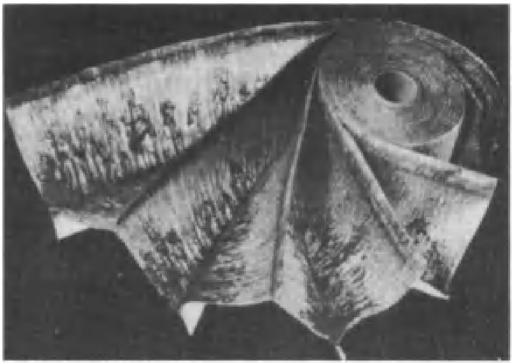


Figure 9.20. Dirt collected in all the 'vee' pleats of an FS diesel fuel filter cartridge.

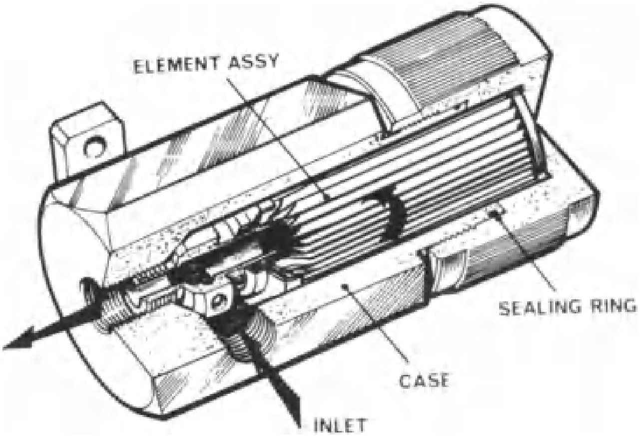


Figure 9.21. A high pressure hydraulic oil filter with a 'disposable' pleated cartridge.

especially successful in this application, because of their higher operating temperature range.

Resin-impregnated cellulose paper may be sufficiently rigid to be self-supporting without need of either a central core or spacers to maintain a gap between adjacent pleats. Illustrative of this is the engine air intake cartridge in Figure 9.25. The function of the spacers is fulfilled by the dimples that can be seen in the surface of each pleat.

Also self-supporting is the large (324 mm diameter, 673 mm high) cartridge illustrated in Figure 9.26, containing 22.3 m^2 of filter medium, comprising a chemically treated blend of cellulose and synthetic fibres. Multiple assemblies of these cartridges are applied in pulse jet cleaned dust filters, notably for the air intake to gas turbine power generation systems.

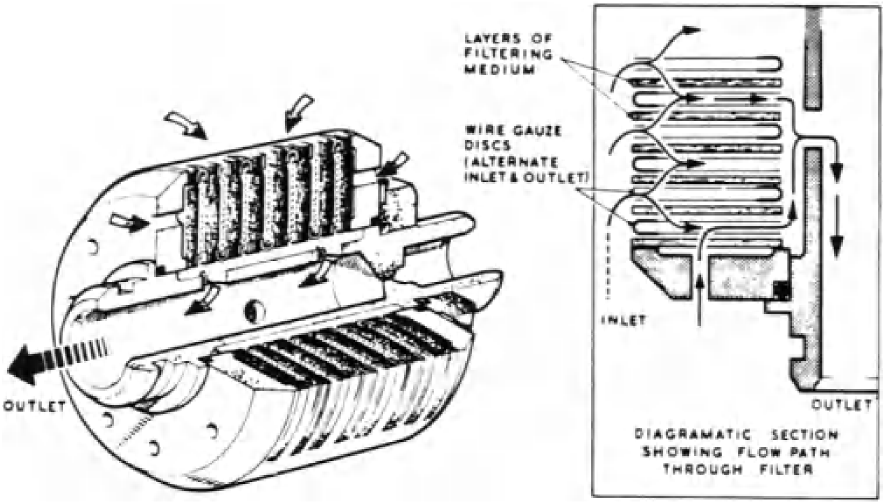


Figure 9.22. A high pressure hydraulic oil filter cartridge.

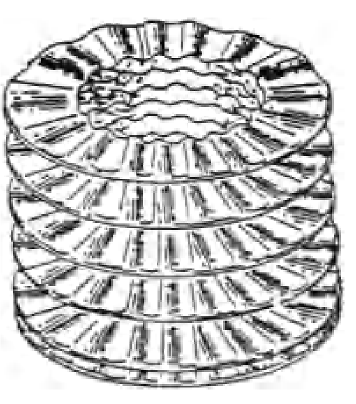


Figure 9.23. Schematic illustration of 3M Series 700B radial cartridge.

It is not only paper-like materials that can be pleated. Media made from sintered metal and even ceramic can now be pleated, as shown in Figure 9.17 and, in multi-cartridge assemblies such as Figure 9.27, for hot or corrosive gas-phase processing duties.

Most pleated cartridges used for gas filtration are circular in cross-section. However, Donaldson has recently described an oval cartridge(2), with shorter, wider pleats, that offers higher filtration efficiency, and greater ease of cleaning. The medium is a polymer nanofibre, acting as a surface filter. The resultant filter housings are smaller than corresponding cylindrical cartridge houses would be.

9.2.5 Lenticular discs

A lenticular disc is one that has the double convex shape of a lens. This is advantageous in a filter, since it allows inward filtration to proceed through both faces, with ample space between them for the flow of filtrate into a central outlet. A stack of such discs assembled on a perforated core provides a convenient

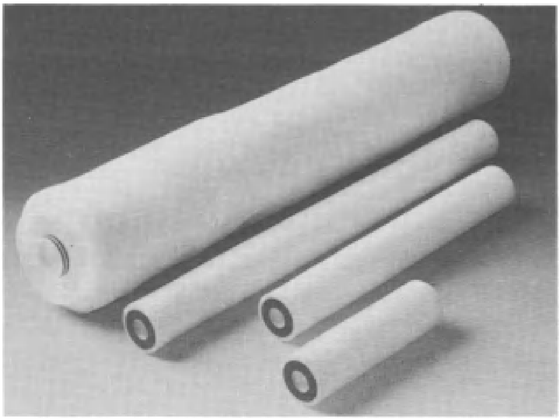


Figure 9.24. 3M filter cartridge compared with conventional 25, 50 and 75 cm cartridges.

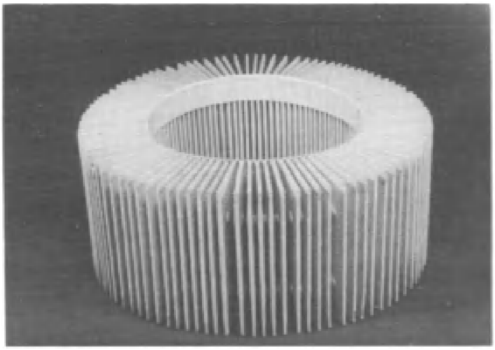


Figure 9.25. A resin impregnated cellulose paper cartridge for an engine air intake filter.

method for constructing a compact cartridge of high surface area. This format is the basis of both throwaway and cleanable long-life cartridges, depending on the type of media utilized.

The filter sheets made by Carlson from cellulose, described in Chapter 4, are available as lenticular filter cartridges. Figure 4.7 in Chapter 4 shows a similar

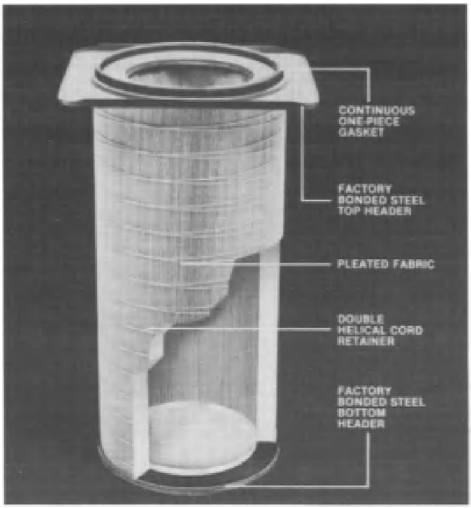


Figure 9.26. A 'Tenkay' dust filter cartridge.

Figure 9.27. A multiple assembly of pleated sintered metal fibre cartridges for high temperature gas filtration.

throwaway cartridge from Cuno's range of lenticular cartridges based on the various grades of Zeta Plus filter media, their modular construction being illustrated in Figure 9.28. A cartridge comprises an assembly of lenticular discs or cells, each of which is composed of two discs of Zeta Plus medium, sealed together around a polypropylene separator. The cartridge is pre-assembled under high compression, and is locked together by three stainless steel bands. Edge sealing of each cell is effected by an injection moulded polypropylene ring.

A similar format is shown in Figure 9.29, now with activated carbon incorporated into the Zeta Plus, in order to provide a combination filter, marketed under the ZetaCarbon brand name. Five different types of carbon can be incorporated, to decolourize liquid streams, and remove organic contaminants. These cartridges have no shedding of carbon into the filtrate, and can be supplied certificated for pharmaceutical use.

Lenticular disc stacks are another type of filter used in the filtration of molten polymers. Sintered stainless steel is the standard material required to withstand the high operating pressures (300 bar) and temperatures of the polymer industry, where, with repeated specialized cleaning, the useful life of a filter is expected to be perhaps 10 years or more. Accordingly, whilst the same lenticular format still applies, there are major differences in the detailed engineering. The most noticeable of these is that the product supplied by the manufacturer is a number of separate filter discs (which are generally known as segments), from which the customer can assemble a stack inside a suitable housing, as in Figures 9.30 and 9.31. These segments or discs are produced in two standard diameters, 175 and 200 mm.

To withstand these rigorous conditions, appropriate multi-layered construction is utilized so as to protect and support the critical layer of filter medium. As illustrated in Figures 9.32–9.35, four standard options are available from Pall, these offering different combinations of sophistication versus cost.

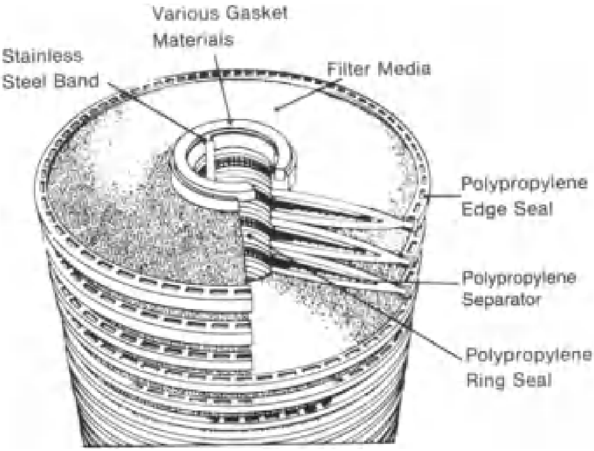


Figure 9.28. The modular construction of Cuno 'HT Series' lenticular cartridges.

9.2.6 Rigidized elements

While pleated cartridges have been the biggest recent competitor for filter bags in gas filtration, a small but important part of the market is now using rigidized elements for this purpose, because of their better operating temperature range. The version developed by Herding, described in Chapter 5, uses a pleated type of surface for a self-supporting structure of filter media, able to operate at moderately high temperatures.

Somewhat similar are the Compact Filter Elements supplied by Madison, which are available in flat, rectangular shape or as cylindrical elements. They can be made from needlefelts, spunbondeds or composites, but are mainly supplied with microporous coated or anti-static media. Their chief claim is that of much reduced cartridge size for a given filtration area.

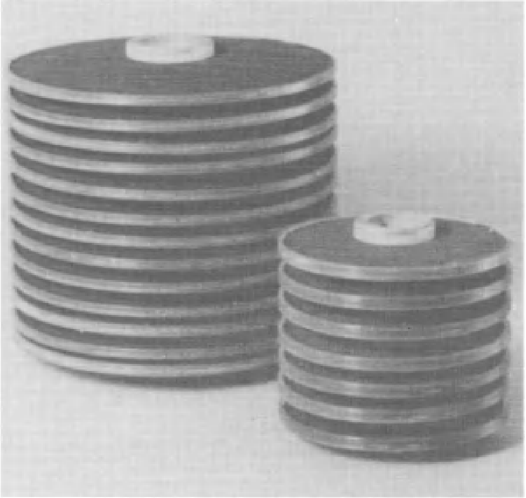


Figure 9.29. Cuno 'Zetacarbon' cartridges, incorporating activated carbon with 'Zeta Plus'.

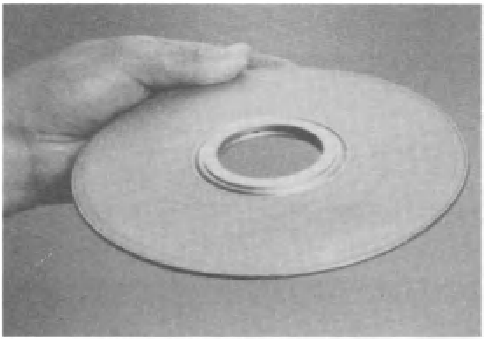


Figure 9.30. A sintered metal segment for polymer filtration.

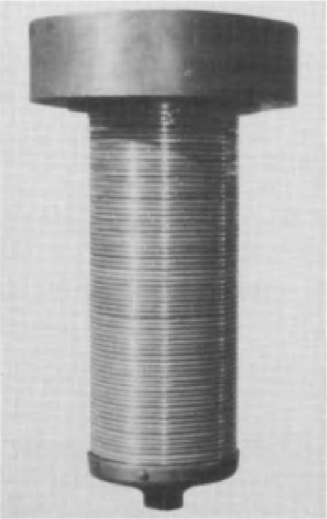


Figure 9.31. A multi-segment stack assembly for polymer filtration.

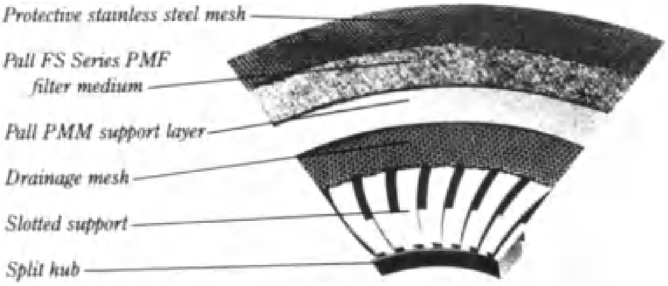


Figure 9.32. The multi-layer construction of Pall's 'Segment' filters for polymer filtration.

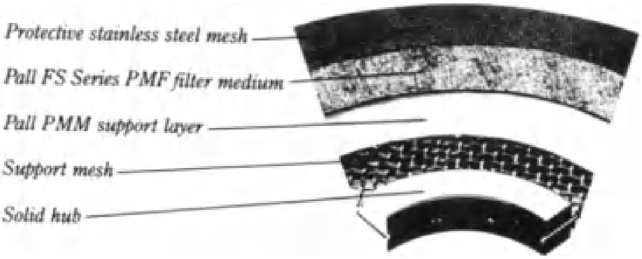


Figure 9.33. The multi-layer construction of Pall's 'Segment-M' filters for polymer filtration.

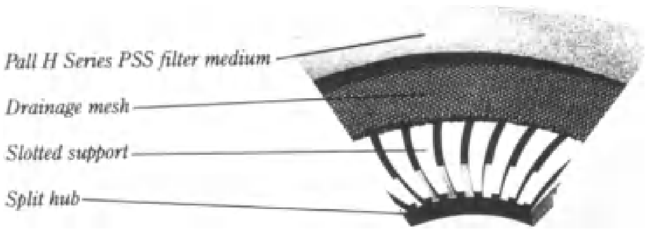


Figure 9.34. The multi-layer construction of Pall's 'Segmax' filters for polymer filtration.

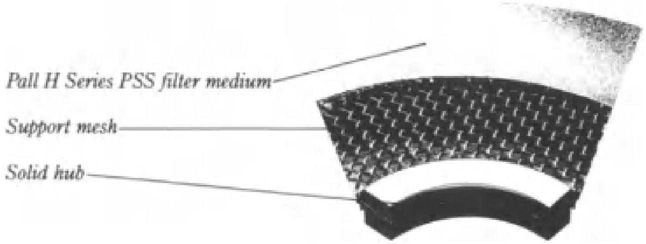


Figure 9.35. The multi-layer construction of Pall's 'Segmax-M' filters for polymer filtration.

9.2.7 Mechanically cleaned filters

A small, but growing, group of filters offers continuous operation by means of automatic mechanical cleaning of the filter element. In these filters, typified by Russell Finex's Eco and Ronningen-Petter's DCF-Series, self-cleaning filters, a rigid cylindrical cartridge of wedge wire or woven mesh construction, which can be mounted vertically or horizontally, operates with liquid flow from the inside to the outside of the cylinder. Dirt accumulates on the inside of the cylinder from which it can be scraped off – in the Eco filter by means of a continuously rotating screw-shaped blade, and in the DCF by means of a disc that periodically moves across the surface. The accumulated dirt is blown out of the filter through a valve.

9.2.8 Cross-flow membrane modules

The modules in which membrane media are supplied are strictly speaking cartridges as defined for this chapter: flat sheet, spiral wound, tubular, perforated block and hollow fibre.

These are generally expensive enough to warrant cleaning once they have reached the end of an operating cycle, so they are likely to be flushed *in situ* or removed for more thorough cleaning. Further details on such modules are given in Chapter 8.

9.3 Specially Fabricated Cartridges

The second main group of cartridges are made from components that are not in themselves filter media, but once assembled can act as very efficient media, mainly for liquid filtration. They are of three main types:

- a continuous yarn wound more or less tightly onto a central core;
- a medium made from fibres assembled into a relatively thick medium on a central core; and
- an assembly of discrete solid components or continuous wires or ribbons, which are mounted on or wound round a central core.

The first two are depth media, the third is a surface medium, that is easily made into an automatically cleaned filter. The cores for the first two types are similar to those shown in Figures 9.12 and 9.13.

9.3.1 Yarn-based cartridges

The most common of the yarn-based cartridges is that in which a continuous yarn of natural or synthetic fibre is wound around a central core. However, there is growing interest in an alternative yarn based design, where a bundle of yarns is held in different orientations at different parts of the filtration cycle.

9.3.1.1 *Yarn wound*

Despite its early origin in the 1930s, the 63 mm diameter × 250 mm long yarn-wound (or spool-wound) cartridge illustrated in Figure 9.36 continues to be widely used in many sectors of industry. Its simple construction, and its convenient versatility in use, resulted in its becoming an unofficial standard as increasing numbers of manufacturers competed for a large and growing market. It also effectively served as a prototype in respect of size and dimensions for the diversity of styles of cartridge developed in more recent years, during which there has also been diversification of both diameter and especially length. Both shorter and longer lengths are common, up to a general maximum of 1.02 m because of the flow restriction of the core.

These cartridges are constructed by continuously winding yarn in a carefully controlled open pattern around a central core, which is typically a perforated metal or plastic tube open at each end. Typically the matrix so formed has a graded structure with pores of decreasing size with the inward direction of flow – a gradation achieved by differing degrees of tightness in the windings. Cartridges are based on a wide variety of yarn materials embracing both natural and synthetic fibres. The yarns used are mostly spun from short staple fibres, the fibrillated surface of which is brushed or teased to produce a fuzzy surface or nap, which contributes importantly to the filtration mechanisms. If monofilament yarns are used they are generally texturized or crimped in some fashion before being formed into a cartridge.

The filtration characteristics of a cartridge depend on the type of yarn used as well as on the way it is produced and wound. Examples of the pressure drop versus flow rate of water through 250 mm cartridges of various yarn materials are provided in Figure 9.37.

Cartridges are typically graded in terms of a nominal micrometre rating, generally with seven or eight models to straddle the range from about 1 to 150 μm. It is customary to identify the grading and constructional parameters of a yarn-wound cartridge by a coding system such as the example shown in Table 9.1.

Considerable care is needed in applying the grading numbers, partly because some suppliers are more optimistic in their claims than others, and also because the performance achieved may vary substantially with the operating conditions. In general, it is unlikely that a cartridge will achieve better than say 80% efficiency against particles of the size specified by the nominal rating: in practice, considerably lower efficiencies may well be achieved.

The possible impact of changes in flow rate on both efficiency and cartridge life is demonstrated by the data in Table 9.2, which is adapted from an early paper by

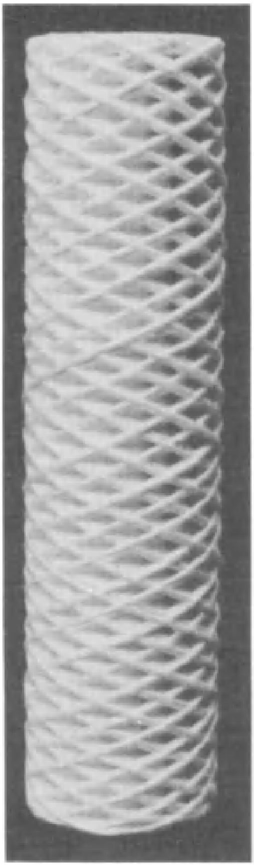


Figure 9.36. A typical yarn-wound or spool-wound cartridge.

Swanson[3]. A study reported by Williams and Edyvean[4], comparing cartridges of nominally identical ratings from three different manufacturers, noted a great deal of variation not just among filters from different manufacturers, but also among a manufacturer's own cartridges. In general, retention efficiency was observed to be low initially, rising during the mid-period and finally falling again: a three-fold extension in filter life was found between cotton and polypropylene cartridges from the same supplier.

The dirt-holding capacity is also dependent on various operating factors including velocity, as can be seen from the data in Table 9.2. Whilst the actual performance depends on numerous factors, as a rough guide it may be assumed

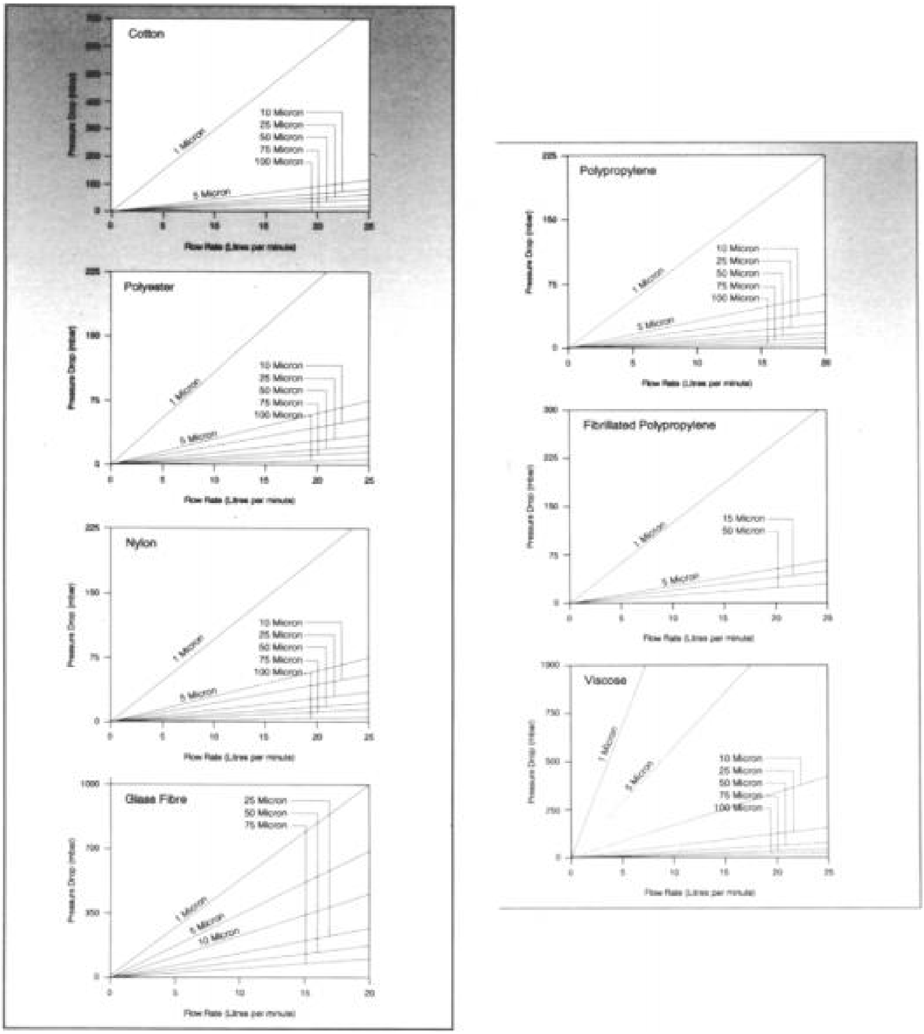


Figure 9.37. Pressure drop versus the flow rate of water through Ametek 50 mm wound cartridges.

that the weight of dirt that can be held in a standard 25 cm cartridge is approximately 50 g for a 1 µm grade, 90 g for 15–20 µm, and 120 g for 50–100 µm.

Figures 9.38 and 9.39 are reproduced from Williams and Edyvean(4) since they produce an interesting comparison between polypropylene and cotton cartridges, and demonstrate the magnitude of some of the variations that can

Table 9.1 Coding system used to specify a filter cartridge[a]

Length			Micron rating		Yarn		Core type		Diameter		End fitting	
Inch	mm	Code		Code		Code		Code	mm	Code		Code
4	100	04	0.5	A5	Polyester	01	Polyester	1	62	1	Standard end (DOE)	0
5	125	05	1	01	Polypropylene	02	Polypropylene	2	50	2	Millipore (6)	2
6	160	06	3	03	Fibrillated polypropylene	03	304 St steel	3	100	6	Millipore (0)	3
9.75	248	09	5	05	Bleached cotton	04	316 St steel	5	66	7	Gelman (D)	6
9.875	251	10	10	10	Glass fibre	06	Tinned steel	7			Pall (7)	7
10	254	11	20	20	Nylon	07					Pall (8)	8
19.75	500	19	25	25	Rayon viscose	08					Ametek	9
20	508	20	50	50	Washed polypropylene	09						
29.5	750	29	75	75								
30	762	30	100	99								
39.25	1000	39										
40	1016	40										
Example: 29				20		02		2		1		0

* PTI Technologies Ltd.

Table 9.2 The effect of flow rate on the performance of filter cartridges

Cartridge grade (µm)	Flow rate (l/min)	Initial pressure drop (bar)	Filtration efficiency (%)	Total volume filtered up to 2.4 bar final pressure drop (m^3)
1	1.9	0.11	96.2	1.08
1	9.5	0.63	95.2	0.68
1	19.0	1.22	95.6	0.52
10	1.9	0.01	85.4	6.25
10	9.5	0.05	79.4	3.00
10	19.0	0.19	71.6	1.85

occur; the superior performance of cotton was attributed to the stratified surface of its fibres and to their swelling by absorption of water, thereby reducing the porosity.

The Cuno MicroWynd II, shown in Figure 9.40, is a novel form of wound cartridge, which comprises alternate layers, one a blanket of carded fibres and the other wound yarn, both being either cotton or polypropylene. The primary function of the yarn layers is to lock in place the fibre blanket that acts as the main filter medium. The advantages claimed for this patented construction include a three-fold increase in flow capacity and a doubling of the dirt-holding capacity.

Another interesting development[5] claims to overcome many of the problems experienced with yarns made from roving or friction spun yarns of cotton or polypropylene fibre, namely, shedding of fibre and leaching of fibre treatment

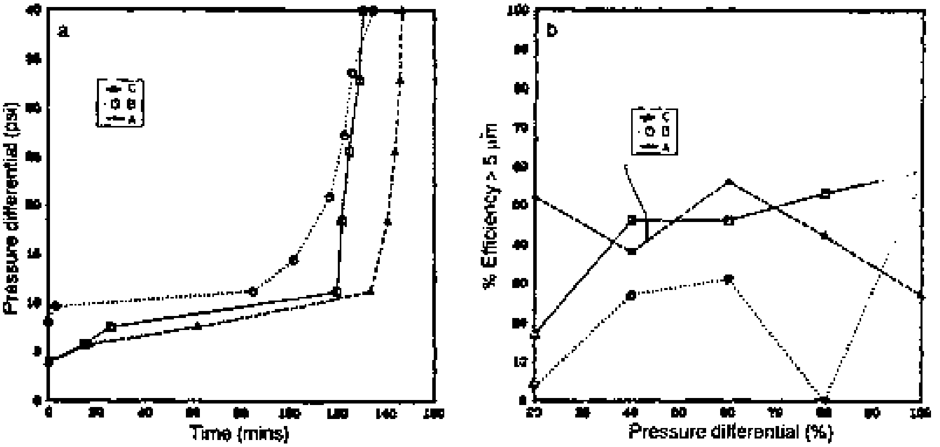


Figure 9.38. The performance of 5 µm polypropylene filter cartridges.

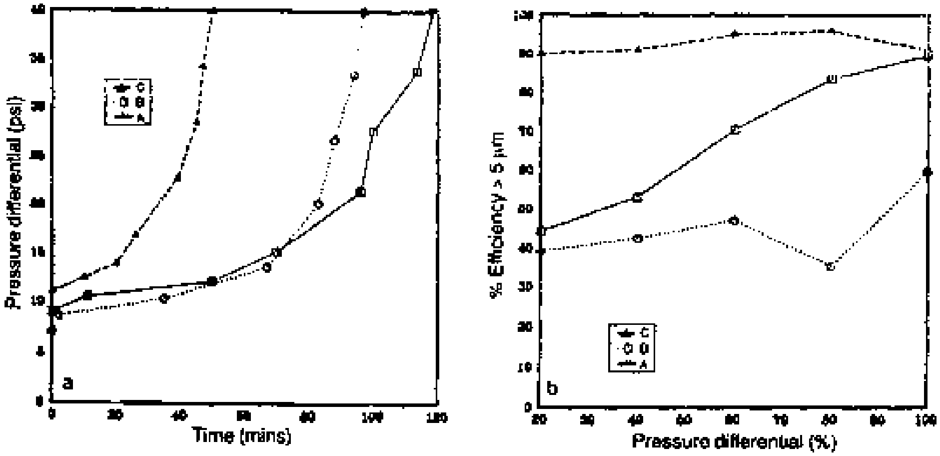


Figure 9.39. The performance of 5 µm cotton filter cartridges.

chemicals. Syntech Fibres uses continuous meltspun filaments of polypropylene to make the yarn. Each of the filaments continues throughout the whole length of the yarn. The filaments are randomly oriented to each other (intermixed, looped and entwined) to form a very bulky, non-round, highly stable yarn. A cartridge wound from this material has a high-efficiency depth filtration mode of operation.

9.3.1.2 Kalsep's Fibrotex cartridge

A unique cartridge of yarns forms the heart of Kalsep's novel Fibrotex filter, which was originally developed by British Petroleum with the water filtration problems on off-shore platforms as the intended target. The cartridge or filter element, shown in Figure 9.41, is formed of a bundle of yarns loosely arranged around a central perforated tube, which is mounted between two circular end plates, with the ends of the yarns also attached to these plates.

The operating cycle of the filter is shown schematically in Figure 9.42. To prepare for inward filtration, the top end plate is moved downwards and simultaneously rotated through about half a turn, so that the yarns are twisted and compressed into a helical pattern that brings them tightly together against the central tube. During backwash cleaning, the element is expanded by upward movement of the top plate and by a reciprocating partial rotation of that plate.

The yarns, which are crimped, are of Nylon-66 or PBT polyester: with both they are six denier (i.e. 30 μm). In their twisted mode they form a bed some 50–

Figure 9.40. The 'Micro-Wynd II' cartridge combines a blanket of carded fibres with wound yarn.

60 mm thick. The filtration efficiency achieved is 98% against 2 μm particles with Nylon-66 and 95% against 5 μm particles with PBT; Figure 9.43 is a grade efficiency curve for Nylon yarns based on challenge tests with AC Fine test dust.

9.3.2 Bonded fibres

The next group of specially fabricated cartridges covers those in which a layer of fibre is laid down on a core and then held in place by some means – chemical or

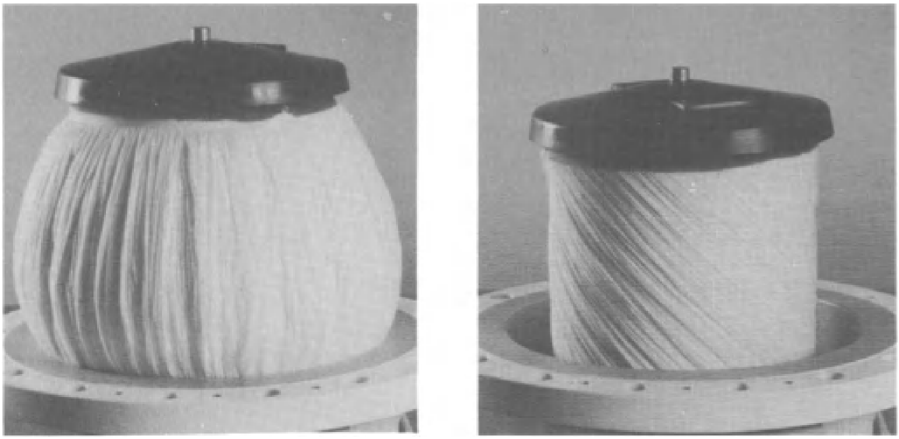


Figure 9.41. The 'Fibrotex' filter element (a) relaxed, (b) twisted.

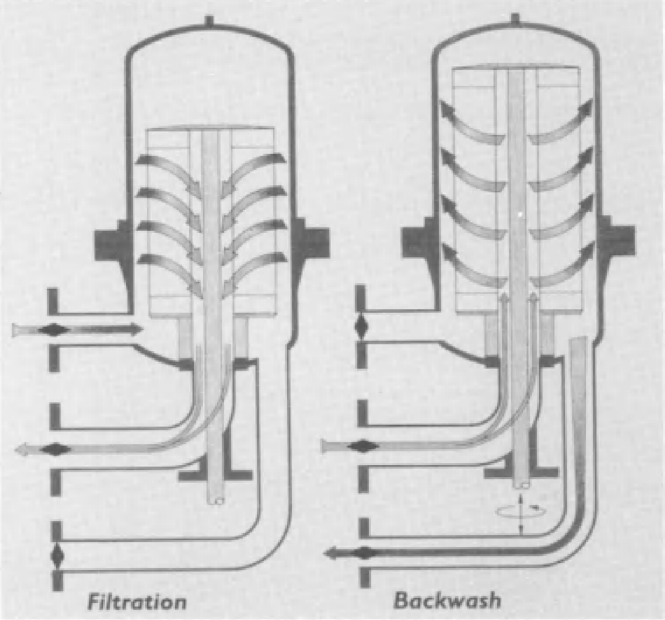


Figure 9.42. The 'Fibrotex' filter element is compressed or expanded during the operating cycle.

thermal. These can give as good a separation efficiency as the yarn-wound cartridges, with a wider range of fibres.

9.3.2.1 Resin bonded

Figure 9.44 shows the structure of a cartridge formed from glass microfibres that are bonded together by either a phenolic resin (for general applications) or melamine (to meet the special requirements of food, beverage and pharmaceutical duties). The microfibres, produced in controlled sizes ranging from less than 0.5 µm to more than 150 µm, are manufactured by the 'pot and marble' process outlined in Chapter 4.

Fibres from this process are sprayed with a resin and then formed into felt-like mats. These are cut into predetermined lengths and rolled on to various sized mandrels, which correspond to the inside diameter of the filter tube. The length of the matter and the rate at which it is rolled onto the mandrel determine the

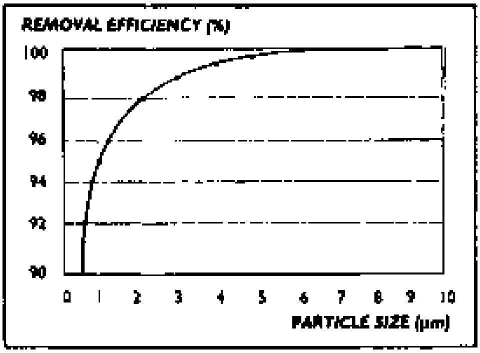


Figure 9.43. Particle removal efficiency of the 'Fibrotex' Nylon 66 filter element.

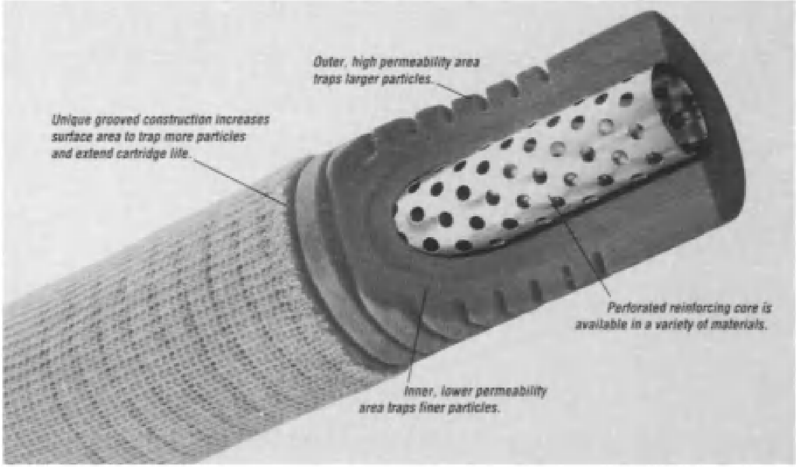


Figure 9.44. A resin-bonded glass microfibre cartridge.

density of the resultant tube, which is of graded density, increasing towards the core. Following curing, each tube is ground to the required diameter and grooved to increase the available surface area.

Various options are available for the core, including polypropylene, metal (tin-coated steel or stainless steel) and resin impregnated. The eight grades produced by Johns Manville are identified simply in numerical sequence from 1 for the finest to 8 for the coarsest, to straddle the range of nominal micron ratings of competing suppliers.

Bonded cartridges of similar form, but made from other fibres, are typified by the coreless Fulflo RBC (i.e. Resin Bonded Cartridge) from Parker Hannifin Corporation. Extra-long acrylic fibres with phenolic bonding are used to make these coreless cartridges. In addition to the grooved form, non-grooved cartridges are available for use where increased depth filtration is required. Both styles are available in seven grades with nominal ratings of 2, 5, 10, 25, 50, 75 and 125 μm.

Acrylic and cellulose fibres are the basis of Cuno's graded-density coreless Beta-Klean cartridges, which are available in both grooved and non-grooved forms. A distinctive feature of this range, linked to its name, is that the cartridges are characterized not by nominal micrometre ratings, but by *absolute ratings* that specify the particle size at a Beta ratio of 1000, corresponding to a filtration efficiency of 99.9%. On this basis, the range of 10 grades extends from the finest at 5 μm up to 70 μm.

9.3.2.2 *Thermoplastic bonded*

Exploiting the thermoplastic properties of synthetic polymers such as polypropylene has proved a fertile ground for the development of novel constructions and manufacturing processes for filter cartridges. Advantages available from these materials and manufacturing techniques include the ability to produce fibres in a wide range of controlled diameters and lengths, and also to form beds of graded pore size, as in the example in Figure 9.45, the finest grade of which has a typical efficiency of 99.999% against 0.3 μm bacteria. In addition, thermal bonding (i.e. without using adhesives) is simple, convenient and compatible with sensitive applications (e.g. food and pharmaceuticals).

Several of these cartridge designs are briefly described below, based partly on a classification by Shucosky(6). They each utilize a different technique to achieve a graded porosity down to a controlled minimum pore size, high permeability to provide a low flow resistance, high dirt-holding capacity, and maximum mechanical stability to withstand deformation under pressure.

The key feature of *thermal moulded polyolefin (TMP) cartridges* is the bicomponent nature of the fibres from which they are formed. These fibres have a sheath of lower melting point polymer surrounding a higher melting point core. Hence, when a web of these fibres is rolled and carefully heated, the sheath material will soften and fuse at the myriad of fibre contact points. This creates a rigid cartridge structure that does not require the support of a central core: end caps and gaskets are thermally welded to the cartridge without use of a resin.

An example of this type of cartridge is the Cuno range of Betapure cartridges. Both polyolefins and polyester versions are available; the former are constructed from long fibres with an inner core of polypropylene and an outer sheath of polyethylene, while the others utilize a core of polyester surrounded by copolymer polyester. The fused bonding of the sheaths, illustrated in Figure 9.46, provides a rigid structure without fibre shrinkage or degradation.

The range of nine polyolefin cartridges are graded only by nominal micrometre ratings, from 1 to 100 μm; during manufacture, the fibres are processed on textile equipment that requires a fibre lubricant. Five grades of polyester cartridge have both nominal and absolute (99.9% efficiency) ratings, as listed in Table 9.3; flow rate of water versus pressure drop characteristics for standard 25 cm long cartridges are summarized in Figure 9.47.

Meltblown depth (MBD) cartridges are manufactured by an adaptation of the meltblown fibre technology outlined in Chapter 3. Molten polymer extruding from spinneret orifices is impacted by high-velocity streams of air, which cause the filaments to fibrillate and disintegrate into fine short fibres. These short fibres are then deposited directly onto a rotating mandrel. The process attempts to produce a desired mean pore size by varying the fibre diameters across the depth of the filter medium; as the filter is being formed, the mean fibre diameter is changed by adjusting the air velocity or other significant variable, such as temperature and polymer pumping rate.

Examples of MBD cartridges are the Osmonics Purtrex, Hytrex II and Selex polypropylene filters. While the first two are graded on a nominal basis only (respectively with efficiencies of 75–80% and 85–90%), the Selex cartridges are rated in Table 9.4 at several efficiency levels up to 99.98% ($\beta = 5000$). Flow rate of water versus pressure drop characteristics for standard 25 cm long cartridges are summarized in Figures 9.48–9.50.

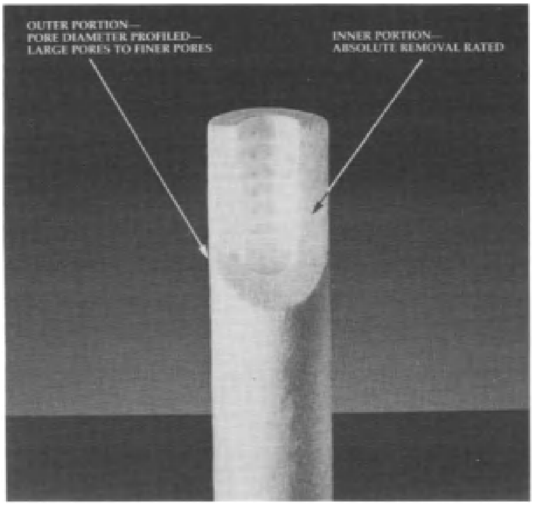


Figure 9.45. A thermally-bonded polypropylene 'Profile' filter cartridge.

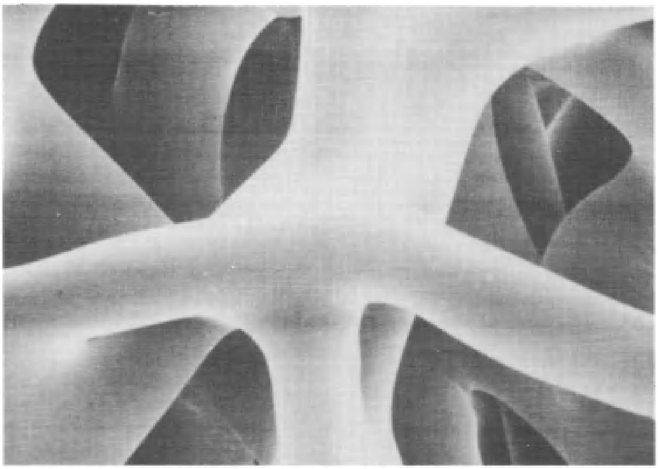


Figure 9.46. Thermal bonding of bicomponent polyester fibres in 'Betapure' cartridges.

Table 9.3 The nominal and absolute ratings of 'Betapure' polyester cartridges[a]

Grade	Nominal rating (µm)	Absolute rating[b] (µm)
A	3	6
B	5	15
C	10	23
E	20	35
G	30	N/A

[a] Cuno Europe.
[b] 99.5% efficiency.

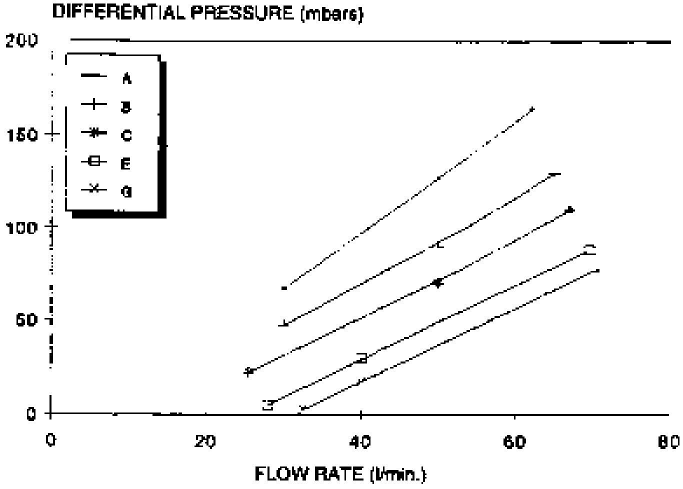


Figure 9.47. Differential pressure versus flow rate of water through 'Betapure' polyester cartridges.

A refinement of this manufacturing technique, with computerized control of fibres extruded simultaneously from multiple spinnerets, results in the closely graded layers of Filterite's Nexis cartridges. These utilize a novel fibre technology identified as co-located large diameter (CoLD) melt fibre technology[7], wherein high-efficiency fibres of 1 μm or less are intermingled with much larger ones (up to 100 μm), which provide mechanical strength to the resultant matrix. A range of 17 grades with nominal ratings (90% efficiency) from 0.5 to 200 μm is

Table 9.4 Nominal and absolute ratings of 'Selex' polypropylene cartridges[a]

Grade of 'Selex' cartridge		E	G	D	A	C	F
Nominal micron rating (μm)		1	3	5	10	20	30
Micron rating @ efficiency.	β ratio						
90	10	0.5	0.7	0.9	1.0	1.3	1.8
95	20	1.1	1.5	1.8	2.0	2.4	3.0
98	50	1.5	1.8	2.9	4.3	5.0	6.5
99	100	3.2	5.2	7.3	8.4	9.7	11.0
99.5	200	15.1	17.5	18.9	19.3	20.0	-
99.98	500	16.6	18.9	20.8	24.2	32.1	-

[a] Osmonics, Inc.

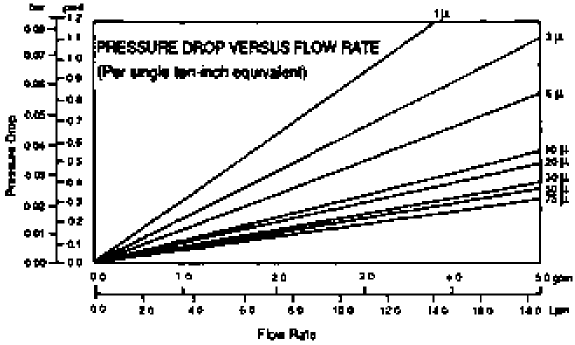


Figure 9.48. Water flow/pressure characteristics of 'Purtrex' 25 cm cartridges.

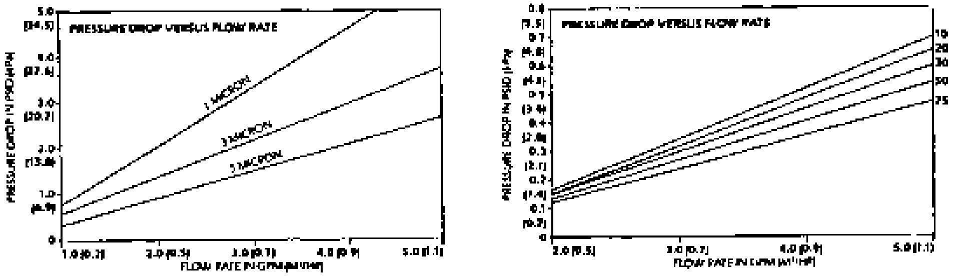


Figure 9.49. Water flow/pressure characteristics of 'Hytrex II' 25 cm cartridges.

supplied, of which the water flow versus pressure drop characteristics are summarized in Figure 9.51; an absolute rated range (99.9% efficiency) from 5 to 20 µm is also available.

The third of these special techniques produces *rolled multi-layer depth (RMD) cartridges*. As illustrated in Figure 9.52, these all-polypropylene cartridges are formed by wrapping multiple layers of graded meltblown media around a rigid core. A continuous length of open mesh runs through the whole construction to support the filter medium layer and to keep the consecutive layers separate from each other. Each layer is fabricated separately and carefully controlled and monitored in respect of parameters such as permeability, porosity, pore size and thickness. Multiple layers of a particular grade are used as appropriate, while the overall form comprises an absolute rated inner section of fine fibres and multiple outer prefilter sections.

The nominal and absolute (99.9% efficiency) particle removal ratings of the eight grades of cartridge produced by Filterite (now part of Pall) are listed in Table 9.5, which also includes ratings at lower β factors and efficiencies. Flow rate of water versus pressure drop characteristics for standard 25 cm long cartridges are summarized in Figure 9.53.

A somewhat similar structure is the basis of Cuno's new PolyNet depth cartridges. These comprise three layers of polypropylene filter media, each with varying flow distribution channels, interleaved with layers of distribution netting. The decreasing size and number of flow channels from one layer to the next creates evenly distributed, longitudinal and latitudinal flow paths across each successive layer, enabling the full capacity of the filter element to be utilized, whilst maintaining consistent levels of filtration. An inner layer of medium without flow channels ensures the absolute rated performance, in the range 1–70 µm.

9.3.3 Metal edge filters

Filters of this category are so named since the apertures through which filtration takes place are created by the close proximity of a series of parallel metal plates, strips or wires, the assembled edges of which thereby form the filter medium.

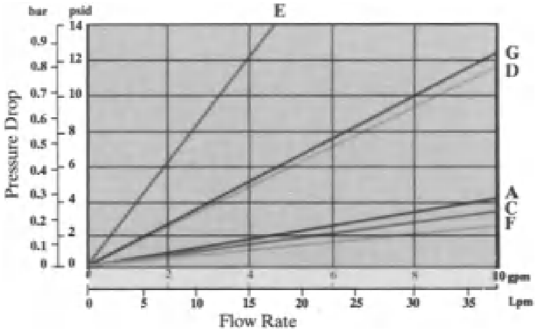
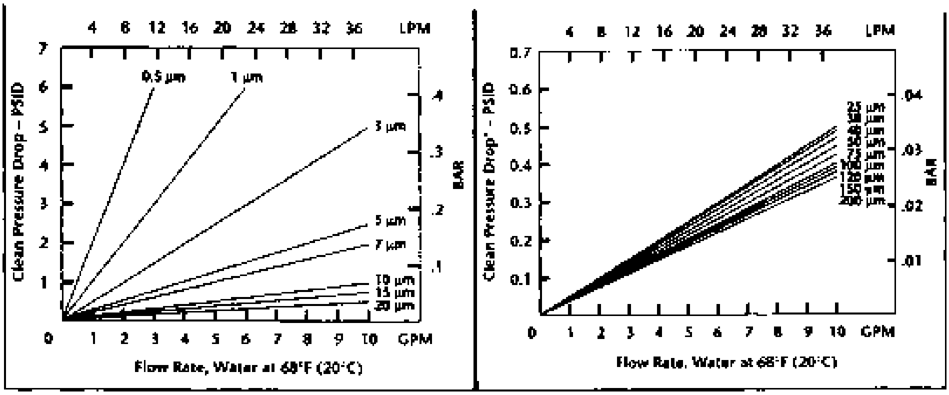


Figure 9.50. Water flow/pressure characteristics of 'Selex' 25 cm cartridges.

9.3.3.1 Wire-wound structures

A typical example of this form of construction is illustrated in Figure 9.54. A screw thread is cut into the surface of the support or former, into which a continuous wire is then wound, with the gap between adjacent turns controlled down to a minimum of about 50 μm: this allows far closer control of the gap size than is possible with welded construction, such as the Trislot tubes described in Chapter 6, for which the tolerance is 10% of the nominal slot.



* Due to the very low flow resistance of the media in the more open grades pressure drop is primarily related to turbulent loss through the center core

Figure 9.51. Water flow/pressure characteristics of 'Nexis' 25 cm cartridges. GPM = US gpm; LPM = l/min.

Figure 9.52. The multi-layer structure of 'Poly-fine ARD' 25 cm cartridges.

The wire may be either of circular section or wedge-shaped with a triangular section, the flat surface facing outwards so that the gaps between the wires widen in the direction of flow, which is radially inwards. The advantage of wedge wire is that the filter element is less prone to blocking, as can be seen from the schematic diagram in Figure 9.55.

Although about 50 μm is the normal minimum gap between wires, much finer clearances are achieved by the Japanese company Arai Machinery Corporation and its US associates Pure-Grade Inc. By machining to close tolerances both the

Table 9.5 Particle removal ratings of 'Poly-fine ARD' cartridges[a]

Beta β:	1000	100	50	10
Efficiency (%):	99.9	99	98	90
Nominal micron rating				
0.5	< 0.5	< 0.5	< 0.5	< 0.5
1.0	0.9	0.8	0.7	< 0.5
3.0	2.5	2.0	1.7	1.3
5.0	3.6	2.8	2.6	2.0
10.0	7.5	5.9	5.2	4.0
20.0	15.0	12.0	11.3	8.3
40.0	33.0	28.0	23.0	18.0
70.0	65.0	60.0	50.0	40.0

[a] Filterite.

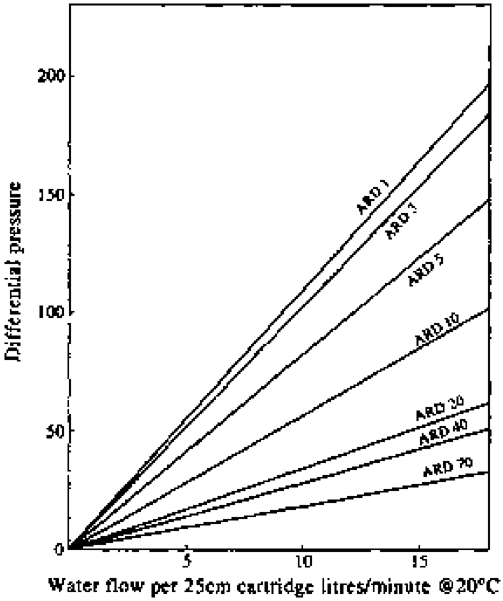


Figure 9.53. Flow/pressure characteristics of 'Poly-Fine ARD' cartridges.

support cylinder and the wedge wire, the standard range of gaps available starts at 1, 3, 5 and 10 μm and extends through another 15 grades up to 300 μm; the gap tolerances are as precise as 0.5 μm for 1 and 3 μm gaps, and 2 μm above this size. In 316 stainless steel or titanium, both externally wound and internally wound elements are produced, as can be seen in Figure 9.56; the smallest is 44 mm diameter by 60 mm long, the largest is 266 mm diameter by 250 mm long.

9.3.3.2 *Ribbon elements*

The filter element shown in Figure 9.57, which was formerly one of the range of Purolator filters, comprised a tightly wound spiral coil of a wedge-shaped metal ribbon, both ends being locked firmly onto a central supporting frame. The height of the projections at regular intervals on the upper broad face of the ribbon determined the width of the apertures between adjacent turns of the spiral, typical widths being from 50 to 500 μm. Cleaning of the filter was by means of a spring steel scraper, rotated around the element.

A superficially similar spiral coil with regular projections forms the heart of the Salisbury and other water filters produced by the Cross Manufacturing Company. But there are significant differences in the Cross coil that explain the success of these automated filters. A small but significant difference is that the cross-section of the metal is not wedge-shaped but rectangular.

The major distinctive feature of the 125 cm long Cross element is that it is a spring coil that, under gravity, opens evenly, whereas a conventional coil forms uneven gaps as illustrated in Figure 9.58. This characteristic results from the patented technology used to manufacture Cross coils from superior aircraft grade stainless steel. Its great advantage is that cleaning by backwashing an opened coil is equally effective over the entire length of the element, since the backwash is evenly distributed. Six grades of element are available with micrometre ratings of 12–400 μm.

9.3.3.3 *Stacks of rings*

Probably the best-known example of the filter element using a stack of rings is that in the Metafilter. It was invented in the 1920s by Pickard (who is also remembered as the author of a classic text on filtration[8]), and found wide use in the precoat clarification of liquids in the chemical, processing and food industries; evidence that some of these are still in operation is the orders for spare parts which continue to be received by Stella-Meta, TM Products Ltd.

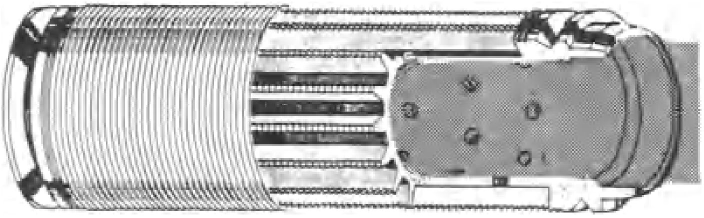


Figure 9.54. A wire wound element based on a former with a screw thread.

The Metafilter element comprises a stack of scalloped rings assembled on a central grooved rod, as illustrated in Figure 9.59. One face of each ring is flat, whilst on the other is a series of scalloped areas (shown shaded) protruding above the surface. They are of a standard size, 19 mm outside diameter, 16 mm inside diameter and 8 mm thick, and may be of various metals (stainless steel, carbon steel, bronze, monel, etc.) or of plastic. The height of the scallops controls the aperture between the adjacent rings of an assembled stack; this may vary but is typically 100 μm.

In the Rellumit Fipoca back-flushing filter, which is mostly used for hydrocarbon fuel oils, the plastic (e.g. Nylon) rings are grooved on both faces, as in Figure 9.60. The cross-sectional shape of each groove is that of an equilateral triangle, its dimensions increasing progressively with the inward direction of flow. The rings have an outside diameter of 35 mm, an internal diameter of 25 mm and a thickness of between 1 and 2 mm, depending on the grade, which ranges from a nominal 5 to 600 μm.

The plate type strainer, as shown in Figure 9.61, used typically for duties such as lubricating oil filtration, is another form of disc stack element. It comprises an alternating assembly of rings of two different diameters, which are separated by spacing washers of a thickness selected to give the required apertures down to about 25 μm. A complementary series of fixed cleaner blades projects into the gaps so that rotation of the element dislodges accumulated dirt and scrapes it clean. Versions of this basic design are the range of Turno Klean filters listed in Table 9.6.

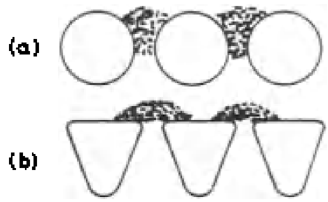


Figure 9.55. Wedge shaped wires (b) are less prone to blocking than circular wires (a).

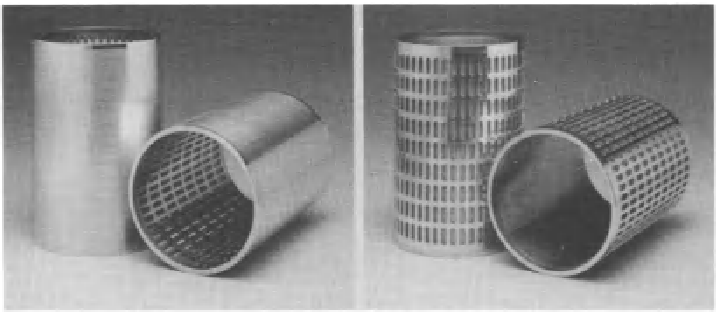


Figure 9.56. Externally and internally wound cells.

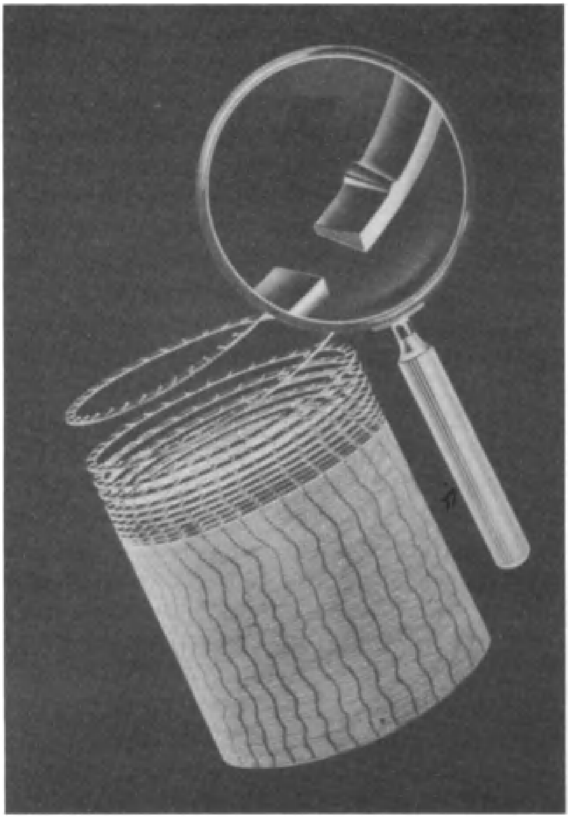


Figure 9.57. The ribbon wound construction of a former Purolator filter.

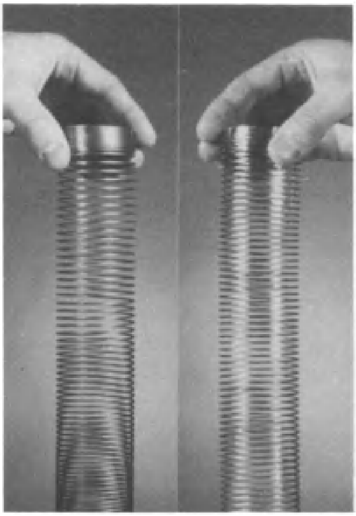


Figure 9.58. Compare the uniform opening of a Cross coil (on the right) with a conventional coil (on the left).

The Streamline filter provides a distinctive use of a stack of rings of material to form an element or cartridge, because the discs are of paper. As shown in Figure 9.62, they are clamped firmly together by a spring-loaded head, and may be of various types of paper and impregnated paper, or of materials such as polypropylene, depending on the liquid to be filtered. Filtration takes place by the liquid flowing through the very narrow interstices between adjacent discs, leaving solid contaminants down to about 1 μm in size on the outer cylindrical surface of the element. Cleaning by reverse blowing with compressed air allows repeated use of the cartridge. Invented in the early 1920s, this unique filter continues to be used primarily for the clarification of insulating oils and of lubricating oils for compressors and hydraulic systems.

9.4 Other Replaceable Elements

There are several small types of filtration device that include filter media as integral parts of the whole unit. These are usually for use in laboratory

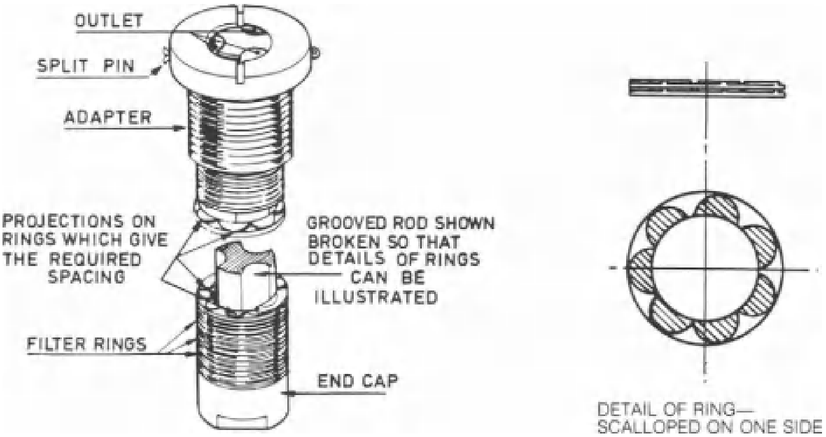


Figure 9.59. Stack of scalloped rings forming an element of a Metafilter.

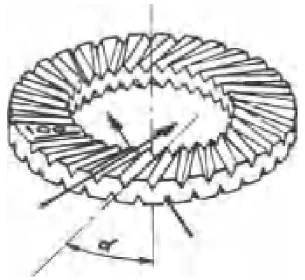


Figure 9.60. Grooved rings form the element of the 'Fipora' filter.

situations, and are frequently called 'capsules'. They are mostly in the form of a polymeric housing, with a disc of filter medium sealed across it, intended mainly for 'guard duty' ahead of some delicate piece of apparatus.

The medium is most likely to be of membrane type, so as to retain viable particles as well as other fine solids.

There is a growing trend to employ this type of filter in industrial situations, especially in the biochemical sector, for the production of biopharmaceuticals and cytotoxic drugs. One of the problems of such operations is to achieve

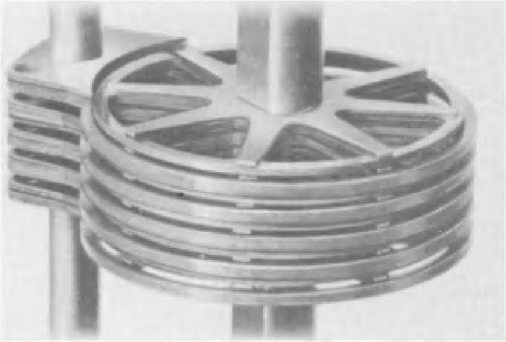


Figure 9.61. The plate type strainer or filter.

Table 9.6 'Turno Klean' and 'Super Turno Klean' plate type filters[c]

Filter element length (inch)	Spacing (μ)	Open area (cm²)	Viscosity CST			
			20	65	150	430
			Flow rate (l/min)[a]			
5	35[b]	17	132	79	42	17
	90	34	57	34	22	10
	125	51	72	49	30	15
	200	64	98	79	42	21
8	35[b]	29	197	129	61	26
	75[b]	57	200	155	76	33
	125[b]	93	200	167	83	36
	90	74	91	57	34	15
	125	83	113	79	49	24
	200	116	159	114	70	34
	380	169	189	133	87	42
	500	192	200	155	100	55

[a] Flow rate clean at 0.21 bar pressure drop.

[b] 'Super Turno Klean'.

[c] Cuno Europe S.A.

adequate degrees of cleanliness in all parts of the plant, including the housings for disposable filters. Pall[9] has two solutions to this:

- a steam-sterilizable capsule filter, with a housing of polyetherimide, and various media materials; and
- a pre-sterilized bag/filter combination, in which a laminated plastic bag, complete with filter, connecting tubing and couplers is provided pre-sterilized by gamma irradiation.

9.5 Selecting Cartridges

There are two distinct filtration zones covered by the cartridge formats described in this chapter:

- coarse or macrofiltration – strainers, metal edge filters, and many bag filters;
- fine or microfiltration – ventilation filters, many bag filters, most cartridges with conventional media, yarn-based and bonded fibre cartridges, and capsules;
- with some forms of the latter increasingly penetrating the submicrometre filtration applications (especially the pleated cartridges using membrane media).

The first decision is therefore of the level of particle size requiring to be removed, and then a medium is sought to match the conditions of the separation: gas or liquid, hot or cold, corrosive or mild, and so on.

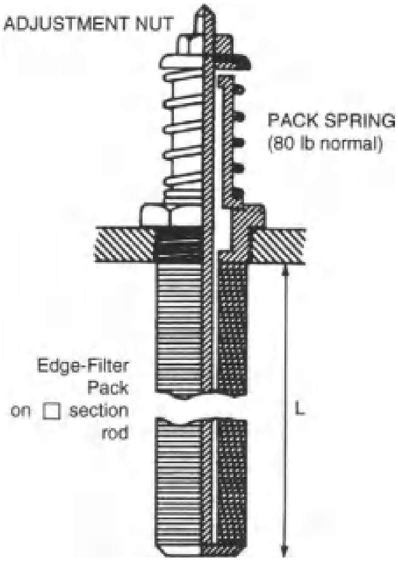


Figure 9.62. The 'Streamline' edge filter element comprises a compressed stack of paper discs.

Most makers of replaceable elements have a large range of types of cartridge on offer, usually with good guidance as to the right choice to be made.

Thus, the specialist cartridge supplier, Amazon, has a range of cartridges described in the detail of Table 9.7. These are in addition to a set of bag filters for liquid use, and a parallel set of housings for bags and cartridges. Each category is allocated to a fairly precise set of applications, mainly in the process industries. The cartridges can be seen to cover a particle size range from the top of ultrafiltration (0.03–0.05 μm) to beyond the top of microfiltration.

The Parker Filtration Division of Parker Hannifin has extended its range of supply from its traditional markets of utility fluid filtration into the process field, and now supplies a very large range of cartridges, as indicated in Table 9.8. In addition to these process filtration cartridges, Parker offers a range of pleated media elements for hydraulic, lubrication and coolant oils, mainly of glass microfibre; a range of compressed air filter elements (mainly from the Balston range); a range of depth and pleated filters and coalescers for engine fluids; a range of high efficiency filter bags for liquid filtration; and absorbent cartridges for hydrocarbon removal from gases.

Table 9.7 Amazon's range of cartridges[d]

Range	Rating	Medium	Type	Grade[a]	Length[a]
SupaGard	Nominal	PP	Bonded	4: 1–100 μm	6: 125–1016 mm
SupaSpun II	Absolute	PP	Bonded	10: 0.5–180 μm[b]	6: 125–1016 mm
SupaSpun NN	Absolute	Nylon	Bonded	9: 1–90 μm	5: 125–1016 mm
SupaPore PP	Absolute	PP	Pleated	7: 0.6–40 μm	4: 247–1016 mm
SupaPore FP	Absolute	Glass	Pleated	3: 0.3–1 μm	4: 247–1016 mm
SupaPore VP	Absolute	PES	Pleated	6: 0.03–0.8 μm	4: 247–1016 mm
SupaPore TP	Absolute	PTFE on PP[c]	Pleated	5: 0.05–1 μm	4: 247–1016 mm
SupaPleat	Absolute	Glass or PP	Pleated	8: 1–75 μm	6: 125–1016 mm

[a] Number of size grades or cartridge lengths and range.
[b] $\beta = 5000$ for 0.5–20 μm.
[c] PTFE membrane on polypropylene substrate.
[d] Amazon Filters Ltd.

Table 9.8 Parker's range of process filtration cartridges*

Yarn wound	Polypropylene, cotton, Nylon, glass microfibre, rayon, polyester (0.5–150 μm)
Resin bonded	Probond acrylic (1.0–120 μm)
Thermally bonded	1.0–120 μm: Megabond absolute rated spunbonded PP; Durabond bicomponent; Ecobond graded density PP
Pleated	0.2–70 μm: Abso-Mate absolute rated PP; Glass-Mate absolute rated glass microfibre; Poly-Mate nominal rated PP; PCC nominal rated cellulose; Flo-Pac nominal rated, large diameter cellulose; Slurry-Mate PP for solid particle classification
Membrane	PES, Nylon, PTFE (0.03–1.0 μm)

* Parker Filtration Division, Parker Hannifin.

The ranges illustrated in Tables 9.7 and 9.8 show the very wide range of cartridges available. Both of these suppliers, as do most other manufacturers, offer extensive guidance to potential users of their products, and, by extension, to the whole range of replaceable element filters covered by this chapter.

9.6 References

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CHAPTER 10

Packed Beds

Apart from the specific use of granular activated carbon in some combination filters, all the media discussed in this Handbook so far have been continuous, even if made from discrete particles or fibres. Now it is the turn of those discrete particles or fibres, used in bulk, to be described, as they are themselves used as filter media.

10.1 Introduction

The structure of this chapter is based on the recognition that there are two distinct modes for utilizing loose powders, fibres and granules as filter media. These are:

- precoat filtration (including filter aids), and
- deep-bed filtration.

Precoat filtration is so named since, prior to each filtration cycle, there is a preliminary phase during which the surface of the filter is coated with a fresh layer of precoat powder, which is deposited by filtration of a specially prepared suspension. The main filtration then takes place through this layer, which acts as the filter medium, so that the collected process solids accumulate as a cake on top of the precoat, as illustrated in Figure 10.1; both layers of solid (precoat plus process solids) are discharged together when the filter is cleaned (e.g. by backwashing). It is implicit that the precoat layer is formed on the surface of a secondary filter medium (usually a very open cloth or wire mesh), which the precoat protects from plugging.

Precoat filtration is most commonly associated with the clarification of liquids, using equipment such as pressure leaf filters, candle filters or rotary vacuum filters. Less common is its role in the filtration of difficult dusts using filter bags in fabric filters(1).

Deep-bed filtration, as its name implies, involves filtration vertically through a packed bed of granular or fibrous material, whose height is considerably greater than even the thickest of continuous filter media. It is typified by the conventional sand filter, which clarifies water by depth filtration mechanisms as it flows through a bed of graded sand that may be up to 1 m in depth.

Deep-bed filters are of very simple construction: a vessel (usually cylindrical), a supporting grid at the base of the vessel, and the bed of granules – plus the necessary inlet and outlet piping. Effectively, the medium is the filter.

Materials such as activated carbon, fuller's earth and ion exchange resins, which are used in deep packed beds of granules, but which function by other mechanisms (primarily adsorption), are excluded from coverage by this chapter since they are not strictly filter media, even though occasionally they overlap in their applications.

It should be noted that, in addition to being used as a precoat, the various types of granular and fibrous materials discussed below are also frequently used as *filter aids* (or body aids) in the filtration of liquids. In this role their function is to accelerate the filtration of a difficult suspension, typically where the solids are very fine, gelatinous or in low concentration. To offset these factors, a controlled quantity of filter aid powder is dispersed into the feed suspension so that the suspended solids and the powder are intimately mixed and therefore are removed together as a mixed cake during filtration. In this way it is possible to produce a more porous cake so that the filtration process proceeds faster and more easily.

Optimizing this use of filter powders involves decisions in respect of the dosage, type and grade of the filter aid, which may differ from that used as the precoat. Logically it is often appropriate to consider alternative separation techniques, including the use of pre-treatment reagents that act as 'filter aids' by means of

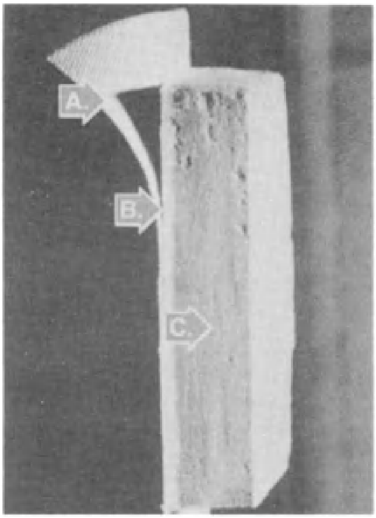


Figure 10.1. The three layers in precoat filtration: (A) a filter cloth or mesh, (B) the precoat layer protecting the cloth from plugging, (C) the filter cake.

chemical reactions. These topics are outside the scope of the present text but are dealt with at length elsewhere(2).

10.2 Precoat Media

A useful overview of the available types of precoat filter media is provided by Table 10.1, which is based on the product range of one leading supplier.

Recommended thicknesses for the precoat layer are typically in the range 1.5–3 mm, corresponding to 500–1000 g/m^2, applied by filtering a dilute suspension at a flow rate of 40–80 l/m^2/min. One leading supplier (Celite) recommends the apertures in the supporting septum or mesh to be no less than 0.13 mm; another (Grefco) relates the suitability of a range of screens to the different grades of its products as summarized in Table 10.2. Finer grades may be supported on one or two layers of increasingly coarse grades.

The materials used as precoats are both inorganic and organic, characterized by being relatively light and voluminous, so as to be able to set up the basic filter cake layer on the support quickly and efficiently. The materials include:

- natural silica – diatomite and perlite;
- cellulose and wood flour; and
- inactive carbon, polymers and miscellaneous powders.

Table 10.1 Summary of major types of filter aids[a]

Product	'Dicalite' diatomite	'Dicalite' perlite	'Solka-Floc'
Composition	Silica	Glassy silica	Cellulose
Number of grades	15	8	8
Range of relative flow rates[b]	1–23	1.7–9.3	5–23
Specific gravity	2.25–2.33	2.34	1.5
Wet cake densities	0.32–0.38	0.24–0.34	0.17–0.34
Retention on coarse screens	Good	Good	Excellent
Solubility (at room temperature)			
In alkalis	Slight in dilute	Slight in dilute	None in dilute
In acids	Slight in dilute	Slight in dilute	None in dilute
Prime advantages and applications	General use for maximum clarity. Reduced dosage on pressure and vacuum filters.	Outstanding on rotary filters.	Excellent for precoating coarse screens. Highest purity for adsorption of oil from condensate and removal of iron from caustic.

[a] Illustrated by 'Dicalite' and 'SolkaFloc' products of Grefco, Inc.

[b] Water permeability ratio relative to Dicalite 215 assumed as 100.

Table 10.2 Suitability of various screens as supports for precoat

Mesh per cm:	8×8	20×20	24×24	32×32	10×44
Apertures (cm):	0.89	0.32	0.25	0.24	0.008
Diatomite grades					
215	No	No	No	No	No
Superaid	No	No	No	No	No
UF	No	No	No	No	No
Speedflow	No	No	Yes	Yes	Yes
Special Speedflow	No	No	Yes	Yes	Yes
Speedplus	No	No	Yes	Yes	Yes
Speedex	No	No	Yes	Yes	Yes
4200	No	No	Yes	Yes	Yes
4500	No	Yes	Yes	Yes	Yes
5000	No	Yes	Yes	Yes	Yes
6000	No	Yes	Yes	Yes	Yes
Perlite grades					
416	No	No	No	No	No
426	No	No	No	No	No
436	No	No	No	Yes	Yes
476	No	Yes	Yes	Yes	Yes
CP 150	No	Yes	Yes	Yes	Yes
4106	No	Yes	Yes	Yes	Yes
CP-175	No	Yes	Yes	Yes	Yes
4156	No	Yes	Yes	Yes	Yes

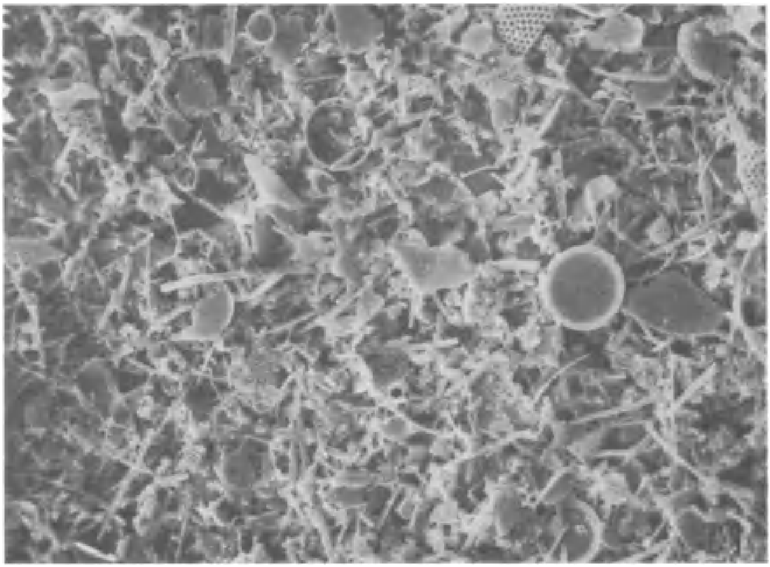


Figure 10.2. Diatomite filter aid at low magnification.

10.2.1 Diatomite

Known also as diatomaceous earth and kieselguhr, diatomite is the classic material for use either as a precoat or as a filter aid. Diatomaceous earth is the fossilized remains of microscopic algae, several million years old, of which over 10 000 varieties have been recorded. Figure 10.2 shows the characteristic appearance of a typical diatomite material under low magnification.

The name 'diatom' is derived from the Greek word meaning 'to cut through', referring to the way in which the individual cells are joined together into zigzag chains that are easily separated. But it also aptly describes the way in which single cells of algae reproduce or replicate by dividing into two almost equal parts. This division happens very simply, since all the different species have an outer shell basically very similar to a pillbox, with one half fitting neatly into the other; it is the difference in shape of the plan view of the pillbox, as shown in Figure 10.3, that gives each diatom its own characteristic appearance. As the diatom grows, the plan view remains unaltered, but the two parts of the shell are forced progressively apart, until cleavage results in two diatoms, where previously there was only one.

The shell of the diatom is virtually pure silica, which is extracted from the water in which diatoms live. After the death of the diatom, the silica shell survives, because of the chemical stability of silica. It is a vast multitude of these minute skeletons that goes to make up a bag full of diatomite for use in industry.

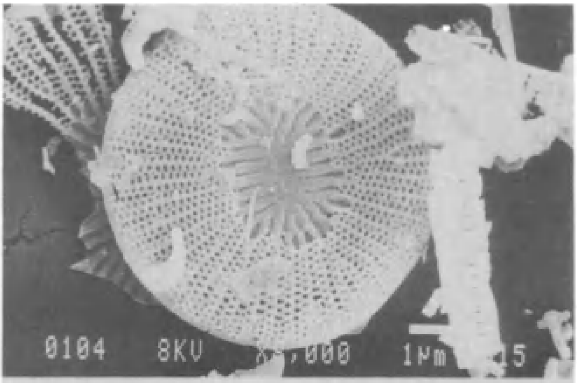
Diatoms occur in both salt and fresh water, and fossilized deposits occur around the world, where former seas and lakes have long since dried up. The commercial value of these deposits varies greatly, due both to soluble impurities and to insoluble contaminants such as clay. Commercially important deposits include those in Algeria, France, Iceland, Japan, Spain and California in the USA.

The deposits are worked by open-cast methods, the amorphous rock being then subjected to a sequence of crushing, grinding, screening, washing, drying and calcining operations. Three basic types of refined product are produced, one without calcining and two with; of the latter, one involves the addition of a fluxing agent such as soda ash. The effect of this refining is that the initial light rock, with a density of 300–500 kg/m^3 and containing 20–40% of water by weight, is converted into a series of ever lighter materials, with bulk densities between 100 and 150 kg/m^3. Moreover, calcining affects the surface of the diatoms, increasing the particle size and reducing the surface area, but markedly increasing the relative filtration rates, as can be seen in Table 10.3.

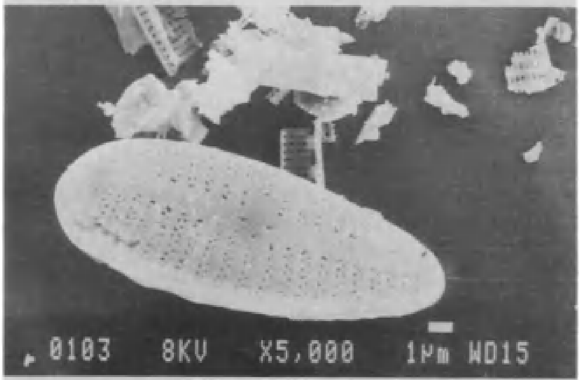
There is inevitably some variation in the chemical composition of the various competitive grades of commercially available diatomite, but the differences are generally relatively small as compared with the composition of alternative materials such as perlite; Table 10.4 shows typical figures for one manufacturer for the composition of refined diatomites.

Far more variation between competitive products is likely to occur in respect of particle size analysis, because of differences both in the quarried rock and in the equipment and techniques used to process it; moreover, it is essentially a subjective matter to decide the best balance of fractions to produce from an initial mixture of particles ranging from about 1 to 100 µm. The data given in Table 10.5 for one manufacturer's range of products are therefore likely to differ considerably from those of a competitor.

In practice, these filter aids are generally characterized by their performance when submitted to a filtration test: unfortunately, each manufacturer tends to have its own test procedure, and then to express performance as a ratio to the slowest filtering material in its own range. Typically, the procedure is to form a precoat layer and then to filter through it under pressure a batch of either water or a slurry to which some filter aid has been added, recording the cumulative volume of filtrate with time. The nature of the aqueous slurry varies, sugar liquids being used by some manufacturers, while others use water containing bentonite clay; the reason for using a slurry is that, besides giving a measure of flow rate, the test then makes it possible to evaluate both the achievable degree of clarity and the ability of the filter aid to maintain the porosity of the cake as it is deposited.



Diatom type cyclotella X 3000



Diatom tyoe Navicula X 5000

Figure 10.3. Diatoms at high magnification.

A summary of the typical properties of one range of diatomite media is provided in Table 10.6. The permeability figures are expressed both as a relative flow rate compared with a nominal value of 100 for the slowest grade, and in darcies. The results of the empirical tests to determine that size of particles which can be retained by certain grades are given in Figure 10.4.

Table 10.7 gives some guidance on the correspondence of certain grades of competitive diatomite media. It reproduces a modified version of an original publication by Eagle-Picher.

10.2.2 Expanded perlite

Since it was first introduced in the 1950s, expanded perlite has established itself as a serious competitor to the diatomite that had dominated the precoat market for the previous half century. Both types of material derive from vast geological deposits, the processing of which have many similarities: but their origins, and hence their chemistry and physical characteristics, are very different.

Table 10.3 Effect of calcining on the properties of 'Dicalite' diatomaceous earths

	Natural	Calcined	Flux calcined
Relative filtration rate	1	1–3	3–20
Wet cake density (g/cm^3)	0.24–0.35	0.24–0.37	0.26–0.34
Sedimentation particle size distribution (%)			
+40 μm	2–4	5–12	5–24
20–40 μm	8–12	5–12	7–34
10–20 μm	12–16	10–15	20–30
6–10 μm	12–18	15–20	8–33
2–6 μm	35–40	15–45	4–30
−2 μm	10–20	8–12	1–3
% retained on 325 mesh screen	0–12	0–12	12–35
Specific gravity	2.00	2.25	2.33
Surface area (m^2/g)	12–40	2–5	1–3
pH	6.0–8.0	6.0–8.0	8.0–10.0

Table 10.4 Typical chemical analysis of refined diatomites[a]

	Natural	Calcined	Flux-calcined
SiO_2	85.8	91.1	89.6
Al_2O_3	3.8	4.0	4
Fe_2O_3	1.2	1.3	1.5
CaO	0.5	0.5	0.5
MgO	0.6	0.6	0.6
P_2O_5	0.2	0.2	0.2
TiO_2	0.2	0.2	0.2
Na_2O+K_2O	1.1	1.1	3.3
Ignition loss	3.6	0.5	0.2
Water	3.0	0.5	0.1

[a] Data for three typical grades of the range of Johns Manville Co. Ltd.

Table 10.5 Typical particle size[a] analyses of Celite diatomites[b]

Weight % finer than micron size (laser size)																	Median particle size in microns
Micron size	1.0	1.5	2.0	3.0	4.0	6.0	8.0	12.0	16.0	24.0	32.0	48.0	64.0	96.0	128.0	196.0	
Celite 5000	2	2	4	6	10	19	27	41	54	65	78	91	93	97	100	100	14.7
Filter Cel	2	3	4	8	12	22	31	45	58	72	80	92	94	98	100	100	14.0
Celite 577	2	3	4	7	12	21	30	41	53	66	75	83	87	95	99	100	14.6
Std. Super-Cel	2	3	4	6	9	17	25	34	52	64	77	90	93	99	100	100	15.4
Celite 512	2	2	4	5	8	15	22	36	49	65	75	87	92	97	99	100	16.4
Hyflo Super-Cel	1	2	3	5	7	11	16	25	36	51	67	86	91	97	99	100	22.3
Hyflo RV	1.4	1.7	2.7	3.4	4.5	6.1	8.1	11.5	25.6	37.9	50.2	67.6	75.7	88.5	99.8	100	32
Celite 501	1	2	3	4	6	9	15	20	31	50	64	82	84	95	99	100	24.3
Celite 503	2	2	3	4	5	7	10	16	25	43	56	76	88	92	98	100	25.4
Celite 503 RV	1	1.4	2.2	2.7	3.9	4.6	6.1	9	14.4	28	37.1	56.2	65.7	76.1	81.1	100	40.0
Celite 535	1	2	3	4	5	7	10	16	21	36	49	70	79	91	99	100	34.3
Celite 545	1	2	2	3	4	5	6	9	14	26	40	55	74	92	99	100	36.2
Celite 560	1.1	1.6	2.3	3.2	4.5	6.9	9.5	11.9	14.2	26.2	34	47.8	55.8	70.1	92.5	100	55

[a] The coarsest particles of the coarser grades of filter aid exceed the dynamic range of a laser sizer, so data shown for those grades indicate a somewhat finer particle size distribution than actual.

[b] Celite Corporation.

Perlite is a rock of much the same composition as granite, and, like granite, is of volcanic origin; its formation and properties result from molten lava discharging from an erupting volcano into water, where it was quenched and rapidly cooled. Perlite is consequently a super-cooled liquid or natural glass, differing from true rocks such as granite in being amorphous, with no crystalline

Table 10.6 Typical properties of 'Dicalite' diatomite filter aids[a]

Dicalite grade	Colour	Specific gravity (kg/m³)	Relative flowrate[b]	Permeability (darcies)	Dry bulk density (kg/m³)	Wet cake density (kg/m³)	Particle[c] median size (μm)	pH of 10% slurry	Moisture content (%)
Calcined									
215	Pink	2.25	100	0.02	128	384	10	6–8	<0.5
Superaid	Pink	2.25	140	0.04	128	384	10.5	6–8	<0.5
UF	Pink	2.25	200	0.08	128	384	11	6–8	<0.5
Speedflow	Pink	2.25	320	0.22	160	368	16	6–8	<0.5
231	Pink	2.25	430	0.36	144	368	19	6–8	<0.5
Flux-calcined									
341	White	2.33	510	0.65		368	22	9–10	<0.2
Speedplus	White	2.33	700	1.00	160	352	32	9–10	<0.2
375	White	2.33	820	1.40		352	35	9–10	<0.2
Speedflex	White	2.33	930	1.80	224	352	40	9–10	<0.2
2500	White	2.33	1080	2.40		336	48	9–10	<0.2
4200	White	2.33	1300	3.30	256	336	59	9–10	<0.2
4500	White	2.33	1450	4.00	256	336	64	9–10	<0.2
5000	White	2.33	1600	5.00	304	384	71	9–10	<0.2
6000	White	2.33	2000	8.00	320	384	77	9–10	<0.2

[a] Grefco, Inc.
[b] Compared with Dicalite 215 rated as 100.
[c] Median particle diameter by Malvern analyzer.

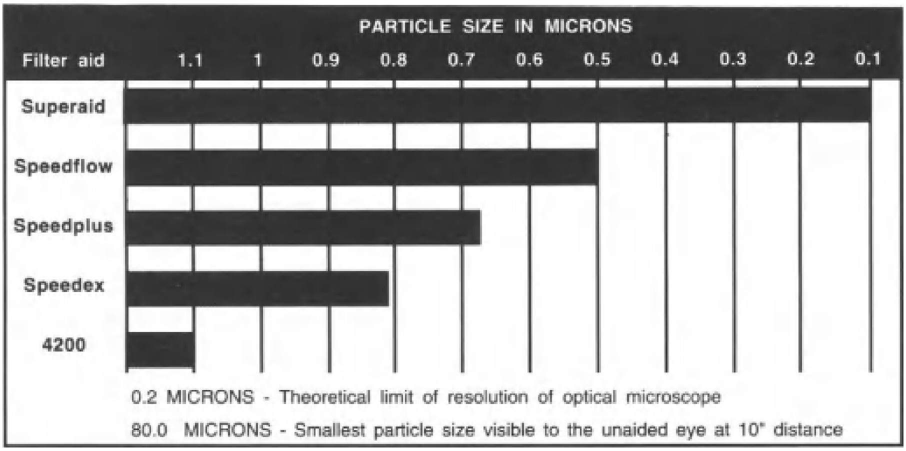


Figure 10.4. Chart showing the sizes of particles removed by five grades of 'Dicalite' filter aids.

structure. Instead, it comprises a mass of small pearl-like 'pebbles', which give the mineral the names pearlstone or perlite. The pebbles may be up to 25 mm across, but are generally the size of lead shot or smaller. Occluded within them, as a result of the quenching of the lava, is a small amount of water; this, together with other water absorbed into the mineral at a later stage, gives a total water content of 3–4%.

Table 10.7 Equivalent grades of diatomite filter aids from four major suppliers

Standard ratios[a]		Eagle-Picher	Celite	Dicalite	Ceca
Flow rate	Clarity				
100	1000		Filter Cel, Celite 505 and 577	Dicalite 215, UF Grade Superaid	CBL3 CBL
200	995	Celatom FP-4	Standard Super Cel	Speedflow	CBR
300	986	Celatom FW-6	Celite 512	Dicalite 231 Special Speedflow	DCB-R
700	970	Celatom FW-12	Hyflo Super Cel	Speedplus CP-100, 689	DIC-B
800	965	Celatom FW-14	–	375	DIC
950	963	Celatom FW-18	Celite 501	CP-5	DIC-S
1000	960	Celatom FW-20	Celite 503	Speedex, 757	DIC 3
2500	940	Celatom FW-50	Celite 535	4200, CP-8	DIT-R
3000	936	Celatom FW-60	Celite 545	4200, 4500	DIT-2R
5500	927	Celatom FW-80	Celite 560	5000	DIT-3R

[a] Based on bomb filter tests with 60° Brix raw sugar solution, 80°C.

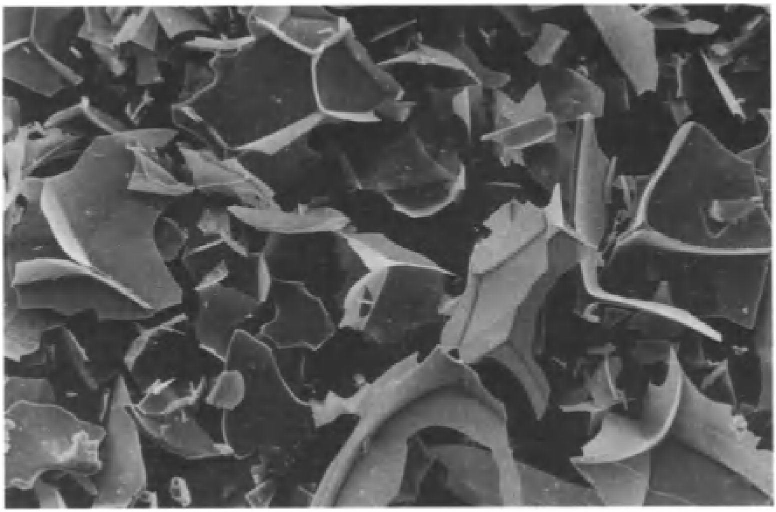


Figure 10.5. 'Harborlite 900S' expanded perlite at high magnification.

The expanded perlite, for use as a precoat, is prepared from the mineral by a sequence of operations that include crushing, grinding, screening and calcining. The key operation, however, is the rapid heating of the crushed perlite to its softening point, when the occluded water vaporizes, causing the individual pebbles to expand to some 20 times their initial volume. The small hollow balls thus formed are subsequently broken up by grinding, to give a mixture of thin irregularly shaped particles, which, as can be seen in Figure 10.5, are rather like pieces of eggshell. Some of the fragments are so shaped that they contain cavities in which small air bubbles can be trapped, thereby causing them to float to the surface when dispersed in a liquid; these floaters can cause operational difficulties if present in sufficient amounts.

By careful control of the manufacturing process, the density of expanded perlite can be varied over a considerable range, to suit the intended application. Typically, expanded ores direct from the furnace are reported by Blunt[3] to have bulk densities in the range 30–60 kg/m^3. Following subsequent grinding and classification, products intended for use as precoat or filter aids may have bulk densities from about 60 up to more than 150 kg/m^3. It is their very low density that enables expanded perlites to compete so strongly with the much denser diatomites, since the weight of perlite needed to form a precoat is thereby proportionally less.

Table 10.8 gives the chemical analysis of a typical expanded perlite, and it can be seen to differ significantly from the composition of diatomites in Table 10.4, notably in respect of sodium and potassium. Particle size analysis data, including the content of floaters, are provided in Table 10.9, while Table 10.10 summarizes the typical properties of one commercial range of perlites.

Based on permeability data in expressed in darcies, the relative flow rates of perlites can be compared with those of diatomites. Figure 10.6 thus summarizes the three different product ranges of Grefco (including its Solka-Floc cellulose fibre materials). It is important to note, however, that equivalence in flow rate does not correspond to identical performance in terms of the clarification achieved; where maximum clarity is required, diatomite is likely to be superior, since it is more effective in removing submicrometre particles, as indicated in

Table 10.8 Chemical analysis of a typical expanded perlite*

	% weight
SiO_2	74.7
Al_2O_3	13.2
Fe_2O_3	0.67
CaO	0.83
MgO	0.03
P_2O_5	Trace
TiO_2	0.01
Na_2O	4.40
K_2O	5.08
Ignition loss	1.0

* Johns Manville Co. Ltd.

Table 10.11, which compares these media in respect of several other criteria as well.

An interesting refinement in processing perlite is recommended by Mayer, based on cooperation between DuPont as a user and Nord Perlite as a manufacturer[(4)]. Laboratory- and plant-scale investigations and trials revealed the impact of the content of particles smaller than 1 μm on performance when pressure filtering waste waters. As shown by the data in Table 10.12 comparing the performance of specially prepared Perflo 30SP with standard quality competitive materials, the shortest filtration was achieved with the Perflo material. Moreover, whereas there is no evidence of a correlation between filtration time and any of the other size analysis parameters in the table, there is a strong relationship to the Sedigraph weight percent of fines of less than 1 μm.

10.2.3 Cellulose fibres

In comparison with diatomite or expanded perlite, natural cellulose fibres have certain advantages for precoat filtration, as a consequence both of their distinctive structure as seen in Figure 10.7, and of their different chemistry. With their lengths varying from as low as 20 μm up to 600 μm or more, it is not surprising that these fibres rapidly form precoats, with little if any penetration through the supporting screen; moreover, the precoat is more stable to pressure fluctuations during the subsequent filtration cycle, and in addition it releases cleanly from the screen when the filter is cleaned. Because of these characteristics, cellulose fibres are frequently used in combination with other types of precoat, either as a preliminary layer or in the form of a mixture.

The cellulose fibres are derived from wood chips, which are subjected to an extensive sequence of processing stages to dissolve out the lignin and other soluble impurities such as wood resins and miscellaneous polymerized sugars. The resultant highly purified pulp is formed into sheets that are dried and then mechanically processed to separate and break up the individual fibres into short

Table 10.9 Typical particle size analyses of expanded perlites[a]

Grade	Permeability (darcies)	Floaters (%)	Micron diameter[b] at which wt.% is <					Wt.% on 106 μm mesh
			10%	25%	50%	75%	90%	
J300S	4.5	5.6	16	–	41.6	–	88	20
J250S	3.9	5.0	15	31	48	–	89	18
J150S	3.2	5.0	14	24	36	56	85	16
J100	2.2	3.7	–	21	33	52	–	18
J2	1.6	2.1	–	19	30	47	–	7
J1	1.2	1.2	–	17	29	46	–	2.5
J4	1.2	2.3	–	17	28	45	–	5.5
J208	0.4	0.5	–	11	20	31	–	2.0
J206	0.15	0.5	–	–	18	–	–	0.9 on 45 μm mesh

[a] Harborlite (U.K.) Ltd.

[b] By Coulter analyzer.

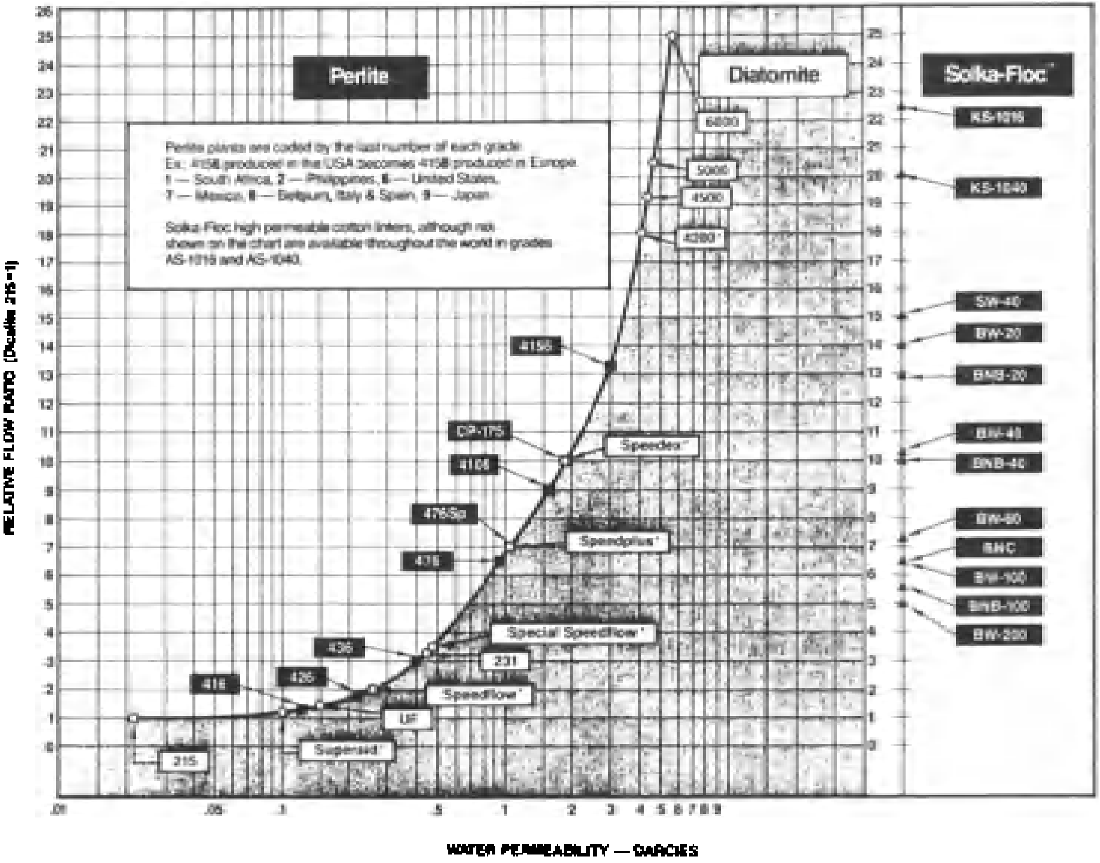


Figure 10.6. Relative flow rate chart for 'Dicalite' filter aids.

Table 10.10 **Typical properties of 'Dicalite' expanded perlite filter aids**[a]

Dicalite grade	Colour	Specific gravity (kg/m^3)	Relative flowrate[b]	Permeability (darcies)	Dry bulk density (kg/m^3)	Wet cake density (kg/m^3)	Particle[c] median size (μm)	pH of 10% slurry	Moisture content (%)
416	White	2.34	170	0.06	88	336	11	5–8	<1.5
426	White	2.34	300	0.18	80	272	14	5–8	<1.5
436	White	2.34	400	0.34	96	272	24	6–9	<1.5
456	White	2.34	520	0.56	n/a	256	31	6–9	<1.5
476	White	2.34	640	0.84	112	240	37	7–9	<1.5
476SP	White	2.34	700	1.00	144	256	42	7–9	<1.2
4106	White	2.34	800	1.30	144	256	50	7–9	<1.0
4156	White	2.34	930	1.80	176	272	57	7–9	<1.0

[a] Grefco, Inc.

[b] Compared with Dicalite 215 rated as 100.

[c] Median particle diameter by Malvern analyzer.

lengths prior to final classification into a series of low-density, free-flowing powders. These comprise pure cellulose, which is chemically inert, containing only trace amounts of inorganic elements, as indicated by Table 10.13; it is consequently ashless, which facilitates disposal by incineration, as well as recovery of catalysts or rare metals.

Examples of these fibres are the Solka-Floc products, whose flow properties are included in the summary chart of Dicalite filter aids reproduced in Figure 10.6. Their other main properties are listed in Table 10.14, while Table 10.15 summarizes the typical applications of the various grades; note that, for economy applications where high purity is not essential, some less refined grades (BNB and BNC) are available.

Table 10.11 Summary guide comparing diatomite and perlite[a]

	Diatomite	Perlite
Typical wet density (g/l)	360	180
Particle size removal	Submicron and above	Less efficient for submicron particles
Particle quantity removal	Typically <0.5% w:w	Typically <2% w:w
Max. operating pressure	6 bar	4 bar
Penetrability in rotary vacuum filter cakes	Good resistance	Usually poor resistance
Ease of filter cloth cleaning	Very easy	'Sticky' cake
Precoating candle filters	Admixture with perlite or cellulose recommended	Very good

[a] Celite France.

Table 10.12 Influence of content of submicron particles on performance of expanded perlite

Parameter	Perflo 30SP[a]	Standard filter aids		
		A	B	C
Weight % <625 mesh	27.0	68.8	39.3	35.4
Coulter Counter analysis				
weight % <2 μm	61.8	70.0	65.4	54.7
D_{50} size (μm)	1.5	1.4	1.5	1.8
Sedigraph analysis				
weight % <1 μm	1.0	9.0	6.0	3.5
D_{50} size (μm)	4.8	3.7	4.6	5.2
Relative filtration time	1.0	2.0	1.8	1.5

[a] Special grade of Nord Perlite filter aid.

An extensive range of precoat and filter aid products is made from wood and other vegetable cellulose by the German company Rettenmaier. The main range of products is described in Table 10.16, with more details of filtration characteristics given in Table 10.17. Figures 10.8 and 10.9 show the relationship between permeability and clarifying action for two of the product ranges.

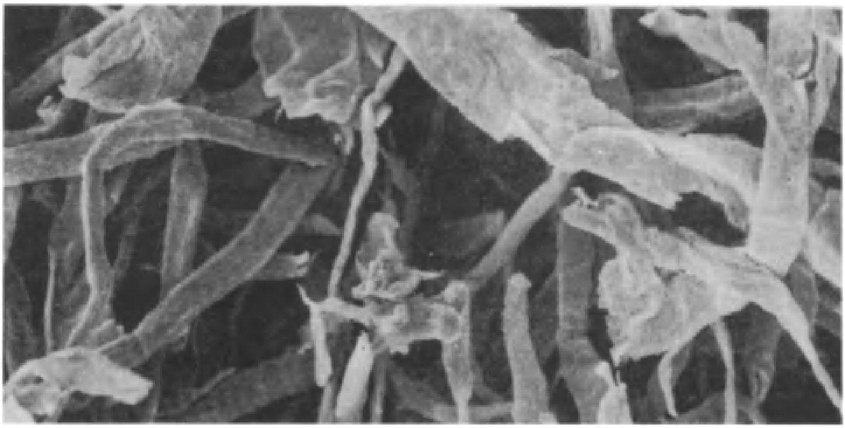


Figure 10.7. Celite 'Fibra-Cel SW-10' cellulose fibres at ×200 magnification.

Table 10.13 Typical element content of 'Solka-Floc' cellulose fibres[a]

	ppm element
Sodium	380.0
Calcium	260.0
Iron	120.0
Aluminium	3.8
Magnesium	31.0
Potassium	37.0
Silicon	15.0
Barium	4.1
Boron	0.34
Lead	2.0
Manganese	1.5
Chromium	0.12
Nickel	0.23
Molybdenum	0.23
Tin	0.41
Lithium	0.40
Copper	1.3
Silver	Trace
Titanium	0.17
Strontium	1.2
Other elements	Nil

[a] Grefco, Inc.

A major development by Rettenmaier[15] has been its "Extract-Free Cellulose" (EFC), for which natural cellulose has been treated by solvent extraction to remove extractable components that might otherwise have led to odour, taste or colour in the filtrate. EFC is marketed under the product name of Filtracel, and is an economical way to achieve a precoat with US FDA approval for use with foodstuffs. Details of the Filtracel products, which now outsell all of the other Rettenmaier lines put together, are given in Table 10.18.

Cellulose fibres are frequently blended with other media, especially diatomites, to facilitate precoat formation and minimize initial penetration through the supporting screen, as well as strengthening the precoat bed, so that it is more resistant to fluctuations in flow rate and pressure. An example of a range of blended cellulose/diatomite powders, with variations in both the proportions and the grades, is summarized in Table 10.19.

Eagle-Picher has a corresponding range of mixed diatomite and cellulose, marketed under the brand name Dialose, based on six grades of the Celatom diatomite (FP-4, FW-6, -12, -14, -20 and -60), mixed with one grade of Pre-co-Floc cellulose fibre (PB-40M), in five different proportions (5, 7.5, 10, 15 and 20% of cellulose fibre).

10.2.4 Wood flour

Wood flour is produced by a process of grinding and double sifting, and is utilized in a wide diversity of industrial applications. Typical standard grades are characterized by screen sizes: 25 mesh (600 µm), 60 mesh (250 µm), 90 mesh (180 µm), 120 mesh (125 µm), 180 mesh (90 µm), and 300 mesh (53 µm).

Table 10.14 Typical properties of 'Solka-Floc' cellulose filter aids[a]

Grade	Colour	Density (kg/m^3)		Specific gravity	% Retention (US Std. Screens)[b]			Fibre length (µm)	pH	Ignition loss
		Loose weight	Filter cake		40M	100M	325M			
KS-1040	White	55	175	1.5	16.0	53.0	87.0	–	7.0	99.8
KS-1016	White	50	170	1.5	16.0	52.0	87.0	290	7.0	99.8
SW-40	White	65	165	1.5	0.5	37.0	81.0	100–140	6.5	99.8
BW-20	White	105	215	1.5	9.0	33.0	68.0	80–120	6.0	99.8
BW-40	White	130	225	1.5	1.0	14.0	56.0	50–60	6.0	99.8
BW-100	White	175	270	1.5	TR	8.0	38.0	45–55	6.0	99.8
Special BW-100	White	200	305	1.5	TR	6.0	31.0	35–45	6.0	99.8
BW-200	White	230	305	1.5	0	2.4	25.0	30–35	6.0	99.8
BNB-20	Brown	95	190	1.5	10.0	31.0	63.0	80–120	7.0	98.7
BNB-40	Brown	105	200	1.5	3.0	23.0	59.0	60–100	7.0	98.9
BNB-100	Brown	135	230	1.5	1.0	3.0	25.0	35-45	7.0	98.9
BNC	Grey	130	250	1.5	5.0	17.0	52.0	–	7.0	98.6

[a] Grefco, Inc.

[b] Apertures of US screens: 40M = 425 µm; 100M = 150 µm; 325M = 45 µm.

A detailed investigation of the potential of some of these flours for use as precoats was undertaken by Wakeman[6], who reached cautiously favourable conclusions, despite the compressibilities being relatively high as compared with

Table 10.15 Typical applications of 'Solka-Floc' cellulose filter aids[a]

Applications		Grades
1.	Alkaline chemicals – e.g. 50% sodium hydroxide, sodium silicate, preparation of alumina and plating solution, where the soluble silica in diatomite and perlite makes them unsuitable	KS-1040 KS-1016 SW-40 BW-20 BW-40
2.	Brine filtration – electrolytic cells of chlorine/caustic plants	BW-100 BW-40
3.	Condensate – removes solid particles and traces of oil	BW-40 BW-100 BW-40 BW-100 special
4.	Emulsions – breaks oil-in-water and water-in-oil	BW-20 BW-40
5.	Catalysts and rare earth metals – ashless 'Solka-Floc' aids recovery by incineration	BW-40 BW-100
6.	Beer and beverages – avoids bleed-through of diatomite or perlite	KS-1040 KS-1016 SW-40 BW-40
7.	Miscellaneous chemicals – where highest purity is not the prime consideration, lower cost unrefined fibres are economic	BNB-20 BNB-40 BNB-100 BNC

[a] Grefco, Inc.

Table 10.16 Rettenmaier's range of cellulose fibre products[*]

Product	Source	Composition
Lignocell	Natural untreated wood cellulose fibres	60–75% cellulose; 20–35% lignin; 3–5% extractables
Rehofix	Natural vegetable fibres from annual plants	70% cellulose; 20% lignin; 10% carbohydrates
Vitacel	Highly purified α-cellulose powder from wood	99.5% cellulose
Arbocel	Highly purified α-cellulose fibre from wood	99.5% cellulose
Vivapur	Micro-crystalline cellulose from wood	99.7% cellulose

[*] J Rettenmaier & Söhne GmbH & Co.

conventional precoats. Data illustrating the effect of compression on porosity, permeability and specific cake resistance are reproduced in Tables 10.20–10.22. An indication of their solubility in various solvents is provided by Table 10.23. As a low-cost material, wood flour has proved to be successful for certain precoat filtration duties, such as for removing protein from glucose solutions.

10.2.5 Inactive carbon

Filter aids of inactive carbon have occasionally been produced, using coal as the ultimate raw material; it is uncertain if any are currently available commercially. As part of a development programme for the direct liquefaction of

Table 10.17 Filtration properties for Rettenmaier cellulose products[a]

Property	Lignocel	Rehofix	Vitacel	Arbocel	Vivapur[b]
Number of grades	7	2	4	19	
Fibre length (μm)	20–350	80–400	20–350	20–2000	10–200
Dry bulk density (g/l)	100–150	300–500	60–270	10–270	150–360
Wet cake density (g/l)	120–230		90–280	40–350	150–400
Permeability (darcies)	1–32	>5	0.8–10	0.8–15	0.2–15
Permeability[c] (per min)	210–4000	>1000	100–3500	100–2500	40–2000
Chemical stability	Low	Low	Very high	Very high	Very high
pH range	2–11	2–11	1–14	1–14	1–14
Max temperature (°C)	180	180	200	200	200

[a] J Rettenmaier & Söhne GmbH & Co.

[b] Vivapur is a very minor product by comparison with the others.

[c] Permeability as measured by Schenk 'Wasserwert-Methode'.

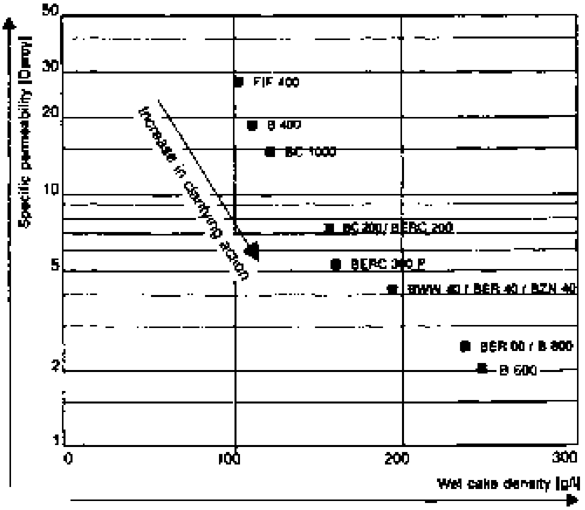


Figure 10.8. Permeability and clarifying action of 'Arbocel' cellulose filter aids.

coal, Kimber and Davies[7] report that (the then) British Coal evaluated the precoat performance of six carbonaceous products derived from coal and petroleum as possible alternatives to Celite 560: the materials tested were petroleum cyclone fines (a by-product of calcined coke), calcined petroleum coke crushed to nominally 100 µm, regular petroleum cokes crushed to nominally 50 and 100 µm, coal extract cokes crushed to nominally 100 µm, and pitch cokes (from coal liquefaction). Best results were achieved with petroleum cyclone fines, the other materials all deteriorating more rapidly. The specific filtration resistances of all coke cakes were less than 3×10^{10} m/kg, within the range of commercial filter aids.

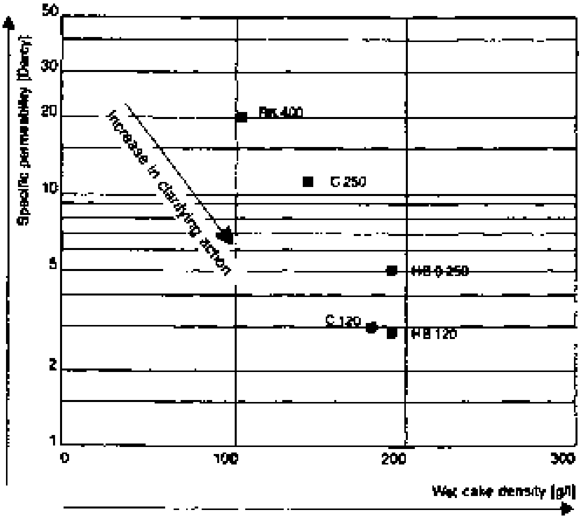


Figure 10.9. Permeability and clarifying action of 'Lignocel' cellulose filter aids.

Table 10.18 Properties of Filtracel EFC cellulose precoat fibres[a]

Property	EFC 100	EFC 450	EFC 800	EFC 1000	EFC 1400	EFC 2000	EFC 3500
Fibre length (µm)	30–50	30–100	50–150	70–150	80–180	150–250	800–3000
Dry bulk density (g/l)	125–180	110–160	110–145	105–130	105–145	120–180	130–170
Wet cake density (g/l)	155–190	155–180	150–165	150–160	150–162	150–190	145–170
Permeability (darcies)	0.3–1.0	2.1–3.8	4.7–6.5	6–8	9–11	12–17	20–28
Permeability[b] (per min)	50–150	350–550	700–900	850–1150	1300–1500	1800–2200	3000–4000

[a] J Rettenmaier & Söhne GmbH & Co.

[b] Permeability as measured by Schenk 'Wasserwert-Methode'.

The various grades of the different carbonaceous materials that have been produced appear all to have broadly corresponded to the coarser end of the range of diatomites and perlites. Their special value would be in their chemical inertness as compared with silica.

10.2.6 Other materials

In principle, any inert bulky granular material could be used as a precoat. Because of their chemical inertness and insolubility, powders of synthetic polymers are potentially applicable as precoat materials and are occasionally reported in use.

Almost any commercial by-product or waste powdered material might be a suitable substitute for a commercial precoat or filter aid. In practice, even if it proves possible to achieve consistently satisfactory standards of qualitative

Table 10.19 'Fibra-Cel' blends of diatomite and cellulose filter aids[a]

Grade[b]	DE component	Cellulose (%)							
		2.5	5	7.5	10	12.5	15	17.5	20
Fibra-Cel 1	Filter-Cel®	A	B	C	D	E	F	G	H
Fibra Cel 2	577	A	B	C	D	E	F	G	H
Fibra Cel 5	Standard Super-Cel®	A	B	C	D	E	F	G	H
Fibra Cel 6	512	A	B	C	D	E	F	G	H
Fibra Cel 7	Hyflo Super Cel®	A	B	C	D	E	F	G	H
Fibra Cel 9	503	A	B	C	D	E	F	G	H
Fibra Cel 10	535	A	B	C	D	E	F	G	H
Fibra Cel 11	545	A	B	C	D	E	F	G	H

[a] Celite Corporation.

[b] Example of grade: Fibra-Cell 6F comprises Celite 512 + 15% cellulose.

Table 10.20 Effect of compressive load on porosity of wood flour

Compressive load[b]	Porosity[a]		
	Wood flour grade		
	120	180	300
0	0.8452	-	-
11.1	0.8420	0.8225	0.8230
16.0	0.8300	0.8100	0.8075
20.8	0.8225	0.8045	0.7990
25.7	0.8125	0.7955	0.7930
35.5	0.8015	0.7890	0.7750
46.0	0.7955	0.7785	0.7660
55.0	0.7920	0.7705	0.7590
64.9	0.7820	0.7660	0.7500

[a] Dimensionless.

[b] Units: kg/m^2.

performance with a low- or zero-value material, a careful analysis of all the relevant cost factors is more likely ultimately to reveal a deficit than a profit.

An interesting example is the RHA filter aid material pioneered by enviroGuard Inc. RHA is an abbreviation for rice hull ash, of which some four million tons are generated in the USA annually, as waste material from milling

Table 10.21 Effect of compressive load on permeability of wood flour

Compressive load[b]	Permeability[a]		
	Wood flour grade		
	120	180	300
0	4.61×10^{-12}	–	–
11.1	1.72×10^{-12}	8.60×10^{-13}	1.20×10^{-12}
16.0	1.61×10^{-12}	7.70×10^{-13}	7.26×10^{-13}
20.8	1.18×10^{-12}	6.49×10^{-13}	6.32×10^{-13}
25.7	1.06×10^{-12}	5.20×10^{-13}	6.00×10^{-13}
35.5	8.50×10^{-13}	4.69×10^{-13}	8.06×10^{-13}
46.0	9.44×10^{-13}	3.68×10^{-13}	4.21×10^{-13}
55.0	8.30×10^{-13}	3.65×10^{-13}	3.89×10^{-13}
64.9	6.30×10^{-13}	3.54×10^{-13}	3.21×10^{-13}

[a] Units: m^2.

[b] Units: kg/m^2.

Table 10.22 Effect of compressive load on specific filtration resistance of wood flour

Compressive load[b]	Specific filtration resistance[a]		
	Wood flour grade		
	120	180	300
10	2.64×10^{9}	4.62×10^{9}	4.64×10^{9}
20	3.45×10^{9}	6.11×10^{9}	5.96×10^{9}
30	4.06×10^{9}	7.59×10^{9}	7.29×10^{9}
40	4.40×10^{9}	8.54×10^{9}	8.10×10^{9}
50	4.87×10^{9}	9.01×10^{9}	8.54×10^{9}
60	5.20×10^{9}	9.26×10^{9}	8.70×10^{9}

[a] Units: m/kg.

[b] Units: kg/m^2.

Table 10.23 Solubility of wood flour

Liquid	pH	Colour change of solution?[a]
Dilute sulphuric acid	1	Yes
Dilute hydrochloric acid	1	No
Benzene	4	Yes
20% sodium hydroxide	11	Yes
Water	7	No

[a] Attributed to chemical reaction.

and processing rice. It is 95% amorphous silica with 5% carbon, and minimal amounts of trace elements, so it is an obvious potential substitute for conventional filter powders. Encouraging results were reported by Rieber[8] from both laboratory and plant trials.

10.3 Deep-bed Granular Media

Many different granular and crushed materials have been used to form the deep beds employed in the large gravity and pressure filters common to the water purification and sewage treatment industries. In addition to sand, which is the classic and most common material, others used include garnet, ilmenite, alumina, magnetite, anthracite and quartz; coke and pumice have also been used but, because of their porosity, they are troublesome to clean and consequently give rise to the danger of uncontrolled breeding of bacteria.

The suitability of a granular material for use in a deep bed filter depends both on the application and on the type of filter. Conventionally, there are two main types that operate with gravity flow downwards through a 0.6–1.0 m deep bed; these are identified respectively as 'slow' and 'rapid' sand filters.

Slow sand filters operate with a velocity of 0.1–0.2 m/h down through the bed. They function by a form of straining through the so-called 'schmutzdecke' or biological layer that forms on the surface of the bed. They are cleaned occasionally by the reasonably complete removal of this layer, without disturbing the rest of the bed.

Rapid sand filters utilize a velocity of 5–15 m/h and function by depth filtration within the bed. They are cleaned frequently by cessation of process flow, followed by a reverse upward flow of wash water at such a rate that the bed expands and releases the trapped dirt particles: this cleaning flow may be augmented by some form of agitation, such as injecting compressed air below the bed or hydraulic jets impinging on the surface. This cleaning process has an important secondary effect, which is to reclassify the granules of the bed based on the combined influence of their size and their density, so that the washed bed is graded from finest at the top to coarsest at the bottom.

A variety of other types of filter have been subsequently developed from the rapid sand filter, starting with pressurized versions such as that illustrated in Figure 10.10. A more radical variation is the use of upward flow so that the incoming raw water encounters the coarsest granules first and the finest last (as in the Immedium filter). These beds are also washed by an expanding upward flow, with the dirty effluent withdrawn separately.

Multi-layer filters with conventional downward filtration achieve the same results by means of beds comprising two or more materials of different densities so that the hydraulic classification of cleaning places the finer, denser particles on top of the coarser, less dense particles.

The most modern version of the rapid sand filter is that which uses a moving bed of sand, whereby both filtration and cleaning proceed continuously and simultaneously. Recent evidence (from the US EPA) suggests that such filters can be as effective as membrane filtration plants in the removal of such pathogens as *Cryptosporidia* and *Giardia* from water intended for drinking.

10.3.1 Characterization of granular media

A practical approach to assessing the suitability of granular materials for use as deep-bed filter media has been provided by Ives(9): the physical properties identified as being of interest were particle size, particle shape, density, durability, solubility, cleanliness and settling velocity. An indication of the variation of some of these properties is provided by Table 10.24, reproduced from Mohanka(10).

Many of Ives' procedures have been included or adapted in the 'Granular Filtering Materials Standard' first published in 1993 by the then British Effluent and Water Association (BEWA), and in a final version in 1996(11) by British Water (into which BEWA had merged). This document specifies a total of 15 items of information, as listed in Table 10.25, which are recommended for inclusion in a supplier's data sheet for a product offered as a filter medium for water, and discusses each in some detail.

The discussion below is based mainly on Ives but also includes some references to the British Water document. Both omit any measurement of filtration efficiency; the reason for this is the complex nature of deep-bed filtration, which involves interaction between a suspension and filter medium. As Ives

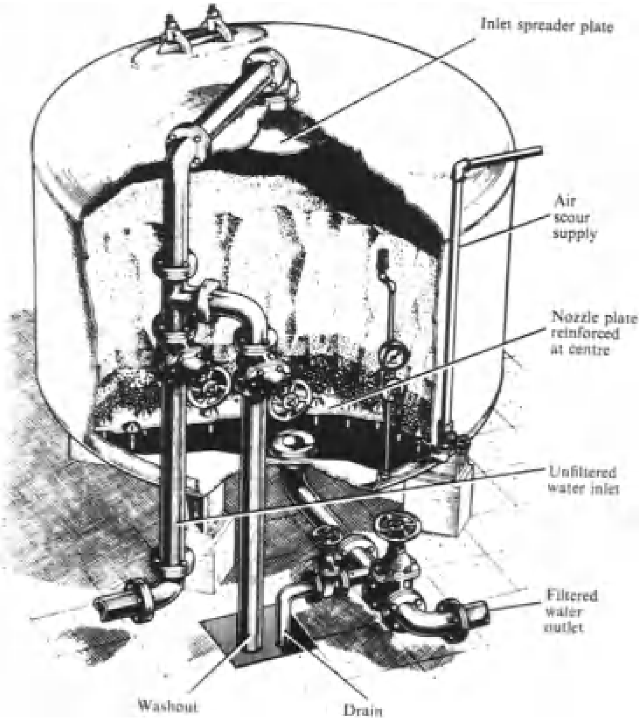


Figure 10.10. A vertical pressure sand filter.

Table 10.24 Physical characteristics of various granular filter media

Physical parameters	Multilayer filter				
	Polystyrene	Anthracite	Crushed flint sand	Garnet	Magnetite
Sieve size (mm)	3.175–2.057	1.676–1.405	0.853–0.699	0.599–0.500	0.500–0.422
Fall velocity (cm/s)	3.30	6.35	8.10	9.40	10.95
Hydraulic diameter (mm)	2.50	1.14	0.60	0.467	0.415
Sphericity	1.00	0.745	0.78	0.865	0.90
Density (g/cm^3)	1.04	1.40	2.65	3.83	4.90
Porosity	0.35	0.425	0.464	0.47	0.42

Physical parameters	Sand filter				
	Crushed flint sand	Crushed flint sand	Crushed flint sand	Quarry sand	Quarry sand
Sieve size (mm)	0.500–0.422	0.599–0.500	0.853–0.699	1.676–1.405	2.411–2.057
Fall velocity (cm/s)	5.00	6.54	8.10	16.85	20.90
Hydraulic diameter (mm)	0.38	0.435	0.60	1.165	1.36
Sphericity	0.83	0.80	0.78	0.765	0.62
Density (g/cm^3)	2.65	2.65	2.65	2.65	2.65
Porosity	0.464	0.464	0.464	0.39	0.39

Table 10.25 Information recommended by British Water for inclusion by granular media suppliers in their product data sheets

1. Type of material, e.g. sand, anthracite
2. Information relating to the size grading available, e.g. standard available grades
3. General description, e.g. appearance and shape of material
4. Source and production procedure. Geological classification, if relevant
5. Dirt (dust) content limits
6. Grain effective specific density
7. Bulk density (in backwashed condition)
8. Abrasion resistance (state if water only or air and water)
9. Friability data
10. Poured and packed voidage
11. Acid solubility
12. Impact resistance (support material only)
13. Impurity leach data

14 Backwash (a) head loss data for standard gradings
(b) expansion versus upflow @ 5, 10, 15 and 20°C for standard grades

15 Filtering head loss data at rates of 5–15 m/h

commented[12], there is no such thing as a 'good filter' unless the suspension to be filtered is simultaneously specified: in some cases, coarse grains are required, in others finer grains or multiple layers of different materials.

10.3.1.1 Particle size

Granular media are generally characterized by sieving tests that report the mass retained on a series of successively finer screens. The data are conventionally expressed graphically as the cumulative percentage finer than the size of openings in each screen, as in Figure 10.11.

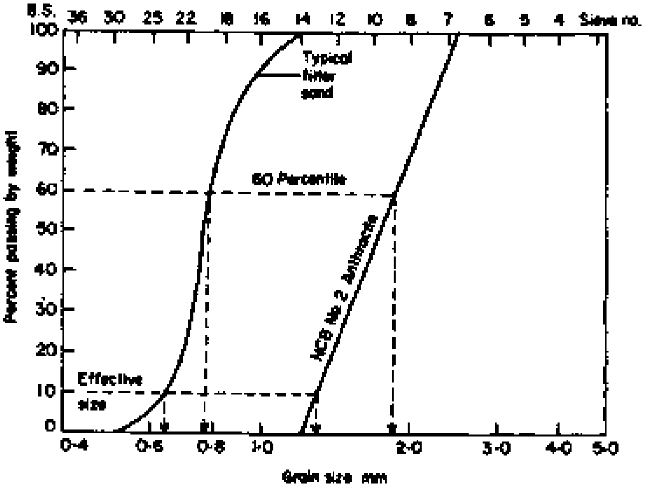


Figure 10.11. Grain size distribution of typical waterworks filter sand and anthracite. Note: The 10-percentile is the Hazen effective size: inverse ratio of this to 60-percentile is the Hazen uniformity coefficient.

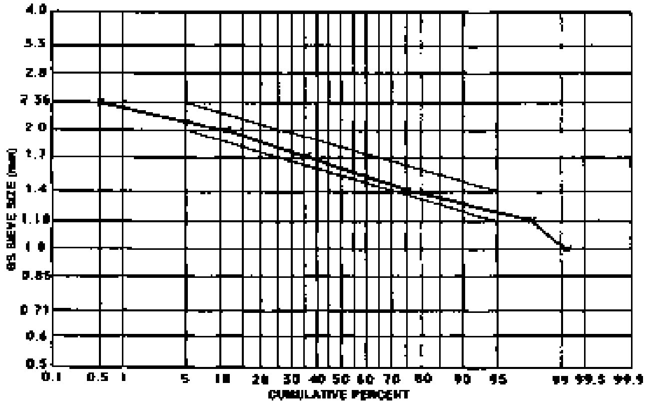


Figure 10.12. Example of a plot of sieve test data on a log/probability basis, with tramline limits (based on an example in British Water Standard[11]).

The British Water standard recommends the use of the log/probability form of plot illustrated in Figure 10.12. An advantage of this format is that the acceptable tolerance limits can be defined as a pair of parallel 'tramlines', as shown.

There are several different numerical forms of expression of particle size and size range, which are summarized in the following notes.

(a) Percentile limits of 5% and 95%. The size range is defined in terms of the lower and upper sieve sizes, the lower being that which retains 95% or more by weight (i.e. passes 5% or less), and the upper that which retains 5% or less (i.e. passes 95% or more). The sieve sizes should preferably be specified by the dimensions of their openings in millimetres (rather than as sieve numbers or meshes per centimetre or inch). This corresponds to the British Water definition. Thus, a 0.5–1.0 mm material specifies not more than 5% by weight is below 0.5 mm or above 1.0 mm.

(b) Hazen effective size and uniformity coefficient. These two parameters were invented by the American engineer Hazen for slow sand filters, wherein the sand sizes remain fixed. It is common practice but inappropriate to apply them also to the stratified beds of rapid sand filters; British Water recommends that this use should be discontinued.

The *effective size* is the sieve size d_{10} that 10% by weight would pass, as indicated in Figure 10.11. The *uniformity coefficient* is the ratio d_{60}/d_{10}, where d_{60} is similarly the sieve size that 60% would pass. The larger the value of this coefficient, the greater the range of grain sizes.

Hazen discovered empirically that, if all the sand of a bed is replaced with grains of one size only, then that size must be d_{10} for the head loss (or hydraulic resistance) for the two beds to be identical; this contrasts with the expectation that the average or modal size d_{50} would produce this effect. The explanation that subsequently emerged is that the modal size *by number* is approximately equal to d_{10} *by weight*: and head loss is determined by surface area, which depends on the size and number of grains, not on their weight.

Later research demonstrated that, even when restricted to slow sand filters, the uniformity coefficient is of little relevance to the performance of the filter(13).

(c) Hydraulic diameter (d_h). This is a concept introduced by Ives enabling the shape of a particle to be expressed quantitatively in terms of its sphericity. It is the diameter of a spherical particle that has the same settling velocity in water as the actual particle.

The hydraulic diameter can be calculated from the observed settling velocity of a particle by calculation of the drag coefficient for the particle, C_D, in the form of the dimensionless group relation between drag coefficient and Reynolds number, Re:

$$\frac{C_D}{\mathrm{Re}} = \frac{4g(\rho_s - \rho)\mu}{3\rho^2 v_s^3}$$

where ρ_s = particle density, ρ = liquid density, μ = liquid viscosity, v_s = particle settling velocity. The Reynolds number for the particle is given by:

$$\mathrm{Re} = \rho d_h v_s/\mu$$

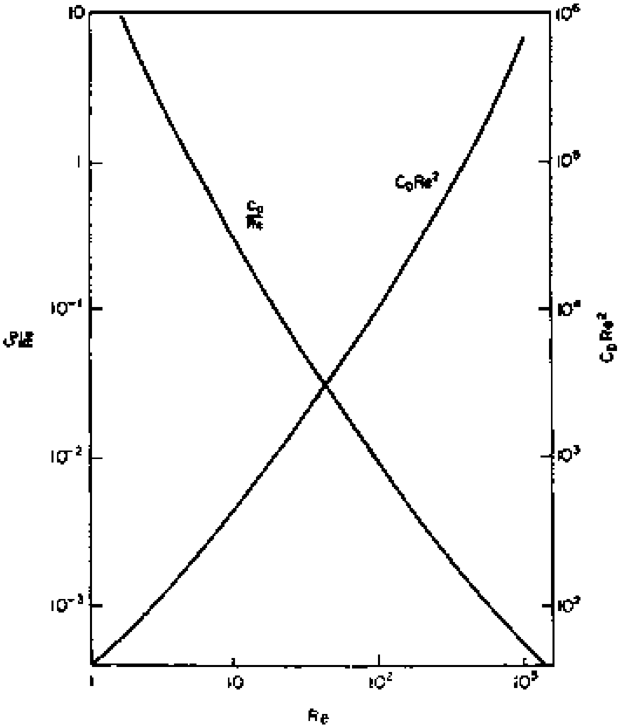


Figure 10.13. Curves of dimensionless groups C_D/Re and C_D/Re^2 versus Reynolds number Re.

and can be determined from the curve in Figure 10.13, and the hydraulic diameter calculated by rearranging the definition of Reynolds number:

$$d_h = \mu Re / \rho v_s$$

(d) Hydraulic size. This is a term preferred by the British Water standard over Ives' hydraulic diameter. Hydraulic size, D_H, is defined as 'the uniform grain size that would produce the same resistance to flow as the material under consideration (at the same voidage)'. The concept of hydraulic size is based on a theoretical model of the filter bed as a series of discrete layers corresponding to the sizing fractions retained on a set of test sieves. Each layer is characterized by the respective sieve aperture (i.e. the grain size) and by the retained percentile (i.e. the relative thickness of the layer).

The theoretical background to this was summarized by Stevenson(14), utilizing the relationships developed by Kozeny and Carman to evaluate the particle size that gives the same surface area as the actual mixture and therefore has the same hydraulic behaviour.

The British Water standard and Stevenson's paper both provide a very simple calculation procedure for evaluating D_H, comprising the following four steps:

1. divide the percentage retained on each successive sieve by the size of the sieve aperture;

2. add up all the figures thus obtained and divide by 100;
3. obtain the reciprocal of the above sum; and
4. add 10% to the reciprocal, to correct the 'retained' size to the centre size between adjacent sieves (sieves are spaced at 20% increments).

A specimen calculation in this manner is shown in Table 10.26.

10.3.1.2 Particle shape

The shape of a particle is important because it affects the way in which the particle settles into the packed bed, and the consequent bed voidage. An indication of the extent to which the shape of particles departs from the spherical is provided by the list of shape coefficients for a range of materials in Table 10.27. This utilizes two different shape coefficients, K_a and K_v, by which the surface areas and volumes of particles are related to the 'average' diameter, d_{av} – an average depending on the sizing technique used:

Surface area = $K_a d_{av}^2$

Volume = $K_v d_{av}^3$

Table 10.26 Specimen calculation of hydraulic size

Sieve aperture (mm)	% retained	Calculation
2.8	0.1	0.04
2.36	0.5	0.21
2.0	10.2	5.1
1.7	22.1	13.0
1.4	42.3	30.25
1.18	22.5	19.1
1.0	1.4	1.4
0.85	0.3	0.35
0.71	0.5	0.7
	100.0	70.1

Divide 70.1 by 100 = 0.701
Reciprocal = 1/0.701 = 1.43
Add 10% = 0.14
Hydraulic size = 1.57 mm

Table 10.27 Shape coefficients for typical granular materials

Particle	Area coefficient K_a	Volume coefficient K_v
Sphere	$\pi=3.142$	$\pi/6=0.502$
Copper shot	3.14	0.524
Sand	2.1–2.9	–
Worn sand	2.7–3.4	0.32–0.41
Pulverized minerals (coal, limestone)	2.5–3.2	0.2–0.28
Coal	2.59	0.227
Mica	1.67	0.03
Aluminium flakes	1.60	0.02

By contrast, Ives preferred a hydrodynamic definition of *sphericity* that relates the sieve size of a particle, d_s, to the hydraulic diameter, d_h (the size of a sphere having the same settling velocity in water as an actual particle). Thus the sphericity is given by:

$$\psi = d_h/d_s$$

Some typical values for sphericity are given in Table 10.28; values below 0.6 suggest an undesirable flaky shape.

In discussing what shape is desirable for filter media particles, Ives[12] commented that there is agreement that flakes are undesirable, but differing opinions on the benefits or disadvantages of being near to spherical roundness. He reported comparative tests to assess the relative quality of filtrate achieved by filtering a suspension through identical beds (in terms of depth and particle size fraction) of glass beads ($\psi = 0.98$), sand ($\psi = 0.85$) and anthracite ($\psi = 0.70$); it was found that anthracite was best, sand next and round glass beads worst. The differences were shown not to be due to surface electrochemical effects, since all had similar zeta potentials (about −20 mV). It is interesting also to note published opinions criticizing highly rounded filter media[15,16].

Elsewhere, Ives reports that a study of the mechanisms of deep-bed filtration shows that changes in local flow direction caused by angularity of the filter medium lead to improved capture of particles[17]. Confirmation of this is provided in the USA where Hambley[18] stated that 'side by side column tests of highly angular sand will markedly out-perform round sand in improved effluent turbidity, in run time to break through, and/or in run time to limiting head loss'; moreover, this has been verified in actual practice with filters of all types, including dual media and multimedia high-rate filters. Hambley concluded that sphericity should be less than 0.6 – the exact opposite of the conclusion of two paragraphs above, which probably set too high a limit on sphericity.

The British Water standard does not focus specifically on shape excepting once in a mention under general description, and then in its list of definitions, which includes *aspect ratio* ('the ratio of the largest to the smallest dimension of a given grain') and sphericity ('the ratio between the surface area of the sphere with the same volume as the grain and the actual surface area of the grain').

Table 10.28 Sphericity and density of common granular filter media

Material	Origin	Density (kg/m)^3	Sphericity (shape)
Quartz sand	UK	2650	0.85
Anthracite	UK	1400	0.70
Hydroanthracite	FRG	1740	0.65
Pumice	Sicily	1180	0.75
Expanded slate	FRG	1500	0.75
Garnet	USA	3950	0.65

10.3.1.3 Density

The British Water standard distinguishes between *grain specific gravity* of non-porous and porous materials. For porous materials, the *effective specific gravity* is for a grain saturated with water.

In multi-layer beds, the buoyancy imposed by water has a significant effect on the relative density of the materials. This can be seen, for example, with the UK and German anthracites in Table 10.28, for which the densities as listed are 1400 and 1740, showing the German material to be the more dense by 24%. Underwater, however, both densities are reduced by 1000 (the density of water) to effective levels of 400 and 740, the German anthracite then being 85% more dense than the other.

10.3.1.4 Durability

It is important for filter media grains to resist attrition and degradation during the repeated backwashing operation that is an essential part of the operating cycle of rapid sand filters. Accordingly, specifications sometimes include a definition of the required degree of Moh hardness, such as 3.0–3.75 for anthracite. In practice, this is insufficient to define durability, which is not necessarily dependent just on hardness since fracture and attrition may result from brittleness.

An accelerated backwashing test was therefore devised by Ives(9). Running continuously for 100 hours in a week, this corresponds to 1000 washings of 6 minutes each, equivalent to about 3 years of washing operations at a typical rate of one per day. The key measurement is the depth of filter medium lost from a 30 cm deep bed contained in a 1 m glass or plastic tube, at least 3 cm in diameter. A similar test is incorporated in the British Water standard.

Where Ives uses 'durability' to embrace the various types of mechanical degradation, the British Water standard distinguishes among abrasion, friability and impact resistance each of which is separately listed as in Table 10.25, and covered by the latest version of the standard.

10.3.1.5 Solubility

It is accepted practice to test media for solubility by utilizing more stringent conditions than are ever likely to occur in practice, the usual problem being some form of calcium carbonate (e.g. fragments of sea shells in beach sand) dissolving in acid. The limit set by the American Water Works Association(19) is a 5% loss by weight into 50% hydrochloric acid; 20% acid was considered adequate by Ives(9), both to establish that grains are not aggregates cemented together and to show up colours indicating the presence of soluble iron salts. This embraces the two parameters the British Water standard identifies as acid solubility and impurity leaching.

10.3.1.6 Cleanliness

Media should be free from dirt, dust, organic matter, clay, etc. This can be checked by swirling a small sample in clean water followed by a visual examination, including use of a low-power (×20) microscope.

10.3.1.7 Settling velocity

The settling velocities of individual particles can be determined by timing their movement between two fixed points in a vertical tube of water. Their value is in calculating the corresponding hydraulic diameter and the sphericity. In addition, in the form of a graphical plot such as Figure 10.14, they also provide a convenient indication of the expected stratification behaviour of mixed-media beds if water alone is used for the final phase of the backwashing. These relationships are utilized by Ives(12), but not in the British Water standard.

10.3.1.8 Head losses and bed expansion

With apparatus similar to that used for the accelerated abrasion test, the British Water standard proposes measurements of flow resistance (head loss) both during filtration and whilst backwashing. Filtration tests should cover the losses of 5–15 m/h. Backwashing involves a range of velocities to achieve levels of bed expansion up to at least 50%, using wash water at temperatures of 5, 10, 15 and 20°C.

10.3.1.9 Porosity/voidage

The British Water standard calls for measurement of the porosity or voidage under both poured and packed conditions, for non-porous materials with variation no more than ±0.5% (e.g. 39.5–40.5%).

10.3.2 Available media

Inert media of various densities are utilized in single- and mixed-media filters, so as to control the classification and pore grading of the bed structure, with coarse filtration in the lower layers and progressively finer filtration towards the top.

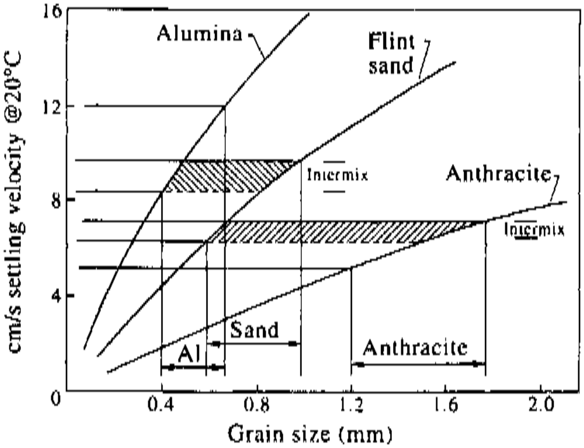


Figure 10.14. Settling velocity versus grain-size curves indicate the intermixing and layering of a three-component deep bed.

A variety of other 'active' materials used as filter media function by chemical reactions that are beneficial in the overall process of water treatment and purification by removing contaminants such as metals (aluminium, iron, manganese, lead, cadmium, etc.), cyanide ions, or hydrocarbons and other organics. These media may be used separately, be mixed with the main bed of

Table 10.29 Technical data sheet specifications of silica sands for water filtration[a]

Mechanical analysis		Aperture (mm)	BSS mesh no.	Percentage by weight retained			Nominal effective size range	Mean uniformity coefficient
Grade (mm)	No.			Typical grading		Cumulative range		
				Fractional	Cumulative			
2.8–1.18	6–14	3.35	5	Trace	Trace	0–0.5	1.25–1.70	<1.7
		2.80	6	2.0	2.0	0–5.0		
		2.36	7	9.0	11.0	5–35		
		2.00	8	16.5	27.5	10–65		
		1.70	10	27.5	55.0	25–90		
		1.40	12	28.0	83.0	70–100		
		1.18	14	14.5	97.5	95–100		
		1.00	16	2.0	99.5	99–100		
2.00–1.00	8–16	2.36	7	Trace	Trace	0–0.5	1.05–1.27	<1.4
		2.00	8	1.5	1.5	0–5.0		
		1.70	10	18.0	19.5	5–35		
		1.40	12	35.5	55.0	25–80		
		1.18	14	29.5	84.5	70–95		
		1.00	16	13.5	98.0	95–100		
		−1.00	−16	2.0	100.0	99–100		
1.70–0.85	10–18	2.00	8	Trace	0.10	0–0.5	0.9–1.18	<1.4
		1.70	10	2.0	2.0	0–5.0		
		1.40	12	23.5	25.5	10–50		
		1.18	14	39.5	65.0	40–90		
		1.00	16	22.0	87.0	70–100		
		0.85	18	12.0	99.0	95–100		
		0.71	22	0.5	99.5	99–100		
1.18–0.60	14–25	1.40	12	Trace	Trace	0–0.5	0.63–0.85	<1.4
		1.18	14	2.0	2.0	0–5.0		
		1.00	16	14.5	16.5	0–35		
		0.85	18	40.0	56.5	25–90		
		0.71	22	31.5	88.0	70–100		
		0.60	25	11.0	99.0	95–100		
		0.50	30	1.0	100.0	99–100		
1.00–0.50	16–30	1.18	14	Trace	Trace	0–0.05	0.54–0.71	<1.4
		1.00	16	1.0	1.0	0–5.0		
		0.85	18	21.5	22.5	10–40		
		0.71	22	30.5	53.0	25–90		
		0.60	25	35.0	88.0	75–100		
		0.50	30	10.0	98.0	95–100		
		0.425	36	1.5	99.5	99–100		

Table 10.29 (*continued*)

Mechanical analysis		Aperture (mm)	BSS mesh no.	Percentage by weight retained			Nominal effective size range	Mean uniformity coefficient
Grade (mm)	No.			Typical grading		Cumulative range		
				Fractional	Cumulative			
For slow sand filters								
0.71–0.25	No. 21	1.00	16	Trace	Trace	0–0.5	0.25–0.38	<1.7
		0.71	22	0.5	0.5	0–0.5		
		0.50	30	38.0	38.5	10–60		
		0.355	44	48.0	86.5	70–95		
		0.25	60	10.5	97.0	90–100		
		0.18	85	2.5	99.5	95–100		

[a] Garside Industrial Sands. CAMAS Aggregates.

Typical Properties

Source: Leighton Buzzard. Bedfordshire. UK

Geological Classification:	Lower greensand	
Chemical Properties:	SiO_2	Approximately 97%
	Loss on ignition @ 1025 °C	Not more than 1.0%
	Weight loss in acid (24h. 20% HCl. 20°C)	<1.0%
Physical Properties:	Specific gravity	2.65
	Uncompacted bulk density	1560 kg/m^3
	Saturated porosity	0.41
	Particle shape – sphericity –	0.85 (sphere = 1)
	Rittenhouse Scale	0.83–0.87
	Durability (100 h accelerated wash test)	Weight loss <0.1%

sand, or constitute separate layers in multi-media filters. Typical reactive materials are calcium carbonate, manganese dioxide and aluminosilicates.

10.3.2.1 Silica sand

The specifications of six grades of filter sand available from one supplier are summarized in Table 10.29. comprising five for rapid filters and one for slow filters. Table 10.30 lists 17 rapid grades of another supplier. whose specifications for two grades for slow filters are provided in Table 10.31.

10.3.2.2 Anthracite- and coal-based media

Data for examples of anthracite- and coal-based media are provided in Table 10.32, while Table 10.33 gives the head loss (mm water) through a 1 m deep bed at filtration rates from 10 to 50 m/h.

10.3.2.3 Volcanic rock, garnet and ilmenite

Typical data for these three materials, which have densities ranging from 2440 kg/m^3 up to 4800 kg/m^3 are provided in Table 10.34. Ilmenite is available as both sand and gravel, the size analyses of which are indicated in Table 10.35.

Table 10.30 Technical data for silica sands for rapid filters[a]

Size range (mm)	Minimum within range (%)
0.20–0.50	90
0.20–0.70	90
0.40–0.63	90
0.425–0.85	90
0.50–1.00	90
0.60–1.20	90
0.80–1.25	90
0.85–1.70	90
1.00–1.60	90
1.00–2.00	90
1.40–2.00	80
1.20–2.40	80
1.20–2.80	80
1.50–2.50	80
1.70–2.50	80
2.00–3.15	80
2.00–4.00	80

[a] Universal Mineral Supplies Ltd.

Physical properties:	Specific gravity	2.65
	Bulk density	approx. 1600 Kg/m^3
	Hardness	6–7 Moh
	Acid solubility	<2.0%
	Abrasion resistance. loss after 100 h back wash	maximum 2.0%
	Uncompacted prorsity	0.38–0.45
Chemical properties:	Silica as SiO_2	>96%

Table 10.31 Technical data for silica sands for slow filters[a]

Grade no.	20	25
Effective size range (mm)	0.25–0.35	0.20–0.40
Mean uniformity coefficient	<2.2	<3.0
Appearance	Dark brown/grey/angular/sub-rounded grains	
Specific gravity	2.65	
Dry bulk density	1560 kg/m^3	
Hardness	6–7 Moh	
Silica as SiO_2	90% minimum	

[a] Universal mineral Supplies Ltd.

The relationship between pressure loss and filtration rate through a 1 m thick layer of volcanic rock of various sizes is shown in Table 10.36.

10.4 Deep-bed Fibrous Media

An unusual deep bed, used in the novel Howden-Wakeman (HW) filter, is composed of loose fibres instead of conventional granules. As shown schematically in Figure 10.15, the bed of fibrous material is compressed by a perforated piston during filtration and expanded by retracting the piston for backwashing; a brief period of reciprocating action aids washing by agitation of the bed.

Table 10.32 Technical data for anthracite- and coal-based filter media

Product name	Anthracite	Aqua-cite	Aqua-cite 'B'	Aqua-fit
Supplier	Progenerative Filtration Ltd	Aqua Techniek bv	Aqua Techniek bv	Aqua Techniek bv
Source	Unspecified anthracite	Unspecified anthracite	Based on coal	Pennsylvania anthracite
Density (kg/m^3)	1400	710–725	Approx. 500	ca. 890
Bulk density (kg/m^3)	720	±400	Approx. 1650	ca. 1650
Chemical analysis (%)				
Carbon	90.0	>90	Approx. 90	94.7
Sulphur	0.7	0.6	Approx. 0.45	-
Volatiles	4.0–6.0	6.4	Approx. 3.5	–
Ash	2.0–4.0	2–4	Approx. 6.5	–
Water	–	1.2	Approx. 2	–
Hardness (Moh)	3–4	–	–	3.0–3.8
Solubility (%)				
In 20% HCl	<2	–	–	<5
In 10% NaOH	<2	–	–	–
Size mm (and effective size)	0.06–1.2 (0.7) 1.2–2.5 (1.3) 1.1–2.36 (1.2) 2.5–5.0 (2.6) and as requested	0.6–1.6 1.4–2.5 2.5–5.0 and as requested	0.8–1.6 1.4–2.5 and as requested	Complete range
Uniformity coefficient	<1.60	–	–	–

Table 10.33 Pressure losses (mm water) through 1 m layers of anthracite- and coal-based media

Filtration rate (m/h)	Aqua-cite media		Aqua-cite 'B' media	
	0.8–1.6 mm	1.4–2.5 mm	0.8–1.6 mm	1.4–2.5 mm
10	150	70	180	80
20	315	160	400	180
30	515	270	720	300
40	780	410	–	440
50	1000	550	–	590

Table 10.34 Other inert media for deep bed filters

Material	Volcanic rock	Garnet	Ilmenite
Produce name	Aqua-volcano	Garnet	Aqua-ilmenite
Supplier	Aqua Techniek bv	Universal Mineral	Aqua Techniek bv
Density (kg/m^3)	2440	4100	4200–4800
Bulk density	1320	2380	–
Chemical analysis (%)			
SiO_2	59.72	36.1	0.30
Al_2O_3	23.22	20.4	–
FeO	–	29.8	
Fe_2O_3	2.66	1.7	29.90
CaO	2.36	1.55	–
MgO	0.40	6.0	–
MnO	–	1.05	–
TiO_2		1.8	64.70
K_2O	3.08	–	–
Na_2O	6.40	–	–
P_2O_5	–	–	0.17
V_2P_5	–	–	0.15
Ignition loss	2.06	–	–
Acid solubility	–	–	>5
Moh hardness	–	7–8	5.0–6.5
Sizes available (mm)	0.8–1.5 1.5–2.5 2.5–3.5	0.3–0.6 1.4–2.36	Sand[a] Gravel[a]

[a] See Table 10.35 for typical analyses of standard sand and gravel.

Table 10.35 Typical analyses of ilmenite sand and gravel[a]

US standard sieve no.	Sieve opening (mm)	% passing typical	% passing specification
Sand			
30	0.600	90	70–100
40	0.425	66	40–80
50	0.300	34	–
60	0.250	21	–
70	0.212	6	–
80	0.180	5	–
Gravel			
4	4.75	95	90–100
6	3.35	61	–
8	2.36	36	–
10	2.00	25	–
12	1.70	16	–
14	1.40	7	0–10
16	1.18	2	–

[a] Aqua Techniek bv.

The filter is claimed to have better filtering capabilities than conventional deep beds[20,21]. An example quoted is the 99.992% removal of 3.5 μm particles after 2 h continuous operation without backwash; effective removal of particles down to 0.2 μm is within its capability.

Various types of fibre are reported to have been used, including wool and carbon. Carbon fibres were found to be particularly attractive since they permit repeated steam sterilization without incurring undesirable side effects such as creep, which was experienced with many polymeric materials. Moreover, with diameters in the range 1–10 μm, these fibres are far smaller than the 400–3000 μm diameter of typical granules; there is a corresponding difference in porosity, 80–83% for the fibres as compared with 35–47% for granules, producing a greater dirt-holding capacity. Figure 10.16 demonstrates the dependence of the flux rate on the bulk density to which the bed is compressed.

Table 10.36 Pressure losses (mm water) through 1 m layers of volcanic rock

Filtration rate (m/h)	Media size (mm)		
	0.8–1.5	1.5–2.5	2.5–3.5
10	190	120	180
20	390	250	180
30	585	400	280
40	800	560	390
50	1030	720	510

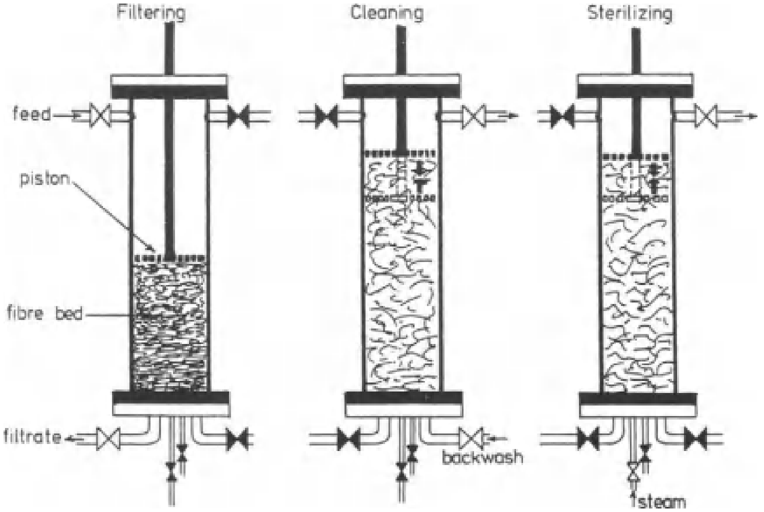


Figure 10.15. Operating modes of the Howden-Wakeman filter.

10.5 Selecting Loose Particulate Media

Both types of media discussed in this chapter are aimed at the efficient filtration of very fine solids, using relatively inexpensive means, especially in terms of the replacement of media that are full of entrapped solid particles. Precoat media enable the use of quite coarse, but strong continuous basic media in a range of filtration equipment (filter press, pressure filters with leaves or candles, and

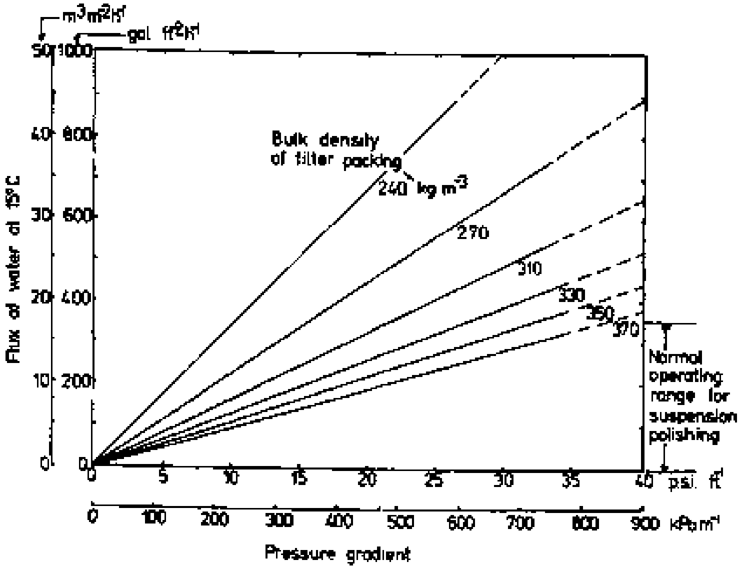


Figure 10.16. Flux versus pressure gradient of Howden-Wakeman filter.

Table 10.37 Comparative grades of diatomite materials*

Celatom DE	Celite	Dicalite	Kenite
FP-1SL	Filtercel	215	
FP-1, FP-2	505	Superaid	100
FP-1W	577	U.F.	
FP-3, FP-4	Std. Supercel	Speedflow	200
FW-6	512	Spec. Speedflow	300
FW-10			
FW-12	Hyflo	341	700
FW-14		Speedplus	900
FW-18	501	375	1000
FW-20	503	Speedex	
FW-40		2500	2000
FW-50	535	4200	2500
FW-60	545	4500	3000
FW-70	550	5000	5500
FW-80	560	5500	

* Eagle-Picher Minerals, Inc.

rotary vacuum filters), with the fine degree of filtration achieved by the precoat material, which may be a single layer or a set of layers of different sized particles (or even different materials), with the finest at the top or upstream face, to create the base for a surface filtration process, generating a cake of separated solid.

Although the granules in a deep-bed filter are graded in the same way (i.e. with finest upstream) they are intended to act by depth filtration, with the long tortuous channels through the bed being sufficient to achieve the required degree of filtration. This pattern of finest on top is a consequence of the bed expansion and resettling during every cleaning step. However, it is perfectly possible to make a deep bed from layers of different materials, such that the coarsest are in the upstream part of the bed – or to reverse the flow to upwards from the base of the bed.

Table 10.38 Comparative grades of perlite materials*

Celatom perlite	Harborlite	Dicalite	Nord	Silbrico	Femco
		416			H-2, H-1
	400	426	734	27-M	
	635	436	634	25-M	H-5S
1200	700	476-CP-100	443	23-S	H-5
1400	800	4106-CP-150		21-S	H-4
2000	900	4156-CP-175	332	19-S	H-9
4000	1800	4186		17-S	H-X
5000	1900				
6000	2000		272	15-S	H-R
	5000				

* Eagle-Picher Minerals, Inc.

Table 10.39 Comparative grades of cellulose precoat materials*

Pre-co-Floc	Arbocel	Technocel	Solka-Floc	Fibra-Cel
PB200M	BE600	50/90	BW300	
PB100M	B800		BW200	BH100
	BE00			
PB100ME	BWW40	100/150	100	BH65
PB40M			40	
PB40ME				
PB40ME-LD	BC200			BH40
PB20M				BH20
PB100	BC1000	200	20	
PB40				
PB33	B400		10	
PB33E				
PB20	FIF400		1016	

* Eagle-Picher Minerals, Inc.

10.5.1 Precoat media

An unavoidable feature of the use of precoat is that some or all of it will be discharged with the accumulated filter cake. Material must thus be chosen whose presence in the cake can be tolerated (e.g. where the cake is itself a waste product intended for immediate disposal), or which can be easily separated from the cake solids by subsequent processing. If the cake solids can withstand it, then incineration could be used to remove an ashless cellulose material.

Of the available range of precoat media, the two mineral products, diatomite and expanded perlite, and cellulose are the most common. The makers of cellulose fibre media claim that it can achieve any required degree of filtration, if properly chosen and laid down, while the mineral media suppliers usually allot cellulose to a base layer of precoat, if any.

The various grades from one or two manufacturers are described in Section 10.2, and a set of comparative grades is given in Table 10.37 for diatomite, Table 10.38 for perlite, and Table 10.39 for cellulose.

10.5.2 Deep-bed media

The largest use by far for deep-bed filters is in the processing of raw water for the production of drinking water (and, to a lesser extent, in waste water treatment). The choice of granular media for this purpose is therefore largely made on the basis of the advice in Section 10.3.1, or the British Water standard[11].

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CHAPTER 11

Testing Filter Media

The bulk of this Handbook has been concerned with the various types of filter media, and has described their properties, as concern filtration. The final two chapters show how these properties are measured, and describe the standards that govern the various detailed characteristics.

11.1 Introduction

A large and ever increasing number of standard tests are available for characterizing either filters or their associated media. These standards are established either by national authorities, such as BSI (the British Standards Institution) and ASTM (the American Society for Testing Materials), by specific industry organizations, such as TAPPI (the American Pulp and Paper Industry) or by regional or international organizations, such as CEN (Comité Européen de Normalisation) and ISO (the International Standards Organization). These standards typically define in detail the recommended testing equipment, its method of operation and the associated procedures for processing and interpreting data. Some of them are of broad relevance, but many are focused on specific types of media, for example sintered metals, or applications, for example lubricating oil for internal combustion engines.

The objective of this chapter is to present an overview of the relatively few principles that underlie the resultant multiplicity of standard test procedures, so that the reader will be better able to assess and interpret much of the data provided in earlier chapters. There is no attempt here to provide detailed guidance on the execution of any of the tests; readers requiring this information are recommended to refer to the appropriate published standards relevant to their geographical location and industrial context.

Apart from mechanical strength, the properties of filter media of particular interest are five of the six 'filtration-specific properties' identified in Table 1.6 of Chapter 1, namely:

1. the smallest particle that the medium is able to retain;
2. the efficiency with which particles of a defined size are retained;
3. the resistance of the medium to the flow of clean fluid through it;

4. the dirt-holding capacity of the medium: and
5. the tendency of the medium to blind, especially when used repeatedly in an operating cycle that includes cleaning, especially where particles adhere tenaciously to the medium.

However, a lot can be learned about a filter medium by examination of its structure. Any newly developed material will normally have undergone microscopic examination to enable its relation to other media to be seen, and to permit some initial estimates as to its likely performance. A novel technique is now available(1) that permits the production of three-dimensional images of materials that are soft enough to slice (i.e. mainly natural fibres and polymers). The technique involves the slicing of a block of material very thinly (to an accuracy of 0.1 μm), the illumination of the new surface with ultraviolet light in a special microscope, and the capturing of the image on a large format digital camera. A thousand images may be taken, and these are then assembled to give a 3-D picture of the material.

11.2 Testing Filtration Characteristics

Most of the test procedures designed to characterize a medium in respect of the filtration-specific properties involve 'challenging' the medium, either with a suitable clean fluid, or with a fluid containing dispersed particles of selected and controlled characteristics.

Challenging with a clean fluid permits evaluation of:

- the permeability or resistance to flow per unit area of medium, such as the flow rate of air or water under a defined pressure: and
- the size of the pores of the medium, in terms of the ideal cylindrical pores assumed in the bubble point test, and hence an approximation of the size of particle that the medium can retain by straining mechanisms.

Challenging with a fluid containing dispersed particles permits the determination of:

- the smallest particle that can be retained with 100%, which is the 'absolute rating' of a medium:
- the relationship between particle size and retention efficiency, typically expressed as a grade efficiency curve:
- the relationship between the quantity of material filtered and the increasing resistance to flow, and hence the dirt-holding capacity, of the medium under the specific operating conditions; and
- a first indication if the medium tends to blind rapidly when used repeatedly with an operating cycle that includes cleaning.

The notes that follow describe the main testing procedures applied to continuous media (i.e. those formed originally in sheets or rolls, or as cartridge constructions).

It should be noted, however, that these tests of filtration performance may not be the only ones of interest for a filter medium – it may be necessary to follow the performance of the same piece of material over a long lifetime, for which simple weighing after successive cleaning cycles may be sufficient^(2)^.

11.2.1 Permeability

The immense variety of expressions formerly used for the permeability of filter media is illustrated by Table 1.10. in Chapter 1. This table was originally assembled in 1966^(3)^, since when there has fortunately been considerable progress in standardization, so that now permeabilities are generally expressed in two main forms, even if in a considerable variety of units. The more common form, appropriate for sheets of media but effectively treating thickness as a constant, characterizes them in terms of the rate of flow of a specified fluid, usually air, per unit area. A far less widely used form, which is more rigorous fundamentally and takes cognisance of the thickness, characterizes a medium by its permeability coefficient.

11.2.1.1 Permeability coefficient

The permeability coefficient of a medium, K_p, is defined by the Darcy equation describing flow through a porous layer:

$$P/L = Q\mu/AK_p \tag{11.1}$$

where P = the differential pressure across the medium (Pa); L = the depth or thickness of the bed or medium (m); Q = the volumetric flow rate of fluid (m^3/s); μ = the kinematic viscosity of the fluid (Ns/m^2); A = area occupied by flow (m^2). When all of these parameters are expressed in SI units, as indicated, then K_p has the units of m^2.

However, K_p is frequently reported in inconsistent units, notably darcies, where the viscosity is defined in centipoise, the differential pressure in atmospheres and the other parameters in centimetres and seconds so that:

$$1 \text{ darcy} = (1 \text{ cm}^3/\text{cm}^2/\text{s}).(1 \text{ centipoise})/(1 \text{ atmosphere/cm})$$

Hydrologists and soil scientists prefer the term hydraulic conductivity, expressed as the velocity of water percolating per unit hydraulic gradient. Factors for conversion of K_p from m^2 to some other units are given in Table 11.1.

Table 11.1 Permeability coefficient units

1 darcy	=	0.99×10^{-12} m^2
1 m^2	≡	1.013×10^{12} darcy
	=	9.8×10^{8} cm s^{-1} (for water at 20°C)
	≡	2.78×10^{12} ft day^{-1}
	≡	2.08×10^{13} US gallon day^{-1} ft^{-2}

Equation (11.1) assumes that the flow regime within the porous layer is laminar, which appears to be correct for the greater majority of filtration applications, where the flow rate per unit area corresponds to a maximum superficial velocity of 0.4 cm/s. However, situations can occur where other flow conditions exist, as demonstrated by Heertjes in respect of woven fabrics and by Morgan for sintered metals. Both made use of the accepted criterion of flow regime, which is the Reynolds number, adapting this to the structural forms of their own studies.

Heertjes(4) used a definition of Reynolds number, Re, based on the pore diameter:

$$\mathrm{Re} = \rho u_p d_p / \mu \qquad (11.2)$$

where ρ = density of the fluid; u_p = fluid velocity through the pore; d_p = pore diameter; μ = fluid viscosity. He reported a transition zone in the range $3<\mathrm{Re}<7$, separating the laminar and turbulent regions. Once the flow is fully turbulent, the proportionality between flow rate and pressure is replaced by $P^{0.55}$.

Instead of the pore diameter, Morgan(5) utilized a dimensional factor M for packed beds of spherical particles, based on the porosity, e, and the specific surface area, S_v, such that:

$$M = (\text{pore volume})/(\text{surface area}) = e/S_v(1-e) \qquad (11.3)$$

His data indicate a fairly sharp transition from laminar to turbulent flow, as shown for five different grades of sintered metals in Figure 11.1. Morgan reports that practical Re values occasionally range as high as 70, when a 50% error can occur if the differential pressure is calculated assuming laminar flow. To avoid this error, he proposed a modified form of equation (11.1):

$$P/L = Q\mu/AK_p + Q^3\rho/A^2K_2 \qquad (11.4)$$

where K_2 = an inertia permeability, with units of length. In many instances, the second term is so small that it may be ignored; this applies especially to liquids where the viscosity is high.

11.2.1.2 Air permeability

The most common form for expressing permeability disregards the thickness of the medium, so that the permeability is empirically quantified by the flow rate of air per unit area, under a defined differential pressure.

An appropriate example is the Frazier scale widely used internationally in the paper and textile industries; this is based on the flow of air and was formerly specified as cfm/sq. ft at 0.5 inch WG. Metric versions require care since they may use various combinations of definitions of air volume (litres or cubic metres), time (minutes or seconds), area (square centimetres, square decimetres or square metres), and differential pressure (mm WG or Pa). Conversion factors for the units used in expressing air permeabilities are shown in Table 11.2, while associated pressure unit conversions are given in Table 11.3.

Considerably higher pressures (than the 12.5, 20 or 25 mm WG used in air tests), ranging up to 1 bar, may be used where flow rates are relatively low, due either to testing with water instead of air or to the fineness of pores in media such as membranes.

11.2.1.3 Measuring permeability

Suitable measurements can be made with apparatus of varying degrees of sophistication, as illustrated by the following examples.

A very simple measuring device is the Gurley Densometer or Air Resistance Tester, shown in Figure 11.2 and used in the paper industry. With this instrument, pressure is provided by a vertical piston that slides down under its own weight, thus forcing a known volume of air through a standard orifice holding the sample being tested. The number of seconds taken for the predetermined volume of air to flow through the sample provides an empirical definition of its permeability.

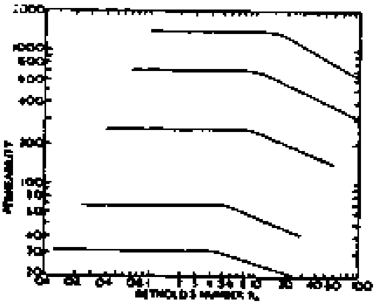


Figure 11.1. Change in flow regime at higher velocities through sintered metals, demonstrated by plot of Reynolds number versus permeability coefficient K_p.

Table 11.2 Conversion factors for various air permeability units

		$l/m^2/s$	$l/dm^2/min$	$cm^3/cm^2/s$	cfm	$m^3/m^2/min$	$m^3/m^2/h$
1 $l/m^2/s$	=	1.00	0.600	0.100	0.197	0.0600	3.60
1 $l/dm^2/min$	=	1.67	1.00	0.167	0.328	0.100	6.00
1 cm^3 cm^2/s	=	10.0	6.00	1.00	1.97	0.600	36.0
1 cfm/ft^2	=	5.08	3.05	0.508	1.00	0.305	18.3
1 $m^3/m^2/min$	=	16.7	10.0	1.67	3.28	1.00	60.00
1 $m^3/m^2/h$	=	0.278	0.167	0.0278	0.0547	0.0167	1.00

Table 11.3 Conversion factors for air permeability

		Pa	mbar	cm WG	in WG
1 Pa	=	1.00	0.0100	0.0102	0.00402
1 mbar	=	100	1.00	1.02	0.402
1 cm WG.	=	98.1	0.981	1.00	0.394
1 in WG	=	249	2.49	2.54	1.00

The Frazier Precision Instrument Company manufactures a Differential Pressure Air Permeability Machine in two models. The first model, the Low Pressure Machine, with air flow generated by suction up to pressure differentials of 5 kPa (0.05 bar), was developed by the US National Institute of Standards and Technology, for measuring the air permeabilities of textile-type materials: it is the acknowledged standard of the US Government and the US textile industry and, in practice, is widely used for any materials that can be fitted to the physical dimensions of the equipment. In conjunction with the US Air Force, Frazier developed a second model, the High Pressure Machine; this utilizes the same principle but with pressurized air flow, providing much greater versatility of use due to its higher attainable air flow with differential pressures up to 0.7 bar.

An example of a Low Pressure Machine is shown in Figure 11.3, its operating principles being illustrated schematically in Figure 11.4 as a version that incorporates the 'guarded cylinder principle'. This latter isolates the test area of a sample from any leakage that may occur around the peripheral clamp seal with locally rigid media, such as woven wire; for flexible media, such as paper and textiles, simple clamps are adequate, while special forms of clamp are used under other circumstances as indicated in Figure 11.5.

The same principles are also the basis of various other devices, such as the SDL Electronic Air Permeability Tester in Figure 11.6, which was developed by the Shirley Institute for all kinds of flat materials. It uses a suction pump to draw air through a circular hole in an interchangeable test head. The test head used is selected to suit the desired standard test procedure, in accordance with options such as those listed in Table 11.4. The specimen, which may be a sheet up to 120 cm × 60 cm, is clamped with a piece of it over the opening in the test head, using a quick release handle. This automatically starts the suction pump to establish and maintain airflow at the pre-selected test pressure between 98 and 2500 Pa

Figure 11.2. Gurley Densometer *for measuring air permeability.*

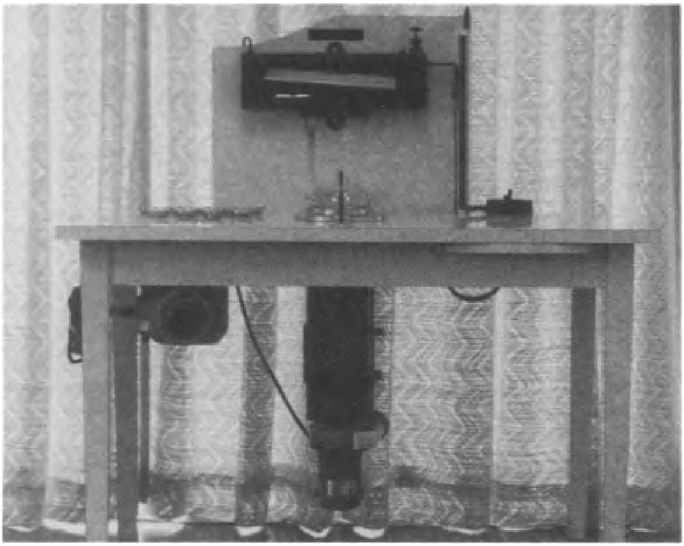


Figure 11.3. Frazier Low Pressure Machine *for measuring air permeability.*

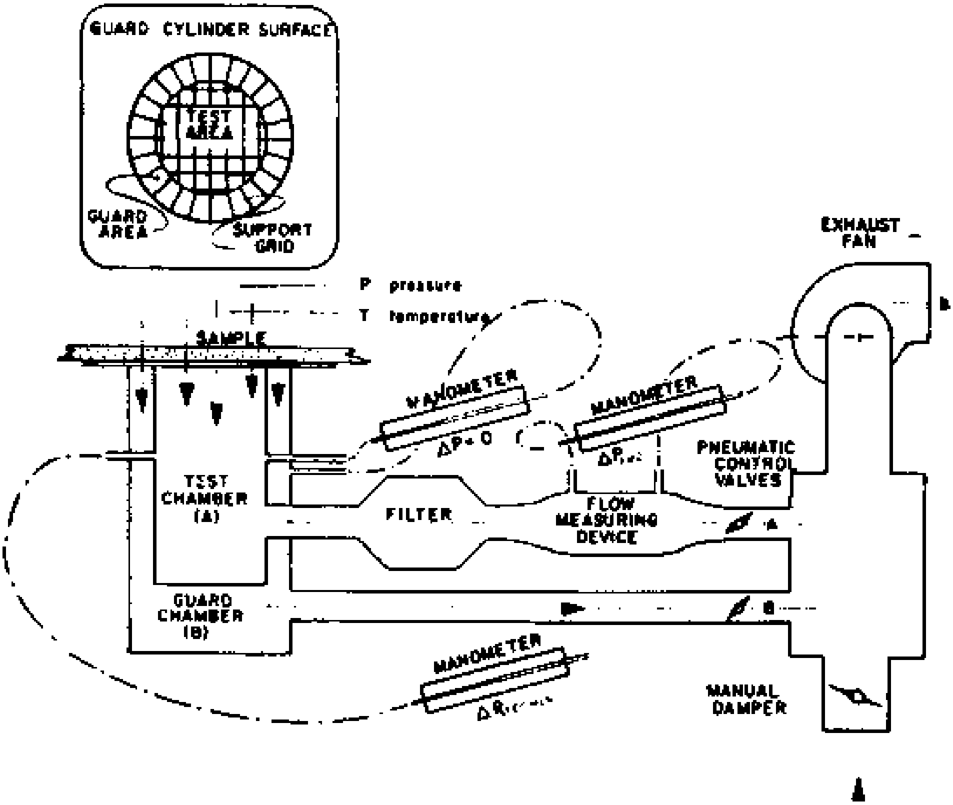
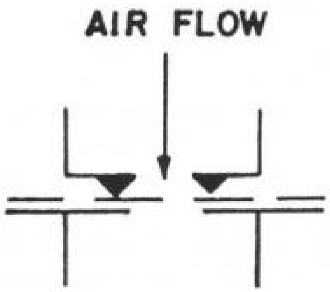


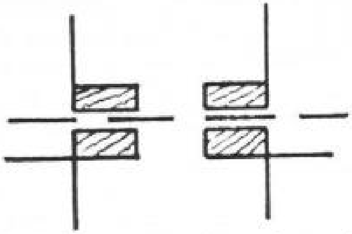
Figure 11.4. Schematic of the Frazier Differential Pressure Air Permeability Measuring Machine.

(0.001–0.025 bar). After a few seconds, the air permeability is digitally displayed in the pre-selected units of measurement, based on measurement of the airflow with a variable orifice.

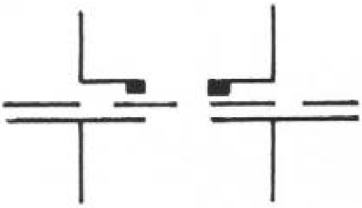
Permeability measurements can be made automatically by pore analysers such as the Coulter Porometer shown in Figure 11.14.



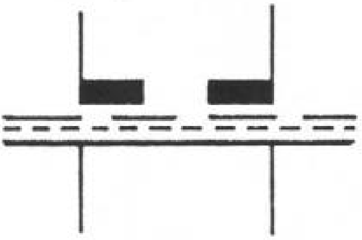
A1.1 Sharp Edge—Top Clamp



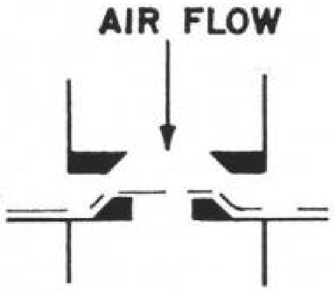
A1.2 Soft Gaskets—top and bottom clamp or chamber



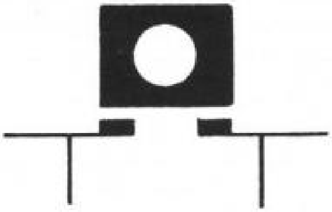
A1.3 Pneumatic actuated top clamp with low surface area sealing



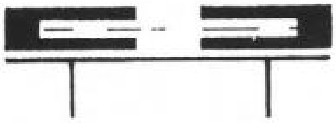
A1.4 Support grid of known air flow resistance and construction



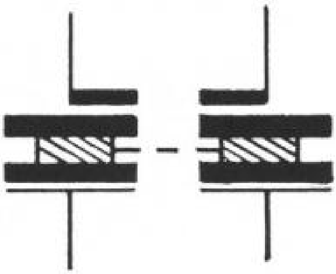
A1.5 Weight ring to produce known tension



A1.6 Thick Rigid Specimen—Impregnate with barrier-type material except for test area



A1.7 Special holder to fit exact thickness of specimen



A1.8 Special holder with crushable gasket to conform to specimen surface irregularities

Figure 11.5. Frazier's suggested clamping arrangements for various types of flat media.

11.2.2 Pore size

Figure 11.7 shows schematically[6] the various types of pore that may occur in a porous material; those that are relevant to filtration are identified as 'through pores'. The four most commonly used methods for measuring the pore size of porous materials are briefly summarized below; the first two are of particular relevance to filter media and are therefore discussed at greater length in this section.

Bubble point testing, also known as *liquid expulsion testing*, utilizes a controlled air pressure to empty through pores that had previously been filled with a wetting liquid. A simple relationship between the pressure, the properties of the liquid and the diameter of an ideal circular pore permits calculation of the equivalent pore diameter. This method is normally used for pores in the size range 0.05–50 μm, but is, of course, only a secondary test, since it does not actually measure a pore dimension.

Challenge tests determine the effective size of open pores by challenging them with suspensions of particles of known sizes. This method is typically used for pores in the size range 0.005–100 μm, and this is now a direct measure of through pore size.

Mercury porosimetry, known also as mercury intrusion, involves filling the pores with mercury under pressures up to 400 MPa. The volume of mercury forced in, which can be measured very accurately, is related to pore size and pressure by the same relationship used in the bubble point test. This method, which is the subject of BS 7591:Part 1:1992, is reported to be suitable for many materials with pores in the size range 0.003–400 μm, and especially in the range 0.1–100 μm.

Gas adsorption, as described in BS 7591:Part 2:1992, typically involves measuring the quantity of nitrogen adsorbed as its relative pressure is progressively increased at a constant cryogenic temperature. The minimum size of pore that can be studied is restricted by the 0.4 nm size of the nitrogen molecule;

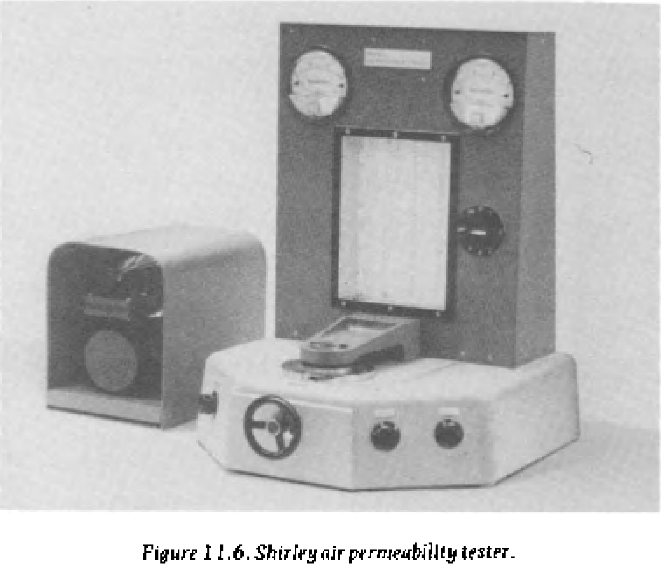


Figure 11.6. Shirley air permeability tester.

the maximum is limited to about 50 nm by the practical difficulty of measuring the amount of nitrogen adsorbed at high relative pressure. The method is therefore most appropriate for pores in the size range 0.0004–0.04 μm.

11.2.2.1 Equivalent pore size by a bubble point test

A very simple form of bubble point test apparatus is shown in Figure 11.8. This includes an enlargement of the holder in which a disc sample of the medium under test is inserted, so that it is submerged under a layer of liquid. Care must be taken to ensure that the sample is thoroughly wetted, with all of its pores filled with liquid; some test procedures require this to be done by vacuum impregnation, so as to eliminate any occluded pockets of air.

The test liquid needs to be chosen so that it will efficiently wet the material of the medium. Recommended liquids include white spirit for fabrics (BS 3321:1986), fully chlorinated hydrocarbon for paper, polymer membranes and cloth (BS 7591:Part 4:1993), and the liquids listed in Table 11.5 for metals.

In essence, the test procedure comprises increasing the air pressure slowly whilst observing the surface of the liquid in the reservoir. Typically, two different pressure values are noted, the first corresponding to the largest pore, which is detected by the appearance of the first stream of bubbles; as the pressure is increased, general bubbling develops, providing an indication of the average pore size.

Table 11.4 International test standards for air permeability

Test standard	Country	Test area (cm^2)	Test pressure (Pa)	Unit of measure
DIN 53.887	Germany	20	200	$l/m^2/s$ or $l/dm^2/min$
AFNOR G 07-11	France	20 or 50	196	$l/m^2/s$
BS 5.636	England	5	98	$cm^3/cm^2/s$
ASTM D 737	U.S.A.	38	125	cfm
JIS L 1096-A	Japan	38	125	$cm^3/cm^2/s$
EDANA 140.1	Nonwovens	20 or 50	196	$l/m^2/s$
TAPPI T 251	Paper	20 or 38	125	cfm or $cm^3/cm^2/s$

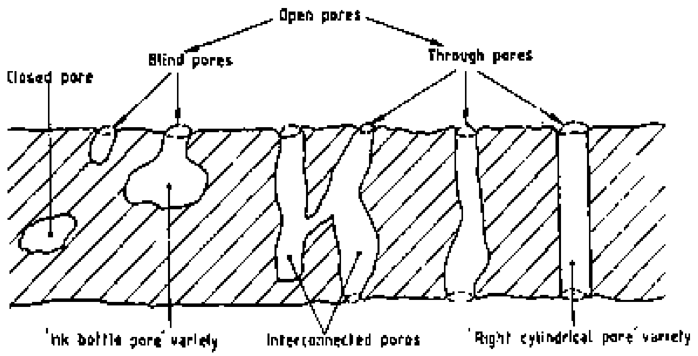


Figure 11.7. Schematic representation of types of pores.

The equivalent pore size corresponding to each pressure reading can be calculated using the following equation:

$$d = [4\sigma(\cos\theta)/P] \times 10^6 \qquad (11.5)$$

where d = the equivalent pore diameter (mm), σ = the surface tension of the liquid (N/m), θ = the contact angle between the liquid and the pore wall (degrees), P = the pressure (Pa). For the preferred test liquids, which are fully wetting, the contact angle is zero, so that the above equation simplifies to:

$$d = (4\sigma/P) \times 10^6 \qquad (11.6)$$

A more elaborate, manually operated apparatus is shown schematically in Figure 11.9. This, together with several extracts, are reproduced with permission from British Standard 7591[6], to provide a summary of a systematic procedure for determining the following parameters:

- the maximum pore diameter;
- the minimum pore diameter;
- the mean flow pore diameter; and
- the pore size distribution.

The procedure involves conducting two test runs on a sample during each of which flow rate versus pressure readings are logged at frequent intervals. First is a wet run on the wetted sample, with a continuing increase of pressure until all the pores are empty of liquid, as shown when the flow rate/pressure plot becomes

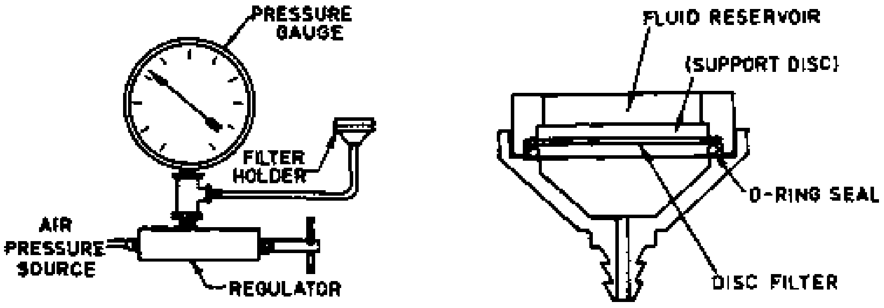


Figure 11.8. A simple bubble point test apparatus.

Table 11.5 Liquids for bubble point testing of porous metals

Test liquid	Density (g/cm³)	Surface tension @ 20°C (N/m)
Methanol	0.79	0.0225
Ethanol (95%)	0.805	0.023
Isopropanol	0.79	0.0215
Carbon tetrachloride	1.59	0.027

linear, as shown in Figure 11.10. The air pressure is then reduced to zero and the dry run commenced immediately through the now dried sample still in the holder; readings are recorded until the dry run plot overlays the wet run plot, and are then continued until the maximum permissible pressure is reached.

The point at which the wet run curve leaves the baseline approximates to the bubble point pressure, from which the maximum pore diameter may be calculated. Similarly, the point where the wet run and dry run points converge corresponds to the minimum pore diameter. Superimposing an extra 'half of dry run' plot on the data plot of Figure 11.10, by simply halving each dry flow value, identifies the mean flow pore diameter at the intersection of this extra plot and the wet run curve.

The pore size distribution is calculated from the wet and dry run plots in Figure 11.10, but for clarity the relevant part is shown separately in Figure 11.11. Repetitive calculations are made for a sequence of small pressure intervals, as indicated by the example in Figure 11.11, between a low pressure, *l*, and a higher pressure, *h*.

Assuming that in this example $l = 0.06$ MPa and $h = 0.065$ MPa, and that the surface tension of the test liquid = 0.016 N/m, then the corresponding pore sizes are 1.07 and 0.98 mm. Hence, the percentage, *B*, of pores between these diameters is given by:

$$B = [(\text{wet flow } h/\text{dry flow } h) - (\text{wet flow } l/\text{dry flow } l)] \times 100 \quad (11.7)$$
$$= (0.4/9 - 0.2/8) \times 100 = 2\%$$

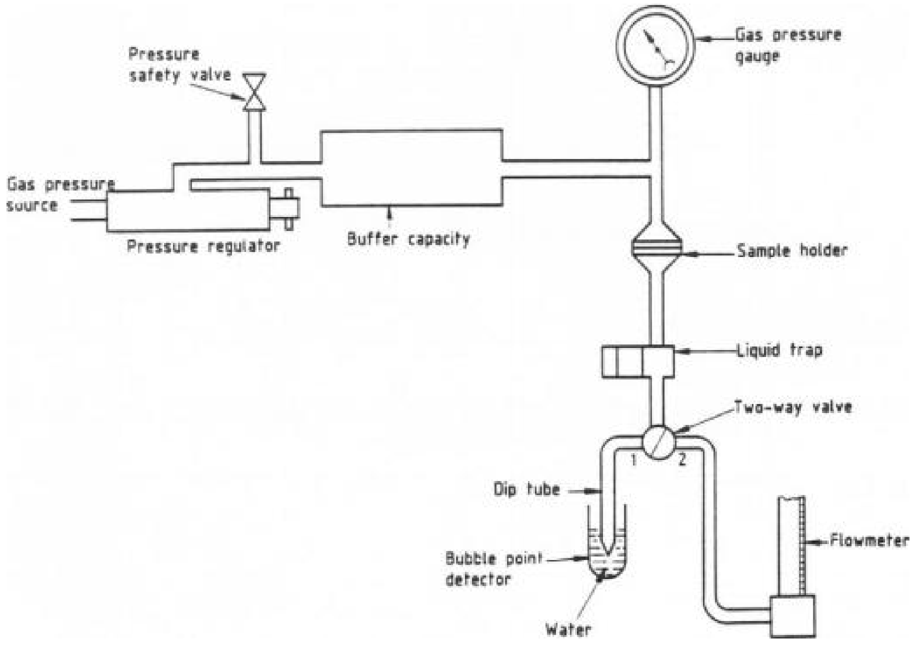


Figure 11.9. The basic form of a typical manually controlled bubble point apparatus.

The pore size distribution by flow is computed by accumulating values of B from the maximum to the minimum pore size. The resultant data may be presented in the form of either Figure 11.12 or Figure 11.13.

The test procedures outlined above, and the computational analysis of the measured data, can be conducted automatically by equipment such as the Coulter Porometer illustrated in Figure 11.14(a) and (b). This is a microprocessor-controlled, menu-driven instrument operating at pressures up to 13 bar, suited to pores from macro-size down to 0.05 mm; the analysis time is typically under 10 min. The medium under test is in the form of a disc that is

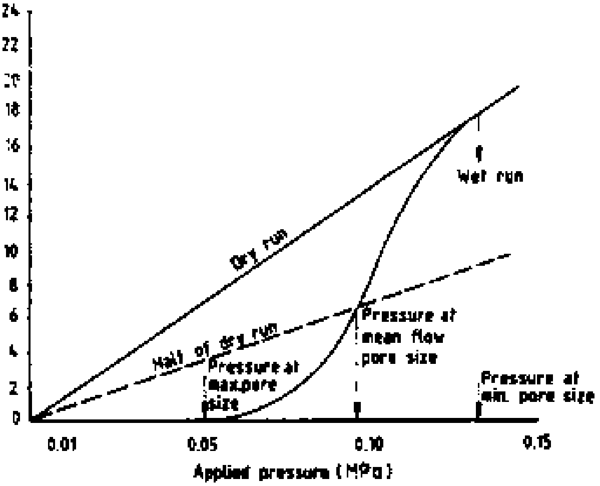


Figure 11.10. Typical plot of flow rate versus applied pressure for wet and dry runs, performed on a single test sample.

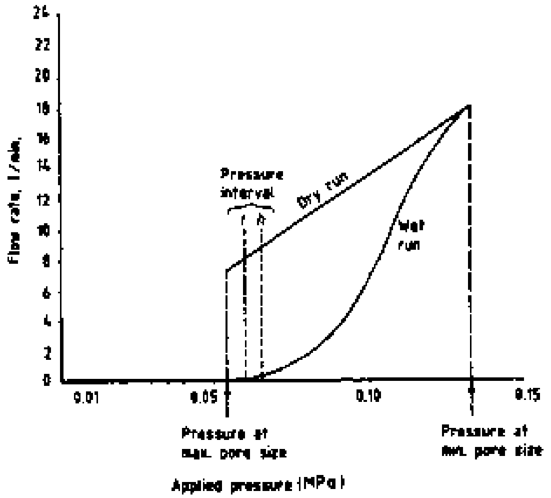


Figure 11.11. Adapting Figure 11.10 for repetitive calculations of small pressure intervals.

mounted in a suitable sample holder after being thoroughly wetted. The resultant data may either be displayed or printed out.

The instrument can also be used to measure permeability of a sample of filter medium. A further use is to determine the integrity of a filter cartridge (i.e. the absence of any significant leaks in it), by the Pressure Hold analysis option. This involves isolating a pressurized filter and monitoring the pressure over a timed period.

11.2.2.2 Effective pore size by challenge tests

The process of a challenge test involves presenting a filter with a fluid containing a known concentration of a defined particulate, and then analysing the filtrate downstream of the filter to determine how much of the particulate material has passed through, and of what sizes. The particulate in the presented fluid may be monosized, or it may comprise either particle sizes over a specified range, or a distribution of sizes over given limits of size.

With test materials of mixed particle size, the largest particle passing is an indication of the size of the largest pore in the filter medium. The medium may be described as 'absolute' to all particles greater than some slightly larger size: with monosized particles, the percentage of particles passing characterizes the filtration efficiency of the medium.

It is clear from this brief introduction that challenge tests rely heavily upon the ability of the tester to measure the particles, for both number (or quantity) and

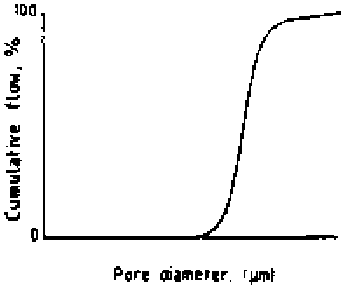


Figure 11.12. Cumulative flow pore size distribution.

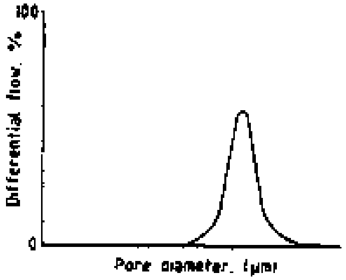


Figure 11.13. Differential flow pore size distribution.

size (or size distribution) both ahead and after the medium being tested. This size and quantity determination accounts for most of the variation among the techniques employing this method.

A well-known example of the challenge process is the glass bead test. In this, a sheet or disc of filter medium is fitted within a filter holder and a suspension of glass beads is sucked through the filter. The suspension comprises beads of specific diameters over a range covering the expected pore size of the filter. Beads that have passed through the filter are trapped on an analysis membrane and examined by a microscope to determined the largest size: in doing this, great care must be taken to ensure that no stray beads inadvertently appear on the membrane, because even just one large bead can totally alter the assessment of

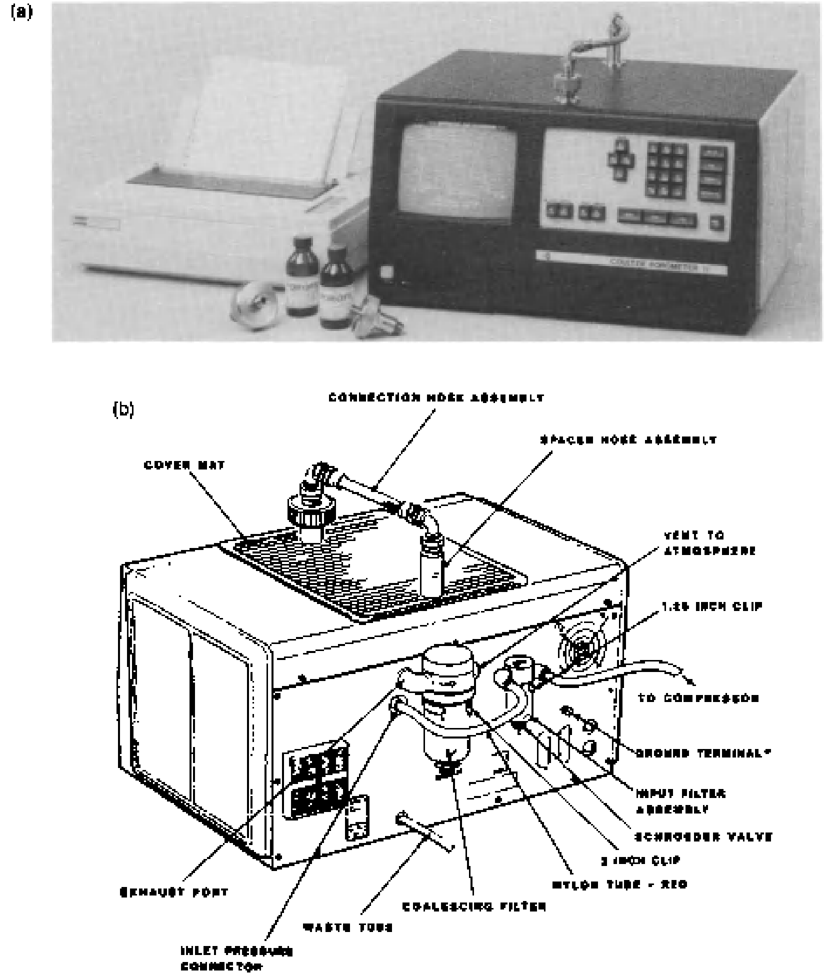


Figure 11.14. *(a) A* Porometer II *automated pore analyzer – front view with sample holder on top; (b) a* Porometer II *automated pore analyzer – schematic of rear view.*

the filter pore size. A glass bead test is included in the US standard for testing filters for hydraulic power systems in military vehicles: examples of the grades of glass beads and other special spherical particles available commercially are given in Table 11.6.

One of the problems with the glass bead test, or with any synthetic dust-like material, is the creation of a size distribution to satisfy the needs of the test. A range of glass microspheres is now available(7), with a narrow size distribution. The various size fractions are produced by means of sonic energy sieving, which enables the solid to be processed down to 15 μm in the dry state (below 15 μm such separations have to be done in liquid suspension, to overcome the electrostatic properties of the particles). One of the particular applications of these closely sized microspheres is in the sizing of screens for use in keeping sand out of undersea oil (which otherwise would cause costly abrasion).

The pharmaceutical industry utilizes a critically important (as regards health) challenge test based on a suspension of the bacterium *Pseudomonas diminuta* ATCC 19146, in which each square centimetre of filter medium surface is challenged with as many as 10 million bacteria. Provided no bacterium passes through, the medium is classed as 0.2 μm absolute rating, despite the fact that these bacteria are slightly larger than 0.2 μm. The detailed sterilization testing procedure, using the system shown schematically in Figure 11.15 is described by Howard and Nicholaus(8).

In reality, numerous factors combine to make questionable the principle of characterizing media by this form of challenge test, which is strictly only suitable where the pores are clearly formed, as in meshes and screens, where the challenge particles are spherical and where the filtration mechanism is simple straining. Under these circumstances it can be very accurate. It is more meaningful generally to express the performance of a medium in terms of its efficiencies against particles of a range of sizes.

A particularly severe challenge test is reported by Endo *et al.*(9) in the testing of a sintered ceramic filter medium made from spherical particles of alumina.

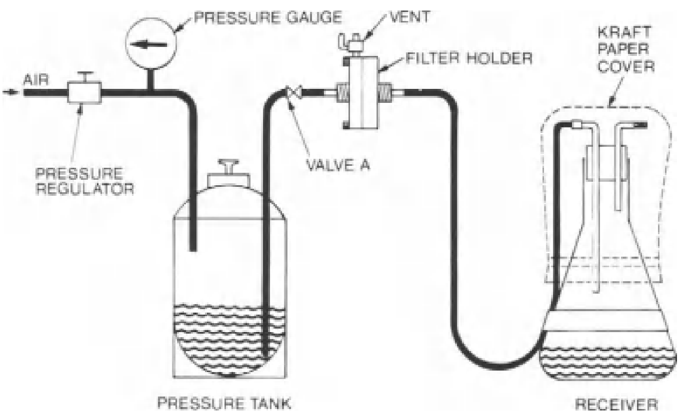


Figure 11.15. System for sterile filtration test.

Table 11.6 Examples of highly graded spherical particles[a]

Description	Size range	Grades	State	Examples			
				Nominal size (µm)	Certified mean diameter (µm)	Size uniformity	
						SD[b]	CV[c]
Certified standards							
Polystyrene nanospheres	20–900 nm	26	1% in water	20	19±1.5	–	–
				100	102±3	5.3	7.5%
Polymer microspheres	1.0–160 µm	26	0.2–5% in water	1.0	0.99±0.02	0.010	1.0%
	200–1000 µm	10	Dry spheres	200	202±4.0	7.5	3.7
Silica microspheres	0.5–1.6 µm	4	2.0% in water	0.5	0.46±0.03	0.02 µm	4.3%
				1.6	1.57±0.06	0.04 µm	2.5%
Borosilicate glass microspheres	2–20 µm	6	Dry spheres	2	2.5±0.5	1.0 µm	40%
				20	20.2±1.4	1.7 µm	8.4%
Soda-lime glass microspheres	1.5–2000 µm	30	Dry spheres	1.5	2.1±0.5	0.9 µm	43%
				750	756±23	22.7 µm	3.0
Research microspheres				*Mean diameter (µm)*			
Polystyrene latex	0.028–3.7 µm	42	Dry spheres	0.028	–	0.0031	11%
				0.652	–	0.0048 µm	0.7%
Polystyrene DVB[d]	3.2–220 µm	15	Dry spheres	3.2	–	1.4 µm	43%
				220	–	16.5 µm	7.5%

[a] Duke Scientific Corporation.

[b] SD=standard deviation.

[c] CV=coefficient of variance.

[d] DVB=cross-linked with 4–8% of divinylbenzene.

The membrane was formed of a 20 μm layer of 0.6 or 0.84 μm spheres supported on a 2 mm layer of 15 μm spheres, and has a high collection efficiency, but with a high differential pressure. The challenge was a polydisperse sodium chloride aerosol, with penetrations as low as 10^{-9} in the size range 0.02–0.14 μm. The particle concentration was determined with a condensation nucleus counter.

11.2.3 Filtration efficiency

The basic principles of challenge testing, utilizing either mixed size or monosized particles, are adapted according to the nature of the fluid (liquid or gas), and the relevant filtration mechanisms (surface straining or depth), associated with the structure of the medium. An overview of the relationship between these variables, the main categories of practical application and the several forms for expressing filtration efficiency, is provided by Table 11.7.

11.2.3.1 Test dusts, aerosols and filtration efficiency

Filtration efficiency is usually stated in terms of the percentage of particles of a certain size that would be stopped and retained by a filter medium. This raises two quite difficult problems:

- where a test dust comprises particles of a range of sizes, what is the actual size to which the percentage efficiency relates?
- the numerical differences in percentage efficiency of a wide variety of media are often relatively small, many media being over 95% efficient – therefore, is percentage efficiency a meaningful basis for comparison of different media?

These two dilemmas are resolved by the use of test particulates of known distribution and by a more sensitive expression for filtration efficiency. As Table 11.8 indicates, a considerable variety of standard test dusts has evolved, many tailored to specific areas of application: one dust widely used for both liquid and gas phase applications is AC Fine Test Dust (equivalent to SAE J 726 Fine), which is described in more detail in Table 5.3 of Chapter 5.

There are two alternative expressions for percentage efficiency: one is percentage penetration, the other is the Beta ratio (β ratio). Very high efficiency air filters, for which efficiencies range upwards from 99.99%, are sometimes characterized in terms of percentage penetration, and are in fact classified as ULPA (Ultra Low Penetration Air) filters: thus, Eurovent class EU 15 can be described as having an efficiency of 99.9995% or a penetration of 0.0005%.

The β ratio is based on counts of particles of specific sizes and is defined as:

$$\beta_n = N_u/N_d$$

where N_u = number of particles $>n$ μm per unit volume of liquid upstream; N_d = number of particles $<n$ μm per unit volume of liquid downstream. The

Table 11.7 Summary of challenge test and filtration efficiency categories

Fluid	Particle size	Comments	Test variables	Efficiency expression	Application examples
Liquid	1. Mixed	Most common	Single pass or multi-pass	1. Grade efficiency curves	General use
				2. Particle size for 98% efficiency	General use
				3. β factor	Hydraulic power systems: critical pharmaceuticals
	2. Monosized	Special cases	Single pass	% efficiency for one size only	Microorganism removal
Gas/air	1. Mixed	Air filter standard	Single pass	% weight retention	Air filter for coarse and fine dusts
	2. Monosized	Air filter standard	Single pass	% efficiency or % penetration for one size only	HEPA and ULPA air filters

percentage filtration efficiency, E, is related to β by the expression $E = 1 - 1/\beta$. Corresponding values for E and β are given in Table 11.9, together with examples of particle number counts. Figure 11.16 shows a typical plot of the β ratios versus particle size for a filter medium challenge test, and demonstrates the usage of this mode for characterizing a medium; thus $\beta_{17} = 200$ indicates an upstream/downstream ratio of 200 for 17 μm particles.

11.2.3.2 Filtration of liquids

Two different techniques are used for determining the efficiency when filtering liquids, respectively identified as the single-pass test and the multipass test. Although these tests have much in common, there is a significant difference in

Table 11.8 Examples of test dusts[a]

Designation	Material		Size range (μ)
BS 1701 Coarse	Quartz		0–150
BS 1701 Fine	Quartz		0–75
BS 2831 No. 2	Fused alumina		0–10
BS 2831 No. 3	Fused alumina		8–32
DEFSTAN[b] 0755	Quartz sand		100–1000
SAE[c] J 726 Fine/AC Fine	Mineral sand		0–125
SAE[c] J 726 Coarse/AC Coarse	Mineral sand		0–200
MIRA[d] Grade 1/BS4552	Fused alumina		2.5–9
MIRA[d] Grade 2/BS4552	Fused alumina		3–11
MIRA[d] Grade 3/BS4552	Fused alumina		6.0–21
MIRA[d] Grade 4/BS4552	Fused alumina		15.0–53
MIRA[d] Grade 5/BS4552	Fused alumina		27.0–90
ASHRAE[e] 52/76	Molacco black	23% (wt.)	0–80
	SAE J 726 fine	72%	
	Cotton linters	5%	
BG[f] Test dust	Black iron oxide	79%	0–400
	Red iron oxide	12%	
	Silica flour	8%	
	Paint residue	1%	
	Cotton linters	0.05%	
RR[g] lubricant contaminant	Lamp black	60%	0–420
	Bearing steel	10%	
	Red iron oxide	5%	
	AC Fine	15%	
	Metco 31 seal material	10%	

[a] Dusts to these and other specifications are manufactured by Particle Technology Ltd.

[b] DEFSTAN, Defence Standard (Ministry of Defence, UK).

[c] SAE, Society of Automotive Engineers. Grades equivalent to Arizona Road Dust.

[d] MIRA, Motor Industry Research Association.

[e] ASHRAE, American Society of Heating, Refrigerating and Airconditioning Engineers.

[f] BB, British Gas.

[g] RR, Rolls Royce.

the particle size distribution presented to the filter, which may significantly affect the stated efficiency of the medium.

The single-pass test, as its name implies, passes a consistent, unchanging distribution of particles through the test circuit just once. A typical circuit for a single-pass test rig for pressure filtration is shown schematically in Figure 11.17. The filter medium, ranging from say a 47 mm diameter disc to a 300 × 300 mm sheet, is held in a leak-free support, with sampling points sited as close to the filter as possible. Bottle samples of fluid are sometimes taken for later examination and analysis; however, this has the disadvantages of risking contamination and of the two samples not being precisely in step, both of which can be avoided by appropriate on-line analysis.

A different version of a single-pass test rig is illustrated in Figure 11.18. This shows the standard assembly used to conduct laboratory bench tests on slurries for making preliminary assessments of the suitability of process filters such as rotary drum, disc and belt filters. The circular cloth-covered filter disc, connected

Table 11.9 Comparison of β-ratios and % efficiencies

Examples of numbers of particles		% efficiency	β ratio
Upstream	Downstream		
10 000	5000	50	2
10 000	1000	90	10
10 000	500	95	20
10 000	100	99	100
10 000	10	99.9	1000
10 000	1	99.99	10 000

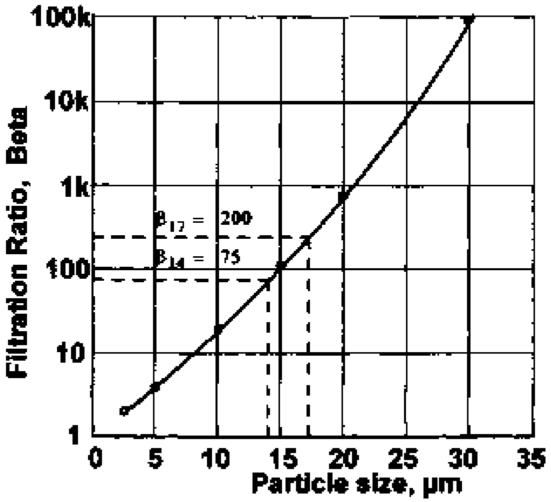


Figure 11.16. Plot of β ratio versus particle size.

to a flexible rubber hose, can be inverted into a container of slurry for a timed period, such as 1 minute, so as to mimic the stage-wise cycle of these continuous filters. Preliminary tests can be conducted with various types and grades of filter cloth to permit initial selection in terms of criteria such as clarity of filtrate, rate of filtration, and ease and completeness of discharge of the filter cake. Full details of the experimental procedures are provided by Dahlstrom and Silverblatt(10).

By contrast, the objective of the multipass test with the pressure filtration circuit shown in Figures 11.19 and 11.20 is to challenge the filter with a gradually increasing percentage of smaller particles; this is felt to be more representative of real systems in which a fluid is recirculated repeatedly and where larger particles are not only removed by filtration but are also being ground down to smaller dimensions. This test was originally developed for hydraulic oils but has become the basis of standards relating to other fluids such as lubricating fluids and water: for example, the internal combustion engine lube oil filter standard is ISO 4585. Therefore the multipass test, as defined by ISO

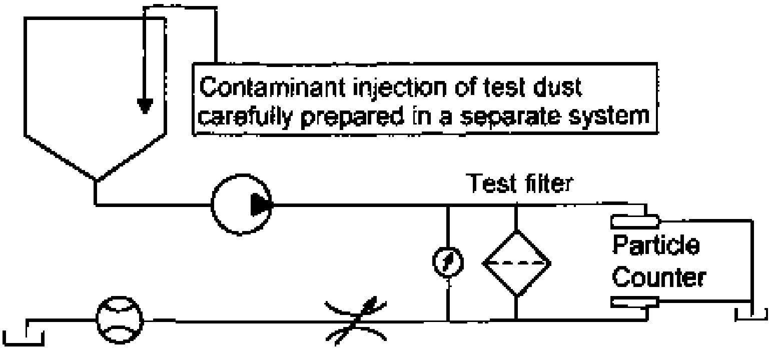


Figure 11.17. A typical single-pass test circuit for pressure filtration.

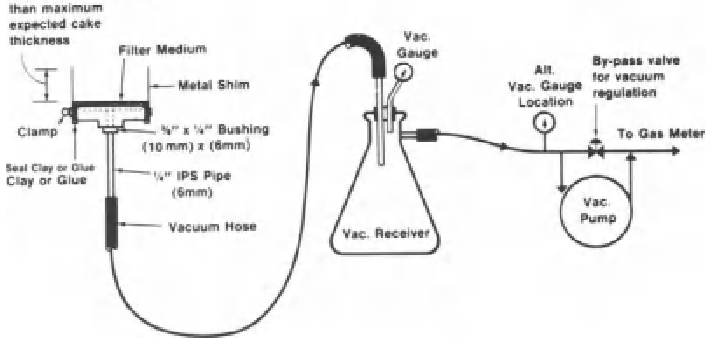


Figure 11.18. A basic set up for conducting leaf tests on slurries in relation to continuous vacuum filters.

4572, now specifies on-line sampling and analysis as mandatory, recognizing that efficiency will tend to change as the filter progressively blocks; continuous monitoring with an analyser such as that illustrated in Figure 11.21 can provide a direct read-out of β ratio.

11.2.3.3 Filtration of gas/air

All gas-phase filtration tests are of single-pass format, but there is considerable variety both in the nature of the suspension of particles used to challenge a filter

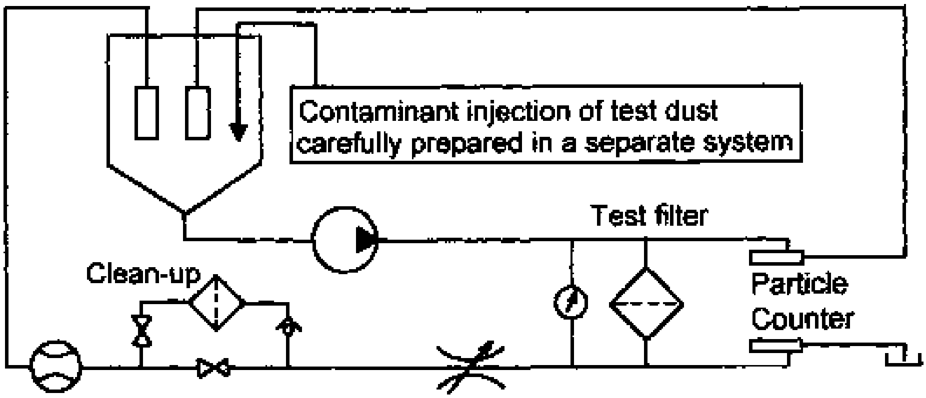


Figure 11.19. A typical multi-pass test circuit for pressure filtration.

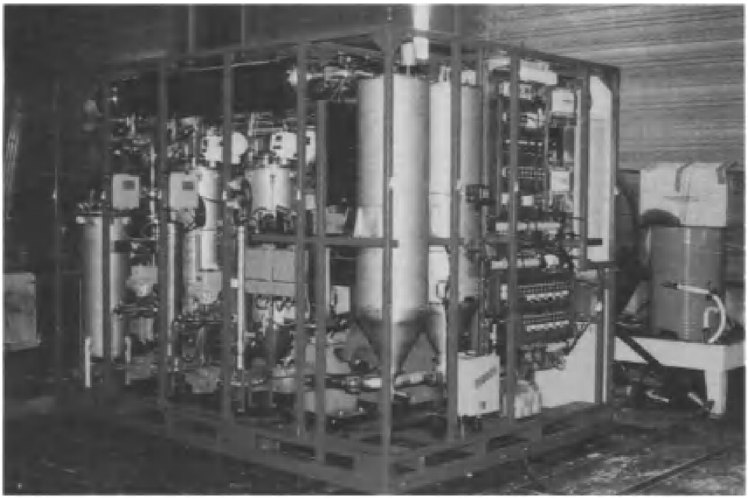


Figure 11.20. A skid-mounted multi-pass test rig handling flows up to 400 l/min at pressure differentials up to 40 bar.

and in the analytical methods whereby performance is assessed. Three types of test can be distinguished, respectively identified as:

- staining tests;
- weight arrestance; and
- particle concentration efficiency.

Atmospheric dust spot efficiency is the first of the *staining tests*. This test is a standard procedure for air filters used in air conditioning and general ventilation. It is described in detail in Part 1 of BS 6540(11), which is based on a EUROVENT standard(12); this in turn is based on an ASHRAE standard(13) that originated in 1968.

The test is based on the intensity of staining of a 'target' filter paper caused by the flow through it of a quantity of atmospheric air. The staining arises from the natural contaminants in the local atmosphere. The intensity of the staining is monitored by an opacity metre and provides an empirical measurement of the concentration of the contaminants in the air drawn through the target.

Over a timed period, this technique is applied simultaneously to two parallel samples drawn at equal mass flow rates from the upstream and downstream sides of a filter under test; the downstream sampling, i.e. the filtrate, is continuous but the upstream sampling is intermittent and controlled by a percentage timer. Suitable adjustments of the timer results in the intensities of the stains on the upstream and downstream targets being approximately equal (i.e. they differ by no more than 20% of the higher value).

Expressed as a percentage, the atmospheric dust spot efficiency can then be calculated from the following relationship:

$$E = 100 \times (1 - Q_1 O_2 / Q_2 O_1)$$

where E = the atmospheric dust spot efficiency, %; Q_1 = the total volume of air drawn through the upstream target; Q_2 = the total volume of air drawn through the downstream target; O_1 = the opacity of the dust spot on the upstream target =

Figure 11.21. A Hyac-Royco BetaRatioMeter. *(Photograph: Pacific Scientific Ltd)*

$(T_{u1} - T_{u2})/T_{u1}$ (T_{u1} = the initial upstream light transmission, %; T_{u2} = the final upstream light transmission, %); O_2 = the opacity of the dust spot on the downstream target = $(T_{d1} - T_{d2})/T_{d1}$ (T_{d1} = the initial downstream light transmission, %; T_{d2} = the final downstream light transmission, %).

The *methylene blue staining test* was formerly used to characterize high-efficiency air filters in terms of the percentage penetration by submicrometre particles. With the methylene blue aerosol identified as 'Test Dust No. 1' (Nos 2 and 3 being fused alumina), it was included in both the 1957 and 1971 versions of the now obsolete BS 2831, which has been superseded by BS 6540. A short summary is provided by Dorman and Ward(14).

The aerosol is generated by atomizing a 1% aqueous solution into a constant stream of clean, dry air, which is then passed through the filter under test, the whole of the effluent being sampled by filtering again through an esparto paper for a known time. After intensification of the blue stain on the sampling esparto paper, estimation of penetration is based on comparison of this stain with a series of standard stains, either by eye or by a photoelectric densitometer.

The standard stains are previously prepared by drawing volumes of 12, 24, 36, etc., cm^3 of aerosol cloud through 125 mm^2 areas of esparto paper and intensifying the blue in steam. Identifying the nearest matching standard stain, or, if necessary, interpolating between two standard stains, defines the amount of blue dye collected on the sampling paper; for example, if the 24 cm^3 standard stain is the nearest match, then the amount of dye on the sampling paper corresponds to 24 cm^3 of unfiltered aerosol cloud. Hence, the percentage penetration is given by $100 \times 24/Q$, where Q is the total air volume filtered during the test.

Disadvantages reported for this test procedure are its increasing inaccuracy for penetrations below 0.01%, a simultaneous increase in the time required, and the need to utilize a high velocity (500 cm/s) for the esparto paper to achieve an adequate filtration efficiency.

The *synthetic dust weight arrestance* test is a standard procedure for air filters used in air conditioning and general ventilation. It is described in detail in Part 1 of BS 6540.

The essence of the procedure is to challenge a filter with a dispersion of test dust, the filtrate passing on through a second or final filter, which collects that part of the dust that penetrates through the filter under test. The dust dispersion is created continuously by a suitable combination of a dust feeder and a compressed air venturi ejector. The weight of dust passing through the filter under test is determined by re-weighing the final filter.

The full procedure, which is designed for testing complete air filters or filter panels (rather than simply a sample of filter medium), includes feeding a weighed quantity of dust in a series of equal increments, the first increment being restricted to 30 g, to permit determination of the initial synthetic dust weight arrestance. Between consecutive increments, measurement is made of the weight of dust passing the filter under test, the corresponding pressure loss across the test filter, and its atmospheric dust spot efficiency (as in the first of the staining tests described above).

The synthetic dust weight arrestance, A (%), for any particular period is given by:

$$A = 100 \times (1 - W_2/W_1)$$

where W_1 = the weight of synthetic dust fed, and W_2 = the weight of synthetic dust passing the filter under test. A typical plot of the resultant test data from this procedure is shown in Figure 11.22, reproduced from BS 6540:Part 1:1985. The data also allow calculation of the dust-holding capacity up to the maximum permissible pressure loss.

Particle concentration efficiency. For the various grades of high-efficiency air filters (HEPA, ULPA, etc.), particle concentration efficiencies are measured and expressed in terms of differences between upstream and downstream concentrations of submicrometer particles determined by continuous on-line monitoring.

Whilst the concept is simple, the practical reality tends to be complex because of the sophisticated technique and equipment required both to generate consistently suitable aerosols and to determine the size, size distribution and concentration of the particles.

Descriptions of the main techniques for the formation of aerosols are provided by Dorman and Ward[14]; they include use of pressure atomization of liquids,

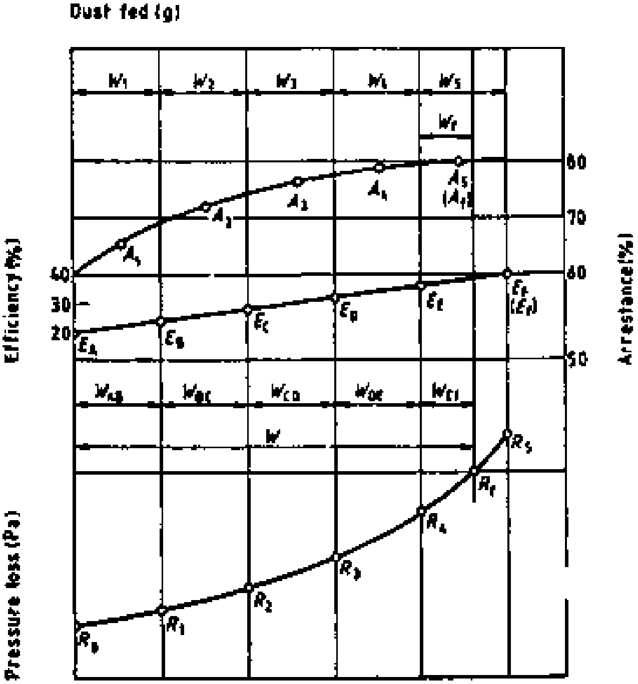


Figure 11.22. Example of plot combining data from test of atmosphere dust spot efficiency, E, *and synthetic dust weight arrestance,* A, *based on BS 6540:Part 1:1985.*

evaporation, condensation and classification. Aerosol particles are variously solid or liquid, and range from almost monosized to heterogeneous mixtures. For example, an aerosol of sodium chloride crystals can be generated by atomizing a 1% solution to produce fine droplets, from which the water is removed by evaporation; the particle size is determined by the atomization step. Alternatively, an aerosol of dioctylphthalate (DOP) droplets is formed by the condensation that occurs when warm air containing DOP vapour is quenched by dilution with cold air; the particle size is controlled by the temperature difference between the two air streams.

Successful monitoring of the concentrations of aerosol upstream and downstream of a filter requires careful integration of two separate operations. The first is the taking of representative samples, which must be done isokinetically with appropriate equipment and techniques; moreover, if the analytical device requires only a very small flow compared with that through the filter under test, then the sample must be withdrawn following a zone of thorough mixing.

The second operation is analysing the sample, the technique and parameter measured being dependent on the nature of the aerosol; with sodium chloride, the total mass concentration of all the particles is measured using flame photometry, with a photometer such as that illustrated in Figure 11.23. Liquid aerosols such as DOP are analyzed by light scattering particle counters (e.g. that in Figure 11.21), the reported sizes being related to the projected areas of the particles.

Definition of an appropriate reference particle size is complicated not just by the above parameters, but also by other factors that affect the filtration mechanism. Thus Figure 11.24 (from Wepfer(15)), which shows penetration

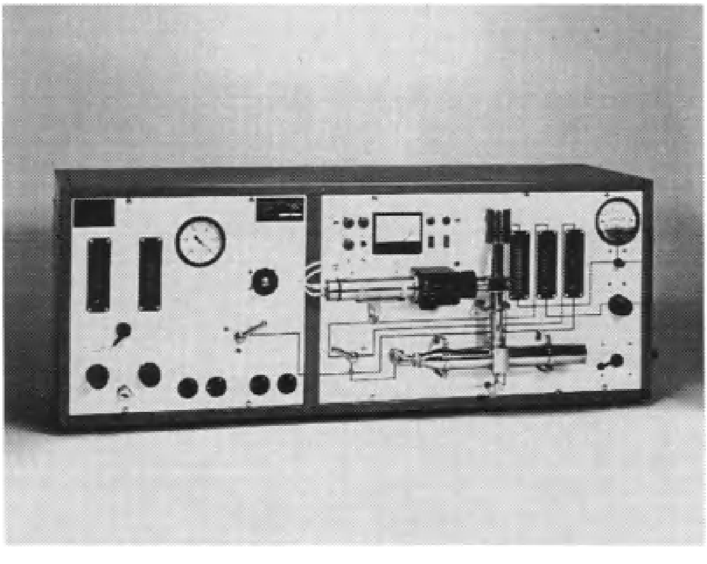


Figure 11.23. A bench rig sodium flame test meter. (Photograph: Moores Wallisdown Ltd)

maximizing in the particle size range 0.1–0.25 μm, illustrates that performance may depend on the air velocity through the medium as well as the nature of the medium; another significant variable is the nature of the aerosol. As indicated in Table 11.10, existing standards relate efficiency or penetration with their nominated aerosols to specific particles sizes (mostly 0.3 or 0.6 μm). By contrast, the new European standard(16) identifies the most penetrating particle size (MPPS) for a specific situation (especially for the most rigorous duties) and determines the penetration or efficiency for particles of this size.

Pierce (in a very good review of the history of HEPA filter testing(17)) notes that a value for MPPS of 0.3 μm has held since Langmuir first developed his theory of capture of small particles by fine fibres, even though it has long been recognized that the actual value was less than 0.3 μm. The paper presents strong support for the MPPS methods, expected to be about 0.13 or 0.15 μm for a HEPA filter.

11.2.4 Dirt-holding capacity

The dirt-holding capacity of a medium can conveniently be assessed as part of either the multipass liquid filtration test or the synthetic dust weight arrestance test for air filters, both described in the previous section.

11.2.5 Tendency to blind

Excepting under extremely unfavourable circumstances (i.e. where failure occurs very rapidly), little investigation of the tendency of a filter medium to blind is possible with small-scale, short-term tests.

11.3 Testing Mechanical Properties

Most filter media manufacturers have their own very specific mechanical property demonstrations. However, there are some generally accepted methods, which are reviewed here.

11.3.1 Strength

The strength of a material is typically characterized by generating stress/strain data using an extensometer such as the simple version shown in Figure 11.25, in which a strip of textile is stretched by a suspended weight. A linear relationship (Hooke's law) exists between applied stress and the amount of extension per unit length up to the elastic limit, beyond which stretching accelerates and then rupture occurs. This pattern provides a variety of parameters and definitions by which the material may be characterized, the most widely used being tensile strength; others are breaking, rupture or yield strength, yield point, elastic limit and ultimate elongation.

The extensometer in Figure 11.25 is not designed to test fabric as far as rupture, but only within the range of stress where both stretching and recovery can occur, i.e. over the linear limits of Hooke's law. To be strictly correct, corresponding tensile strength figures should be expressed (e.g. as kg/cm^2), relating the applied force (e.g. the mass of the suspended weight) to the cross-sectional area of the strip. In practice, with sheet materials such as textiles and paper, it is customary to treat the sheet thickness as a constant and to relate the stress only to the width of the strip, i.e. as kg/cm.

The bursting strength is an empirical value that depends on the diameter of the disc tested in accordance with appropriate standards, such as BS 3137:1995 for paper and BS 4768:1991 for textiles. It is readily determined using apparatus such as the tester illustrated in Figure 11.26, which applies a hydraulic load (up to 70 bar) by the hand wheel, to a sample clamped over the base plate. A renewable rubber diaphragm beneath the base plate protects the sample from direct contact with the hydraulic fluid.

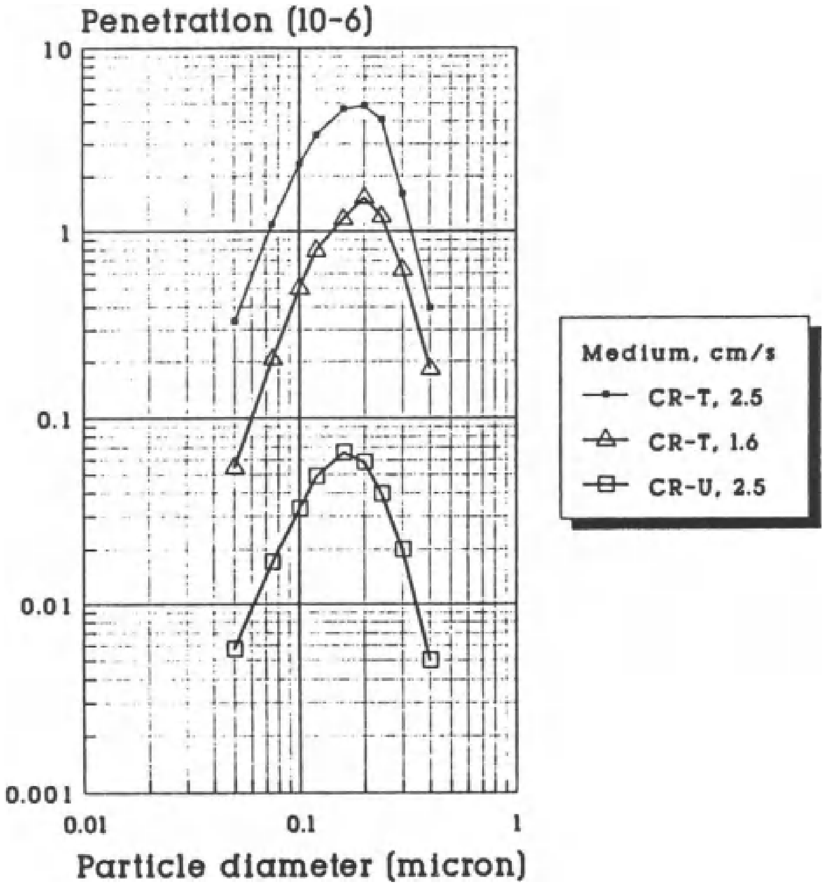


Figure 11.24. Plot of penetration versus particle size for two different media and velocities, showing Most Penetrating Particle Size (MPPS)(15).

Table 11.10 Aerosols and international standards relating to HEPA and ULPA filters

Standard or guideline	Country	Aerosol material	Average size of aerosol (μm)	Parameter measured
BS 3928	U.K.	NaCl salt	0.60	Mass related
Eurovent 4/4	Europe	NaCl salt	0.60	Mass related
AFNOR X44013	France	NaCl salt	0.60	Mass related
AFNOR X44011 uranine	France	Uranine salt	0.15	Mass related
DIN 24.184	Germany	Paraffin oil	~0.45	Area related
M 7605	Austria	NaCl salt	0.60	Mass related
SWKI 84-2	Switzerland	NaCl salt	0.60	Mass related
Mil Std 2282 (DOP)	U.S.A.	DOP oil	0.30	Area/quantity related
Mil Spec F-51068F	U.S.A.	DOP oil	0.30	Area/quantity related
IES-RP-CC001.3-93	U.S.A.	DOP oil	0.30	Area/quantity related
IES-RP-CC007.1-92	U.S.A.	DOS oil+	~0.18	Area/quantity related
prEN 1822 (Jan. 1995)	Europe	DEHS oil	MPPS	Area/quantity related

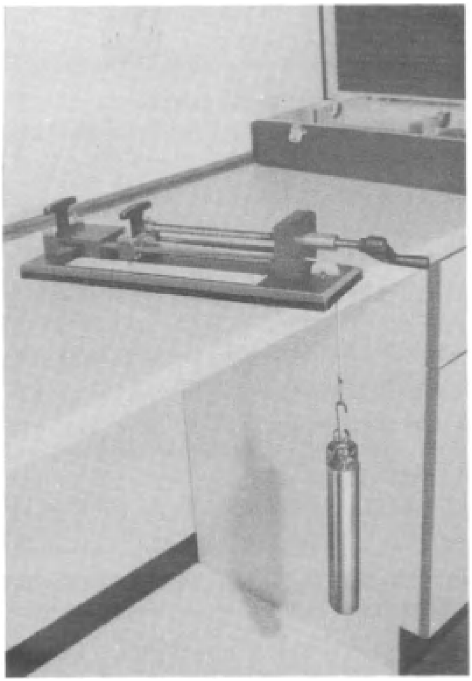


Figure 11.25. A Fryma Fabric Extensiometer.

11.3.2 Stiffness

The resistance to bending of paper is defined in BS 3748:1992 (ISO 2493:1992) as the force (in N or mN) causing deflection through 15° when applied at the free end of a bending length of 50 mm.

The apparatus illustrated in Figure 11.27 is an example of a tester that is applicable to a wide variety of materials, including paper, card, textiles and plastic, in thicknesses up to 6 mm. A sample to be tested is fixed in the clamp so that its bottom 6 mm overlap with the triangular vane attached to the top of the pointer, which is pivoted at its centre. During the test, the sample is moved against the vane, thus displacing it and the pointer until the sample bends and releases the vane; the range of force needed to achieve displacement can be selected to suit the stiffness of the sample by adjustable weights attached to the lower half of the pointer. The maximum displacement reading of the pointer is automatically set to force (mg) and hence to bending moment (g/cm or mN/m).

An empirical test of stiffness used in the textile industry (BS 3356:1990) measures the overhanging length of a horizontal strip necessary for it to bend through an angle of 41.5° under its own weight. With the simple apparatus shown in Figure 11.28, a specimen cut to size (25 mm × 200 mm) using a template is placed on the horizontal plate, with a ruler on top of the sample. The ruler and sample are then moved forward slowly until the bending fabric aligns with two engraved lines. The data may be reported as bending length, which is

Figure 11.26. A digital bursting strength tester with manual clamping.

half the overhanging length and relates to visual stiffness and drape in the material; or as flexural rigidity, G, that relates to tactile stiffness, and is given by:

$$G = 0.1ML^3$$

where M = cloth mass per unit area, g/m^2, and L = the overhanging length, cm.

11.3.3 Resistance to abrasion

Various devices are available whereby the resistance of textiles to abrasion can be quantified. Examples are the Frazier Schiefer Abrasion Tester, and the Martindale and Taber testers available from SDL International; these subject samples to continuous rubbing under a controlled pressure.

11.3.4 Thickness, compressibility and resilience

The Compressometer in Figure 11.29 permits the evaluation of the thickness, compressibility and resilience of a wide variety of materials (textiles, rubber, felt, non-wovens, paper, films, etc.) especially where observations are required at a range of compressive loads extending from 0.3 mbar to 1.7 bar. The sample to be tested is placed between the instrument base or anvil and the circular pressure foot that is fastened to the vertical spindle; three sizes of pressure foot are available (diameters 25, 75 and 125 mm). The lower dial indicates the thickness of the specimen, while the upper dial shows the pressure applied by a helical spring in the tube between them, this pressure being set manually using a rack and pinion device to compress or relax the spring.

11.4 Characterization of Other Media

The tests discussed above have dealt with the filtration and mechanical property tests for continuous media – sheets and rolls, and special cartridges. Although

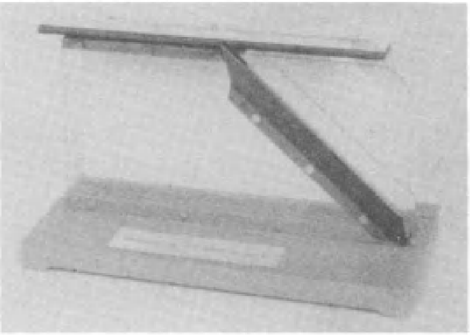


Figure 11.27. Shirley Stiffness Tester.

Figure 11.28. Model 4171-D Gurley digital bending resistance/stiffness tester.

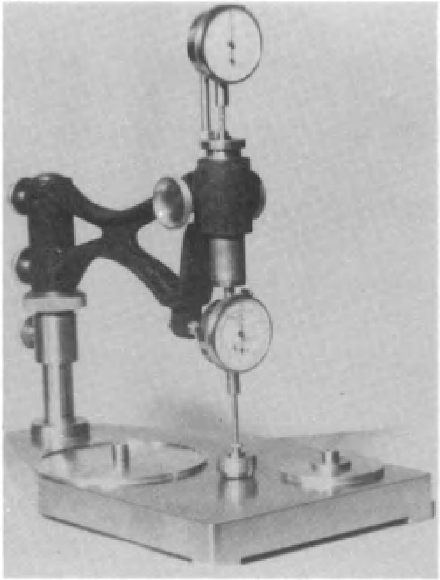


Figure 11.29. A Compressometer for evaluating thickness, compressibility and compressional resilience.

membranes are mainly of this type of material, there are still some special features of tests for membrane media, which are discussed now, together with those for loose granular media.

11.4.1 Membranes

The filtration action of micro- and ultrafiltration membranes is very similar in principle to that of other continuous media. Hence most of the testing methods already described have their equivalents in the testing of the properties of membranes. The delicacy and very fine pore structure of membranes, however, result in some major differences in test methods and procedures.

Characterization methods for porous membranes have already been introduced in Chapter 8. They can be divided into two areas: structure related parameters and permeation related parameters. Certain tests are also used to establish the integrity of membranes in specific applications. The direct measurement of pore statistics is routinely carried out by electron microscopy: by SEM (scanning electron microscopy) and TEM (transmission electron microscopy).

Table 11.11 summarizes the various test procedures used for micro- and ultrafiltration membranes, or for filters incorporating these membranes. It should be noted that the asymmetric structure of most ultrafiltration membranes, with top layer pore sizes in the range 20–1000 Å, means that many of the methods of characterization of microfiltration membranes and other continuous media cannot be applied. Bubble point and mercury intrusion

Table 11.11 Tests for characterizing membranes or membrane filters

Principle of test	Medium	Characteristic
Microfiltration membranes		
Air diffusion	Air	Integrity
Bubble point test	Air	Pore size
Cartridge retention test	Water	Filtration efficiency
Flow rate vs differential pressure	Water	
Particle shedding test	Water	
TOC tests	Water	
Resistivity test	Water	
Bacteria passage test	*Pseudomonas diminuta*	Sterility
Mercury intrusion test	Hg	Pore size and pore distribution
Latex sphere test	Latex sphere dispersion	Integrity
Water penetration test	Water	Integrity
Electron microscopy (SEM, TEM)		Pore size, shape, distribution, density
Permeation measurements		Water flux for pore size and distribution
Ultrafiltraton membranes		
Gas adsorption – desorption	N_2	Pore size and distribution
Thermoporometry	Water	Pore size and distribution
Permporometry	Gas	Pore size and distribution
Solute rejection	Various solutes	MWCO

methods require high pressures that could damage or destroy the membrane structure: SEM is generally not possible and TEM is not always applicable. The methods that can be used with ultrafiltration membranes include permeation experiments and test methods such as gas adsorption–desorption, thermoporometry, permporometry and rejection measurements.

A recent paper[18], basically describing PMI's porometer capability, has a good review of the main methods of membrane characterization, and advocates their use in combination to achieve the best definition of membrane performance.

11.4.1.1 Bubble point test

This standard test for determining the equivalent pore size and size distribution is described earlier in this chapter. It is a non-destructive test that does not contaminate the filter and thus can be used to test the integrity of a membrane as an alternative to destructive tests such as bacterial retention tests for sterilizing membranes.

11.4.1.2 Diffusion testing

A diffusion test is recommended in high-volume systems with final filter surface areas of 0.2 m^2 or greater. This test is based on the fact that gas will diffuse through the liquid in the pores of a fully wetted filter. The diffusion rate is proportional to the differential pressure across the membrane, and to its surface area. The flow of gas is limited to diffusion through water-filled pores at differential pressures below the bubble point pressure of the material under test.

In the diffusion test, pressure is typically applied at 80% of the bubble point pressure of the material. When there is liquid downstream of the filter, the volume of gas flow is determined by measuring the flow rate of displaced water. The rate of diffusion can also be measured by a gas flow meter.

In industrial settings, the flow rate is often measured on the upstream side of the filter, which does not require a tap into the sterile downstream side. The measurement technique used by many automated devices is pressure decay, after the gas on the upstream side is pressurized to the desired test pressure.

11.4.1.3 Mercury intrusion method

The mercury intrusion test, as already described for continuous media earlier in this chapter, relies upon the penetration of mercury into the membrane pores under pressure. The volume of mercury forced into the membrane is related to the pore size and pressure – the size is inversely proportional to the pressure. As with the bubble point test, a morphology or shape factor must be introduced.

In the test the pressure of mercury is gradually increased, and at a certain lowest pressure the largest pores will fill with mercury. The increasing pressure progressively fills the smaller and smaller pores, until a maximum intrusion of mercury is achieved. At high pressure, however, erroneous results may be obtained due to deformation or damage to the membrane material. In addition, the method also measures dead-end pores, which are not active in filtration. The size range of the test covers 5 nm to 10 μm pores, i.e. it covers microfiltration and some ultrafiltration membranes. Overall it gives pore size and pore size distribution.

11.4.1.4 Water integrity test

This test is relevant to sterilizing-grade hydrophobic filters that are used for the sterile filtration of air streams and gases in many pharmaceutical and biological applications. It is based on the same principles as the mercury intrusion test and may be performed *in situ* after sterilization without any downstream manipulations and can be directly correlated to the bacterial challenge tests. The upstream volume of the housing or filter must be completely flooded with water: pressure is then applied by air on the water volume and the rate of water permeation determined.

A water intrusion test has been developed by Sartorius(19) mainly for testing the integrity of sterile air filters, but also for membrane pore characterization. Its prime characteristic is that it can be used *in situ* to confirm the integrity of a sterile filter, because it is non-destructive, unlike a bacteria challenge test.

11.4.1.5 Bacterial challenge test

A bacterial challenge test system for the evaluation of the effectiveness of high-efficiency membrane filters, as illustrated in Figure 11.30, uses a nebulizer adapted from the original Microbiological Research Establishment (MRE) design for high-pressure operations. The device uses two impinger-type samplers in series upstream, and a silt sampler downstream of the test filter. A minimum challenge of 3 × 10^8 spores is recommended for filters operating 300 days per year with average flows of 850 dm^3/min.

The Health Industry Manufacturers Association (HIMA) regulations and the US FDA 'Guidelines on Sterile Drug Products Produced by Aseptic Processing' stipulate that a sterilizing filter, when challenged with a minimum concentration of 10^7 *Pseudomonas diminuta* organisms per cm^2 of filter surface,

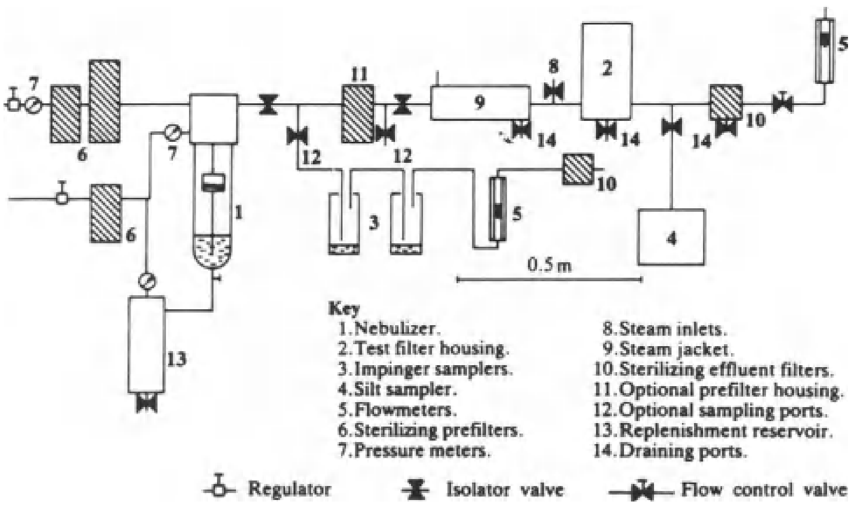


Figure 11.30. Diagram of bacterial challenge testing apparatus.

must produce a sterile filtrate. Filters that produced sterile effluents according to this test were accepted as 0.2 µm in size. In fact, the *P. diminuta* organism is much larger than 0.2 µm: a minimum of 0.3 µm in diameter and 1 µm in length (see Figure 11.31). This means that filters with 'pore sizes' of 0.3 µm and greater could retain the organism.

The bacterial challenge test is a destructive method and it therefore must be correlated with practical non-destructive integrity tests, e.g. bubble point and diffusion methods, to ensure filtration reliability. It has been proposed that a way of overcoming the variability of filter testing methods and to establish realistic, high challenge tests, is to use the log reduction value (LRV) as recommended for liquid sterilization filter tests. The LRV is defined as the logarithm of the ratio of the total number of micro-organisms in the challenge to the number in the filtered fluid. Generally, hydrophilic filters are totally retentive if they exhibit a bubble point of the order of 2.3 bar (i.e. the LRV is greater than 9). Similarly, for hydrophobic filters, a bubble point of 1 bar measured with methanol implies a totally retentive filter. As the bubble point falls, so does the value of the LRV. Such correlations are specific to particular membranes and filters. Filters that retain 100% of the challenge organism *P. diminuta* normally have water bubble point values of 3 bar or more.

Table 11.12 Sphere challenge in SDS

Membrane type	Sphere diameter, µm versus percent relation				
	0.149	0.198	0.220	0.300	0.398
PC	9	99	100	ND	ND
PTFE	31	81	98	100	ND
PVDF	ND	ND	37	60	100
PS	ND	29	46	62	100
N 66	ND	50	41	59	84

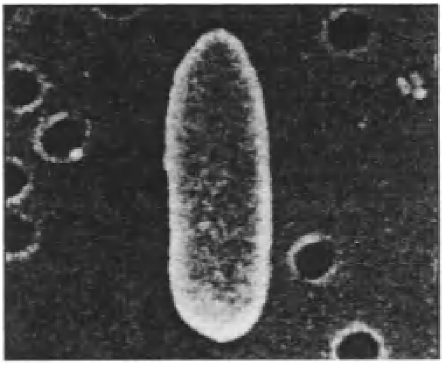


Figure 11.31. A Pseudominas diminuta *bacterium and a 0.2 µm hole.*

11.4.1.6 Latex sphere test

Latex spheres make up one of the variety of closely sized inert test dust materials that may be used in the challenge tests that were discussed previously in this chapter. The object of these tests is to characterize the pore size and the filtration efficiency of media.

Typical tests on a variety of membranes, as summarized in Table 11.12, revealed that, with the exception of the track-etched polycarbonate, the membranes all passed latex spheres of size equal to or greater than the manufacturer's rated pore size. Many 0.2 μm rated membranes actually passed spheres larger than 0.398 μm, despite the fact that they had been rated as sterilizing grade 0.2 μm 'absolute' by the industry standard HIMA bacteria challenge, using an organism with dimensions of 0.3 μm × 1 μm.

11.4.1.7 Gas adsorption–desorption

The use of gas adsorption–desorption is frequently practised for the measurement of pore size and size distribution of porous media. Typically nitrogen is used as the adsorbing medium, the method determining the quantity of gas adsorbed (and desorbed) at a particular pressure up to the saturation pressure. A model is required that relates the pore geometry to the adsorption isotherms. The method is limited generally to more uniform structures. Ceramic membranes have been satisfactorily characterized by this method. The method unfortunately includes the contribution made to the membrane structure by dead-end pores.

11.4.1.8 Thermoporometry

Thermoporometry uses the calorific measurement of solid–liquid transition in a porous medium. The method typically uses water as the fluid and is based on the fact that the freezing temperature in the pores of a membrane (i.e. the top layer) depends upon the pore size. The extent of undercooling is inversely proportional to the pore diameter. The method also measures the dead-end pores in the membrane. The material of the medium should have enough elasticity to resist the expansion of water as it freezes.

11.4.1.9 Permporometry

Permporometry is a method that characterizes only the active pores in the membrane. It is based on the blockage of pores by a condensable gas, linked with the measurement of gas flux through the membrane. The pore blockage is based on the same principle of capillary condensation as used in adsorption.

11.4.1.10 Flow porometry

A novel method of porometry[20] has been developed especially for ceramic membranes, although it could, in principle, be applied to other types. In this method, the membrane sample is soaked in a liquid that fills all the (through) pores in the sample spontaneously. One side of the sample is then pressurized with air, which slowly removes the liquid from the pores. The largest pore will become free first, followed by progressively smaller pores, and the air flow rate can be related to the pore characteristics. Measured gas pressures and flow rates through wet and dry samples are used to evaluate all the required properties of the membrane: largest pore size, mean pore size, pore size distribution, gas and liquid permeability and surface area. A completely automated instrument is used to record gas pressure and flow rates.

11.4.1.11 Solute rejection of ultrafiltration membranes

Ultrafiltration membranes are generally characterized in terms of solute rejection, defined as the fraction of material of a specified size in feed that is retained by the membrane. The terminology of molecular weight cut-off, MWCO, is also often used: this is defined as rejection of 90% of a solute with a particular molecular weight.

The method measures the rejection (or passage) of selected solutes of different molecular sizes under controlled conditions. The solutes should cover the expected size range for 0–100% rejection, and they should not interact with the membrane. Thus solutes such as sodium chloride and glucose (MW 180) are used for the low end (i.e. 0% rejection), and large proteins such as immunoglobulins (MW > 900 000) or blue dextran are used for the upper size range, as these have almost 100% rejection with most membranes. In all, some five or six water-soluble solutes are required for adequate characterization of membrane rejection, as shown in Table 11.13.

There are no standard test conditions for solute rejection characteristics, although recommendations do exist. These include: a pressure of 100 kPa (although this does vary); a temperature of 25°C; a 0.1% (w/v) solution of the challenging solute in a 1% saline solution; and a maximum possible degree of agitation. In addition only a relatively small amount of solute should be filtered to avoid concentration effects. The membrane should be new, cleaned of preservative, and conditioned using a series of soaking, washing and pressurization steps, until a stable and reproducible water flux is achieved.

The results of a series of rejection tests will usually be expressed as a plot of rejection versus MWCO, such as Figure 11.32. Some membranes exhibit sharp cut-offs, with a narrow range of MWCO; others exhibit a diffuse cut-off, with a broad range of MWCO.

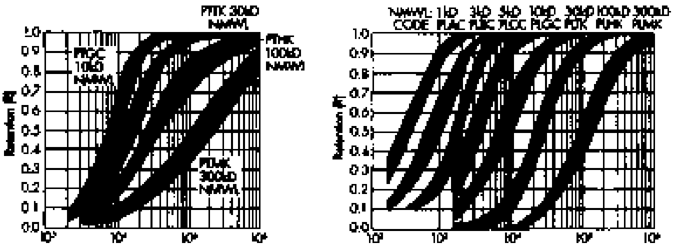


Figure 11.32. Typical rejection characteristics of polyethersulphone UF membranes.

Table 11.13 Typical solute rejection data and solutes used to characterise UF membranes

Solute	Molecular weight	UM 05									XM		
		pH 5	pH 10	UM2	DM5	UM10	PM10	YM10	UM20	PM30	50	100A[b]	300[b]
D-Alanine	89	15	80	0	–	0	0	–	0	0	0	0	0
DL-Phenylalanine	165	20	90	0	–	0	0	–	0	0	0	0	0
Tryptophan	204	20	80	0	–	0	0	–	0	0	0	0	0
Sucrose	342	70	80	50	–	25	0	–	–	0	0	0	0
Raffinose	594	90		–	–	50	0	10	–	0	0	0	0
Inulin	5000	–		80	70	60	–	45	5	0	0	0	0
PVP K15	10 000	–		90	85	65	35	75	–	–	–	–	–
Dextran T10	10 000	–		90	90	90	5	–	–	–	–	–	–
Myoglobin	17 800	>95		>95	–	95	80	>90	60	35	20	-	-
α-Chymotrypsinogen	24 500	>95		>98	–	>95	>95	-	90	75	85	25	0
Albumin	67 000	>98		>98	–	>98	>98	>98	95	>90	>90	45	10
Aldolase	141 000	>98		>98	–	>98	>98	–	>98	>98	>95	–	50
IgG	160 000	>98		>98	–	>98	>98	-	>98	>98	>98	90	65
Apoferritin	480 000	>98		>98	–	>98	>98	–	>98	>98	>98	>95	85
IgM	960 000	>98		>98	–	>98	>98	–	>98	>98	>98	>98	>98

[a] Measured at 55 psi (3.8 kg/cm^2), except where noted by footnote b.

[b] 10 psi (0.7 kg/cm^2).

Overall MWCO values of membranes are no more than a guide to a particular application. The arbitrary setting of the cut-off value, the variability in test procedures and solutes and the effects of other operating parameters mean greater precision is not as yet possible.

Other factors that affect the rejection measurements are the membrane material, the shape and flexibility of the macromolecule solute, its interaction with the membrane, the membrane configuration, concentration polarization phenomena, and interactions between different solutes or macromolecules. Secondary membranes can be formed on the membrane surface, which impede the permeation of lower molecular weight solutes. The adsorption of solutes by the membrane can also result in reduction in the apparent rejection of the ultrafiltration membrane. Overall, therefore, these membrane surface phenomena must ideally be taken into account in characterizing the true (intrinsic) membrane properties. This generally involves indirectly measuring the concentration of solute at the membrane surface using equations describing boundary layer phenomena, or alternatively eliminating these effects by experiments at low-pressure driving forces and low feed concentrations.

11.4.2 Granular media

The testing methods outlined in Sections 11.2–11.4 are concerned with sheet or roll materials, or with special cartridge formulations, and they do not apply (except those describing filter efficiency determination rather than specifically medium behaviour). The loose materials described in Chapter 10 need to be treated in a different way, and the methods of so doing are described in Section 10.3.1.

11.5 Organizations Involved in Filter Media Testing

The testing of filter media is undertaken widely, by a range of organizations:

- manufacturers of media have test rigs for their own products, and some provide a general testing service;
- some filter makers also have media test rigs available for use by others;
- most universities and research institutes that have an interest in filtration have filter or filter media test rigs, and some use them to provide testing services;
- there are a number of commercial suppliers of testing equipment who offer some kind of testing service, usually keyed to the company's range of equipment; and
- there is a very small number of fully independent testing companies, of which IFTS is the best known example.

As well as the makers of testing and particle characterization equipment, there are also the suppliers of test particulates (dust) most of whom at least give advice as to how their products should be used.

The following notes make absolutely no attempt to be exhaustive in their coverage – the 2002 *Filtration & Separation Buyers' Guide* lists nearly 60 organizations under the heading 'Testing Services'. The notes aim only to be indicative of the kinds of service to be expected.

11.5.1 Filtration equipment and media makers

Three-quarters of the names in the *Buyers' Guide* list mentioned above are makers of filters or filter media, all, apparently, offering testing services to outside companies. A not untypical example is that of MikroPul (Charlotte, NC), which provides testing services for bag filter media. These are based upon MikroPul's Filter Efficiency Media Analyzer, which puts media through 100 cleaning cycles, using a standard alumina dust. With PC control, it reports the residual pressure drop after cleaning, the optimum time between cleaning cycles, the weight gain of the medium, and the dust emission in the clean filtrate.

A similar service is offered by the Standard Filter Corporation (Carlsbad, CA), a large maker of filter bags. The company offers a complete in-house laboratory for bag and filter media testing.

11.5.2 Universities and research institutes

Wherever there is a university department with a strong filtration research programme, there is a reasonable chance that contract testing will be undertaken. This is especially true for the University of Sheffield, UK, where a new cartridge test rig for validation trials has been installed, and test facilities for membranes (micro- and ultrafiltration modules) are being installed in 2002, both available for outside contract work (www.shef.ac.uk/-cpc/staff1/burgoyne.html).

University College London (UCL), whose Civil Engineering Department was the home for the work reported in Chapter 10 by Ives, continues to have a testing service for granular media for use in water treatment deep bed filters (www.ucl.ac.uk/civileng/research/resenvir.html).

The Harwell Laboratory, UK, of AEATechnology has, for many years, been the headquarters for the Separation Processes Service, for which filtration, especially of gases, has been a key technology. The service no longer exists in its original research 'club' form, but test work is still undertaken for external clients.

There are several research institutes working in associated fields that have filtration interests, and which either produce testing equipment or undertake tests of specific media, such as the Shirley Institute for textiles, and a range of paper industry bodies, such as TAPPI.

11.5.3 Testing equipment suppliers

The key components of a filter test system are a source of fluid (usually air or water), a source of particles of known size and size distribution, a device that will measure the properties of the aerosol or slurry upstream and down stream of the filter medium under test, and a pressure drop indicator across the medium. To these must be added the instruments used to characterize the macro- and microstructure of the medium. All of these are available from a number of companies, some specializing in filter test equipment, some parts of larger instrumentation companies. Within this range, there are several such companies that offer testing services to customers or potential customers, usually using their own equipment.

Typical of such companies is BIRAL (Bristol Industrial & Research Associates Ltd, UK), which supplies complete testing equipment for disposable respirators, filter cartridges, cabin air filters and associated media, and for HEPA and ULPA panel filters. The most recent addition to the range is a complete scanning test system(21) to enable the determination of MPPS data to match the needs of EN 1822 (www.biral.com).

Another example is offered by PMI (Porous Materials Inc) of Ithaca, NY. PMI is basically a maker of pore characterization equipment, whose porometers have been mentioned earlier in this chapter, and whose equipment can cover fluid flow rates, pressure drop, separation efficiencies, rates of clogging, absolute filter ratings and filter integrity (www.pmiapp.com).

11.5.4 Testing service organizations

Although Palas GmbH (Karlsruhe, Germany; www.palas.de) is also a testing equipment maker, it has a significant testing services business, based upon its general expertise in aerosol technology. It received *Filtration & Separation*'s Product Achievement Award in 1999 for 'Testing and Monitoring Equipment', its expertise in testing covering deep-bed filter media and surface filter media for gas or liquid filtration. It has a test rig designed to satisfy VDI guidelines 3926, Part 1.

IFTS (Institut de la Filtration et des Techniques Séparatives) is based at Agen in southwest France (www.ifts-sls.com). It is perhaps the only truly independent testing company. Its activities are very well known, and its managing director, Christophe Peuchot, is active in testing methods research, and is concerned in the development of many international standards. IFTS specializes in liquid filtration systems(22), and opened a new filter test facility in 2000. Much of the new expansion is concerned with filter testing, but there is an appreciable amount of media testing undertaken as well.

11.6 References

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CHAPTER 12

Filter Media Standards

References have been made occasionally throughout this Handbook to standards as they affect filter media and/or filter testing. A coherent look is now given at the whole range of standards, from several sources.

12.1 Introduction

Particularly in those parts dealing with characterization of materials or testing of filtration performance, the relevant standards have featured in earlier chapters, mainly as guidelines to methods of characterization or testing. Many of these standards are produced by central organizations, but there are also equally valuable documents available from organizations specific to an industry sector. These bodies are listed briefly first, followed by a reasonably complete listing of the relevant standards for filter media in particular, and filter testing in general, plus some comments on the way in which standards are developed and confirmed.

No attempt is made here to expand the details of most of the standards beyond simple listing of the titles – the list is too extensive for that.

12.2 Standards Organizations

Most developed countries have national standards offices, charged with the development and publication of standards for materials and processes in all walks of life. Some of these have long histories of preparation and publication of standards that have had a major effect upon industrial development. Not too surprisingly, a significant number of standards have to do with safety procedures, so that, in the case of filtration, procedures relating to fluid power installations were among the earliest, and remain among the most important. The need for established procedures for the demonstration of the efficiency of high-grade air filters, and for the production of safe water, has led to a fresh burst of standard creation.

However, it is not only national bodies that produce key guidance documents. Several industry-related associations have seen particular needs for standards, and filled them well, with documents that have become classics of their kind – ASHRAE is perhaps the prime example of this kind of body.

With the growing importance of international business, an international standards organization was soon established, and there are now major ISO standards in all fields of filtration work, and most new national standards are related to their equivalent ISO document. The European countries have also established a continent-wide organization, to ensure conformity of national standards.

The leading bodies in the issuance of standards are listed in Table 12.1, which includes some of the international bodies, as well as some industry-specific organizations. The ISO and CEN are non-commercial organizations, while Eurovent is an association of manufacturers. All work through specialized committees or working parties, which can sometimes take a very long time to produce a final version, especially if the 'published for general discussion' stage is a long one.

12.3 Relevant Standards

The prime aims of the inclusion of this chapter on standards relevant to the world of filter media are to show the complexity of the situation, and to highlight those

Table 12.1 Standards producing organizations

International	ISO	International Organization for Standards
	CEN	Comité Européen des Normalisations[a]
	EUROVENT	European Committee of Air Handling & Refrigerating Equipment Manufacturers[b]
British	BSI	British Standards Institution
	BW	British Water
German	DIN	German Institute for Standardization
	VDI	German Institute for Engineers
French	AFNOR	French Association for Standardization
Italian	UNI	Italian Institute for Standardization
American	ANSI	American National Standards Institute
	ASTM	American Society of Testing and Materials
	ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
	AIHA	American Industrial Hygiene Association
	DOE/NRC	Department of Energy/Nuclear Regulatory Commission
	INDA	Association of the Nonwoven Fabrics Industry
	NIOSH	National Institute for Occupational Safety and Health
	NIST	National Institute of Standards and Technology
	SAE	Society of Automotive Engineers

[a] CEN has as its national members the national standards organizations of the EU and EFTA countries, plus Czech Republic and Malta.

[b] Full name is EUROVENT-Cecomaf.

of key interest. The list of standards that follows will also serve as an index to most of the references to standards in earlier chapters of this Handbook.

The standards cover:

- the mechanical testing of the materials used for filter media as to strength;
- the determination of particular filtration characteristics, such as pore size or permeability, of filter media;
- the testing of filtration efficiency (i.e. particle retention or penetration), including the definition of test dusts or aerosols, and methods for their characterization; this is done for filters for liquids and gases, and for particular applications, such as respirators, or lube oil filters.

The ways in which standards are developed for liquid systems – engine fluids and drinking water – has been well described by Peuchot, based on his work at IFTS, and for several standards bodies(1-2). The world of air filtration standards has been reviewed by another international expert, Gustavsson, from his position as a manufacturer and academic(3-4). Both are concerned to highlight changes in standards.

There is, of course, much overlap among standards published by different bodies, national and international. Gustavsson(3) illustrates the relationships between the ASHRAE standards 52.1 and 52.2, and the European EN779 and EUROVENT standards. Thus ASHRAE 52.1 became the US national standard, and was adopted as EUROVENT 4/5, and then as EN 779. These were developed into EUROVENT 4/9, and the new version of EN 779 (prEN 779), and similar developments led to ASHRAE 52.2 – a good review of the derivation of the latter can also be found in the paper by Hanley *et al.*(5).

Perhaps because of the long gestation time for a new standard, manufacturers can move into a perceived gap, as has Hy-Pro with its Dynamic Filter Efficiency method of testing(6), which it claims to be an improvement on even the latest form of multipass test.

Much of the testing of filters and filter media is based upon the selection and definition of good test dusts, and some of the earliest relevant standards were involved in just such a definition. Better and better definition seems possible as shown by Bensch(7) in a review of the impact of modern ISO standards on hydraulic and lubricating fluids.

12.3.1 National standards

A list of all the standards of possible relevance to filter media, including material testing and filtration characteristic determination, would be a vast undertaking, and of no real value to this Handbook. The following sections note the key standards for the British national body, and for one or two other national organizations, including the major international standards.

Tables 12.2 and 12.3 list the British standards covered in earlier chapters of this Handbook, and others of direct relevance, including both those particular to the BSI, and those with direct international equivalence. Table 12.2 has the

Table 12.2 British standards for filter media

Number	Title or comment
BS 1701:1970	Replaced by BS 7226:1989, and in turn by BS ISO 5011
BS 1747-2:1969	Methods for the measurement of air pollution. Determination of concentration of suspended matter
BS 1752:1983 (ISO 4793:1980)	Specification for laboratory sintered or fritted filters, including porosity grading
BS 2576:1986	Replaced by BS EN ISO 13934-1
BS 2831	Replaced by BS 6540
BS 3137:1972	Methods for determining the bursting strength of paper and board
BS 3321:1986	Method for the measurement of the equivalent pore size of fabrics (bubble point method)
BS 3356:1990	Method for determination of bending length and flexural rigidity of fabrics
BS 3406-9:1997	Method for the determination of particle size distribution. Recommendation for the filter blockage method (mesh obscuration)
BS 3748:1992 (ISO 2493:1992)	Method for determination of resistance to bending of paper and board
BS 3928:1969	Method for the sodium flame test for air filters (other than air supply to internal combustion engines and compressors)
BS 4400:1969	Method for sodium chloride particulate test for respiratory filters
BS 4415-1:1992 (ISO 1924-1:1992)	Determination of the tensile properties of paper and board. Constant loading rate method. Replaced by BS EN ISO 1924-2:1995
BS 4552-1:1979	Fuel filters, strainers and sedimenters for compression-ignition engines. Methods of test
BS 4555:1970	Replaced by BS 7355
BS 4768:1972	Replaced by BS EN ISO 13938-1 and 13938-2
BS 4836:1972	Replaced by BS 7403
BS 5295-1 and 2	Replaced by BS EN ISO 14644-1, -2, and -4
BS 5295-3:1989	Environmental cleanliness in enclosed spaces. Guide to operational procedures and disciplines applicable to clean rooms and clean air devices. (See also BS EN ISO 14644-1, -2 and -4)
BS 5540 Part2:1992 (ISO 4402:1991)	Replaced by BS ISO 4406, 11171
BS 5600 Part 3 (ISO 4003:1997)	Replaced by BS EN ISO 24003:1993
BS 5636:1990	Method for determination of permeability of fabrics to air. Replaced by BS EN ISO 9237:1995
BS 6275-1:1982 (ISO 4572:1981)	Hydraulic fluid power filter elements. Method of evaluating filtration performance (multipass method). Replaced by BS ISO 2941, 2942, 2943, 3723, 3724, 16889
BS 6277:1982 (ISO 3968:1981)	Replaced by BS ISO 3968:2001
BS 6347-8:1993 (ISO 789-8:1991)	Performance assessment of agricultural tractors. Method of testing engine air cleaners
BS 6410:1991	Methods of test for filter papers
BS 6540-1:1985	Replaced by BS EN 779:1993
BS 6851:1987 (ISO 7744:1986)	Method for preparing a statement of requirements for hydraulic power filters
BS 6912-22-2:1996 (ISO 10263-2:1994)	Safety of earth moving machinery. Operator enclosure environment. Air filter test
BS 7355:1990	Replaced by BS EN 136:1998 and 143:2000
BS 7403-1:1998 (ISO 4548-1:1997)	Full-flow lubricating oil filters for internal combustion engines. Methods of test for differential pressure/flow characteristics

BS 7403-3:1998 (ISO 4548-3:1997)	Full-flow lubricating oil filters for internal combustion engines. Methods of test for resistance to high differential pressures and to elevated temperatures
BS 7403-4:1998 (ISO 4548-4:1997)	Full-flow lubricating oil filters for internal combustion engines. Methods of test for initial particle retention efficiency, life and cumulative efficiency (gravimetric method)
BS 7403-6:1991 (ISO 4548-6:1985)	Full-flow lubricating oil filters for internal combustion engines. Methods of test for static burst pressure
BS 7403-11:1998 (ISO 4548-11:1997)	Full-flow lubricating oil filters for internal combustion engines. Methods of test for self-cleaning filters
BS 7403-12:2000 (ISO 4548-12:2000)	Full-flow lubricating oil filters for internal combustion engines. Filtration efficiency using particle counting, and contaminant retention capability
BS 7591-1:1992	Porosity and pore size distribution of materials. Method of evaluation by mercury porosimetery
BS 7591-2:1992	Porosity and pore size distribution of materials. Method of evaluation by gas adsorption
BS 7591-4:1993	Porosity and pore size distribution of materials. Method of evaluation by liquid expulsion
BS 7881:1997	Method of test for petrol filters

Table 12.3 British/international standards

Number	Title or comment
BS ISO 2941:1974	Hydraulic fluid power. Filter elements. Verification of collapse/burst resistance
BS ISO 2942:1994	Hydraulic fluid power. Filter elements. Verification of fabrication integrity and determination of the first bubble point
BS ISO 2943:1998	Hydraulic fluid power. Filter elements. Verification of material compatibility with fluids
BS ISO 3723:1976	Hydraulic fluid power. Filter elements. Method for end load test
BS ISO 3724:1976	Hydraulic fluid power. Filter elements. Verification of flow fatigue characteristics
BS ISO 3968:2001	Hydraulic fluid power. Filters. Evaluation of differential pressure versus flow characteristics
BS ISO 4020:2001	Road vehicles. Fuel filters for diesel engines. Test method
BS ISO 4406:1999	Hydraulic fluid power. Fluids. Method for coding the level of contamination by solid particles
BS ISO 5011:2000	Inlet air cleaning equipment for internal combustion engines and compressors. Performance testing
BS ISO 5782-1:1997	Pneumatic fluid power. Compressed air filters. Main characteristics to be included in supplier's literature and product marking requirements
BS ISO 5782-1:1997	Pneumatic fluid power. Compressed air filters. Test methods to determine the main characteristics to be included in supplier's literature
BS ISO 11170:1995	Hydraulic fluid power. Filter elements. Procedure for verifying performance characteristics
BS ISO 11171:1999	Hydraulic fluid power. Fluids. Calibration of automatic particle counters for liquids
BS ISO 11841-1:2000	Road vehicles and internal combustion engines. Filter vocabulary. Definitions of filters and filter components
BS ISO 11841-2:2000	Road vehicles and internal combustion engines. Filter vocabulary. Definitions of characteristics of filters and their components
BS ISO 11943:1999	Hydraulic fluid power. On-line automatic particle-counting systems for liquids. Methods of calibration and validation

Table 12.3 ***(continued)***

Number	Title or comment
BS ISO 12103-1:1997	Road vehicles. Test dust for filter evaluation. Arizona test dust
BS ISO 12103-2:1997	Road vehicles. Test dust for filter evaluation. Aluminium oxide test dust
BS ISO 14269-4:1997	Tractors and self-propelled machines for agriculture and forestry. Operator enclosure environment. Air filter test method
BS ISO 16889:1999	Hydraulic fluid power. Filters. Multipass method for evaluating filtration performance of a filter element
BS EN 136:1998	Respiratory protective devices. Full face masks. Requirements, testing, marking
BS EN 141:2000	Respiratory protective devices. Gas filters and combined filters. Requirements, testing, marking
BS EN 143:2000	Respiratory protective devices. Particle filters. Requirements, testing, marking
BS EN 149:2000	Respiratory protective devices. Filtering half-masks to protect against particles. Requirements, testing, marking
BS EN 405:2000	Respiratory protective devices. Valved filtering half-masks to protect against gases or gases and particles. Requirements, testing, marking
BS EN 779:1993	Particulate air filters for general ventilation. Requirements, testing, marking
BS EN 1822-1:1998	High-efficiency air filters (HEPA and ULPA). Part 1: Classification, performance testing, marking
BS EN 1822-2:1998	High-efficiency air filters (HEPA and ULPA). Part 2: Aerosol production, measuring equipment, particle counting statistics
BS EN 1822-3:1998	High-efficiency air filters (HEPA and ULPA). Part 3: Classification, performance testing, marking
BS EN 1822-4:1998	High-efficiency air filters (HEPA and ULPA). Part 4: Testing flat sheet filter media
BS EN 1822-5:1998	High-efficiency air filters (HEPA and ULPA). Part 5: Determining the efficiency of a filter element
BS EN 1827:2000	Respiratory protective devices. Half-masks without inhalation valves and with separable filters to protect against gases or gases and particles or particles only. Requirements, testing, marking
BS EN 12083:2000	Respiratory protective devices. Filters with breathing hoses (non-mask mounted filters). Particle filters, gas filters and combined filters. Requirements, testing, marking
BS EN 12341:1999	Air quality. Determination of the PM10 fraction of suspended particle matter. Reference method and field test procedure to demonstrate reference equivalence of measurement method
BS EN 12901:1999	Products used for treatment of water intended for human consumption. Inorganic supporting and filtering materials. Definitions
BS EN 12902:1999	Products used for treatment of water intended for human consumption. Inorganic supporting and filtering materials. Methods of test
BS EN 12941:2000	Respiratory protective devices. Powered filtering devices incorporating a helmet or a hood. Requirements, testing, marking
BS EN 12942:2000	Respiratory protective devices. Power assisted filtration devices incorporating full face masks, half-masks or quarter-masks. Requirements, testing, marking
BS EN 13274-1:2001	Respiratory protective devices. Methods of test. Determination of inward leakage and total inward leakage
BS EN 13274-2:2001	Respiratory protective devices. Methods of test. Practical performance tests
BS EN 13274-3:2001	Respiratory protective devices. Methods of test. Determination of breathing resistance
BS EN 13274-4:2001	Respiratory protective devices. Methods of test. Flame tests
BS EN 13274-5:2001	Respiratory protective devices. Methods of test. Climatic conditions
BS EN 13328-1:2001	Breathing system filters for anaesthetic and respiratory use. Salt test method to assess filtration performance

Table 12.3 (**continued**)

Number	Title or comment
BS EN ISO 1924-2:1995	Paper and board. Determination of tensile properties. Constant rate of elongation method
BS EN ISO 9237:1995	Textiles. Determination of the permeability of fabrics to air
BS EN ISO 13934-1:1999	Textiles. Tensile properties of fabrics. Determination of maximum force and elongation at maximum force using the strip method
BS EN ISO 13934-2:1999	Textiles. Tensile properties of fabrics. Determination of maximum force using the grab method
BS EN ISO 13938-1:1999	Textiles. Bursting properties of fabrics. Hydraulic method for determination of bursting strength and bursting distension
BS EN ISO 13938-2:1999	Textiles. Bursting properties of fabrics. Pneumatic method for determination of bursting strength and bursting distension
BS EN ISO 14644-1:1999	Cleanrooms and associated controlled environments. Classification of air cleanliness
BS EN ISO 14644-2:2000	Cleanrooms and associated controlled environments. Specifications for testing and monitoring to prove continued compliance with ISO 14644-1
BS EN ISO 14644-4:2001	Cleanrooms and associated controlled environments. Design, construction and start-up
BS EN ISO 24003:1993	Permeable sintered metal materials. Determination of bubble test pore size

Table 12.4 Other national standards

Country/number	Title or comment
USA	
ASHRAE 52.1-1992	Gravimetric and dust-spot procedures for testing air-cleaning devices used in general ventilation for removing particulate matter
ASHRAE 52.2-1999	Method of testing general ventilation air-cleaning devices for removal efficiency by particle size
Germany	
VDI 3926:1994	Guideline for the characterization and evaluation of cleanable filter media with respect to their long-term filtration behaviour

basic BSI standards, quoting ISO equivalents where they exist, Table 12.3 having the combined national/international standards. The gradual integration of national, regional and international standards can be seen in both tables.

Other national standards are shown in Table 12.4, covering the two key ASHRAE documents on dust removal filter testing, and the VDI guideline on cleanable filter media.

12.3.2 Other international standards

Most of the key CEN and ISO standards have already been listed in Table 12.3, under combined BSI/CEN/ISO numbers – the reader will have to consult Tables 12.2 and 12.3, for example, for all ISO standards of relevance. Table 12.5 lists some more international documents not already covered, including the important EUROVENT standards.

Table 12.5 Other international standards

Organization	Title or comment
Eurovent	
4/4:1984	Sodium chloride aerosol test for filters using flame photometric technique
4/5:1992	Method of testing air filters used in general ventilation
4/8:1985	*In situ* leak testing of high-efficiency filters in clean spaces
4/9:1996	Method of testing air filters used in general ventilation for determination of fractional efficiency
4/10:1996	*In situ* determination of fractional efficiency of general ventilation filters
CEN	
prEN 779:2001	Particulate air filters for general ventilation. Determination of the filtration performance
prEN 13443-1	Water conditioning equipment inside buildings. Mechanical filters. Part 1: Particle rating 80–150 µm. Requirements for performance and safety, testing
prEN 13443-2	Water conditioning equipment inside buildings. Mechanical filters. Part 2: Particle rating 1 to <80 µm. Requirements for performance and safety, testing
prEN 13779	Ventilation for non-residential buildings. Performance requirements for ventilation and air conditioning equipment

Also in Table 12.5 are some CEN standards under review, including the important revised form of EN 779, which aims to introduce a new standard based upon a filter's fractional particle efficiency, covering a lifetime's behaviour, not just as-new performance.

12.4 References

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Glossary

The following descriptions and definitions will help to explain the technical terms used in this Handbook to describe filter media. Some terms particular to filtration equipment are also included.

Abrasion
The wearing away of a material by contact with a hard surface or by the impact of hard particles.

Absolute
A word implying the complete removal of all suspended solid from a fluid, but in fact referring to filters with very high capture efficiency.

Absorption
The entrapment of a particle or a gas within ('ab-') the body of a filtering material – therefore only strictly applicable to liquids, but also used of entrapment within the depth of a thick filter medium.

Activated (carbon)
The energizing of the surface of (usually granular) carbon to render it capable of efficient removal of, for example, odours from a gas, or colour from a liquid, by adsorption.

Adsorption
The entrapment of a particle or a gas by adhesion to ('ad-') the surface of a solid filtering material, which thus needs to be finely granular or fibrous to present the highest possible surface area per unit volume.

Aerosol
A dispersion of solid particles of colloidal dimensions in a gas (although also used of similar dispersions of liquid droplets).

Bag
A filter element consisting of a relatively long cylindrical shape, open at one end, closed at the other (where it is fitted to a supporting frame), which may have a seam along its length and/or closing one end – or may be seamless. The bag may

fit over or inside a metal cage to provide support for the medium. (See also candle, pocket, sleeve)

Baghouse
A somewhat old-fashioned, though still widely used, term for large dust collection filters, employing changeable bags for the collection. Not so widely used now that the separating element can be a pocket or, increasingly, a cartridge. (See also fabric filter)

Bar screen
A filter medium created from a set of bars (each usually of wedge-shaped cross-section) arranged parallel one to another, with the set either flat, or curved, or in the form of a cylinder.

Basket
Filter medium in basket shape, i.e. cylindrical, with its diameter roughly the same as its length, often self-supporting, made from mesh or perforated sheet, and installed either in a strainer housing or in a centrifuge.

Belt
A filter medium, mostly used for harvesting solids from liquid suspension, in the form of a long continuous strip running around a set of rollers, and usually moving from a feed zone, through a filtering zone, possibly through a cake washing zone, and to a cake removal zone, after which the belt returns through a cleaning zone to the start. May run together with an impervious belt that squeezes the cake to improve dewatering.

Beta factor, ratio
Ratio of the number of particles greater than a defined size in a fluid upstream of a filter to the number downstream. Removal efficiency may then be represented by: $100(\beta - 1)/\beta$.

Blinding
The progressive blockage of a filter medium as its pores fill with trapped particles that cannot be removed by back flushing. Blinding may result in the medium's having to be discarded, or it may be possible to clean the medium physically or chemically to make it suitable for reuse.

Bolting cloth
A fine woven wire fabric, used for (usually dry) sieving.

Bonded, bonding
When fine fibres or filaments are held together in a mass, they are bonded – by their own features, or by thermal fusion at the points of contact, or by an adhesive. Bonding does not usually include sintering, but it should.

Bubble point

The pressure at which a bubble of gas or liquid appears downstream of a piece of filter medium, which is immersed in a standard fluid.

Bursting strength

A measure of the medium's ability to resist a potential bursting force when pressure is applied to one side of a piece of the medium, restrained around its periphery.

Cabin filter

Any filter used to clean the air inside a vehicle cabin (automobile, tractor, aircraft, etc.), either from impurities entering from outside (especially diesel fume and pollen) or in re-circulating systems.

Cage

An array of wire, rod or coarse mesh, usually cylindrical in shape, used to support flexible filter media such as bags or sleeves.

Cake filtration

When the surface of a filter is covered by a single layer of particles, newly deposited particles add to that layer and form a cake above the surface. This cake then effectively acts as the filter medium. (See also depth filtration, precoat, surface filtration)

Cake release

Once a cake of collected solids has formed on a filter medium, it must be removed as completely as possible. The ability of a medium to release a cake easily is an important feature of its filtration performance. (See also heel)

Calender, calendering

One of the methods of finishing the filter medium, and especially its surface, by passing the material between a pair of calendering rollers (usually heated). This will consolidate the material, and may flatten and/or emboss the surface(s).

Candle

A cylindrical filter element, long in relation to its diameter, sealed at one end and open at the other. Usually used of rigid media (such as ceramic), and frequently used to refer to multiple elements housed in a single filter vessel. (See also bag, pocket, sleeve)

Capsule

A small, usually self-supporting filter element, shaped like a lens, with filter media as both upper and lower surfaces. May be mounted as a set, one above the other, on a central supporting core.

Also used to describe a small self-contained filter unit, employed in laboratory, medical and pharmaceutical applications, formed usually of a piece of filter medium sealed into a casing fitted with inlet and outlet fluid connections; usually discarded when 'full'.

Capture
The entrapment of a particle or droplet out of suspension in a fluid, by a filter medium.

Cartridge
A fairly general term for a filter element that is cylindrical in shape, relatively rigid in construction, and made in several different ways from a wide range of materials. The most common form is closed at one end, with a supporting device at the other, open end.

Cassette
See Panel.

Cellulose
The main component of wood, and hence of paper. Natural cellulose can be mechanically or chemically broken down into fine fibres, which may then be wet laid as a continuous material. Cellulose can be dissolved in a complex liquid solvent, and then extrusion spun to produce artificial (regenerated) cellulose, rayon (or viscose), which can be made into other materials for filtration use.

Centrifugal filter
A centrifuge in which the separation of solids from liquids is achieved through a filter medium, which will be basically cylindrical in shape, with the filtrate draining outwards from the centre, under the centrifugal force.

Centrifuge
A device for achieving mechanical separations of liquid/liquid or liquid/solid mixtures under the accelerated gravitational force achieved by rapid rotation. The separation can be affected by sedimentation (driven by differences in density) or filtration.

Ceramic
An inorganic material that has been fired to high temperature. It is thus able to resist moderately high temperatures in use. (The term does not usually encompass carbon or glass.)

CIP, clean in place
A system for cleaning any item of equipment that does not need the equipment to be dismantled, even partially. The cleaning will normally be done by a cleaning solution, followed by steam sterilization where necessary. The filter and its medium that are to be cleaned in this way must be capable of resisting the cleaning action and temperatures of the CIP system. They must also be designed so as not to leave any dead spots unreachable by the cleaning fluid.

Clarifying, clarification
A term used to denote the removal from a gas or a liquid of a small amount of suspended impurity. Such separation is normally required to be highly efficient, and low in energy demand.

Cleaning
The cleaning of a gas refers to its clarification; cleaning otherwise refers to the process by which collected material can be removed from a filter. (See also CIP)

Cloth
The use of 'cloth', as in 'filter cloth', is now a touch archaic, referring to when most filtration was done through woven textile media. The word 'fabric' is used in this Handbook, to cover both woven and non-woven materials.

Coalescing
The process by which finely divided liquid droplets dispersed in another liquid are made to merge together into larger droplets, and then a continuous layer.

Coating
A layer of one material applied to the surface of another. Used in filtration to relate specifically to surface treatment of a filter medium, which renders that surface more suitable for use: less easily abraded, more ready to release collected cake.

Collecting, collection
A fairly general term referring to the capture of suspended material by a filter medium, in the various ways that this is achieved. Collection efficiency is a more specific term, relating to the thoroughness with which the medium achieves its required separation. Also applies to the settling down of extruded filaments and fibres onto a flat (and usually moving) surface.

Colloid, colloidal particle
A word originally coined to describe those materials in solution that would not pass through a dialysis membrane, now generally used of very finely divided solids in suspension or semi-solution. A colloidal suspension would not be expected to settle over a long period of time. (See also aerosol)

Combination filter, media
A filter, or its associated medium, that carries out the double duty of filtration and some chemical activity, usually deodorizing or decolourizing.

Composite
Refers to a filter medium that is made of two or more layers of different material – differing by pore size, or chemical nature of the material. A membrane is nearly always a composite material, with a fine surface layer supported on a substrate of coarser material. (See also lamination)

Concentration polarization
The creation of a layer close to a filter medium's surface (especially for membranes) where the solute species is concentrated, hence reducing the liquid flux.

Copolymer
A polymer formed from more than one monomer, either in the same chain or with one cross-linking chains of the other.

Core
A central support, usually cylindrical in shape, and made from sheet metal, metal rods or extruded plastics, on which a variety of materials can be mounted to form a cartridge. (See also cage)

Corrosion
Unwanted chemical attack on a material resulting in material loss, usually into solution, but corrosion by gases is by no means uncommon.

Cotton
Natural fibres from the seed of the cotton plant. Long staple fibres are from 2.5 to 6.5 cm in length, medium staple 1.3 to 3.3 cm, and short staple 1 to 2.5 cm.

Crepe
Crepe paper has a wrinkled finish, which provides some elastic stretch to the material.

Crimp
An intentional kink impressed into a fibre or filament to increase its bulking properties. Wire may also be crimped, especially on a regular pattern, to hold the crossing wires firmly in place after weaving.

Cross-flow (filtration)
Operation of a filter with the suspension being filtered flowing across the medium surface, rather than through the medium. This helps to keep the surface free of accumulated solid by the scouring action of the fluid. (See also dead-end, through-flow)

Cross (machine) direction
The direction in a continuous roll of material that is at right angles to the flow of the roll – termed 'warp' in a woven fabric. (See also machine direction)

Dead-end
Operation of a filter with the feed flowing effectively at right angles to the medium surface, so that all of the fluid passes through the medium. (See also cross-flow, through-flow)

Decitex
A unit of thread, yarn or filament size measurement, equal to 10 tex (NB not 0.1 tex).

Deep bed (filter)
Operation of a filter with a deep bed of granular material as its medium, usually with the fluid flowing downwards. This is normally cleaned by flow reversal, washing the dirt upwards and out of the vessel containing the bed (of sand, anthracite, coke, etc).

Demisting
The removal from suspension of very fine liquid droplets in a gas.

Denier
A measure of the size of a thread, yarn or filament, given by the weight in grams of 9000 m of the material (and dependent upon the material's density). (See also tex)

Depth filtration
Filtration of suspended solids within the thickness of the filter medium, rather than at its surface. The entrapped solid must then be blown or washed out of the medium, if the latter is to be re-used. (See also surface filtration)

Dialysis
A separation process relying on the diffusion of one component (or more) through the pores of a semi-permeable membrane, the driving force being the concentration gradient across the membrane (usually with pure solvent on one side).

Diffusion
The movement of ions or molecules through the material of a medium under the influence of a concentration gradient.

Dirt-holding capacity
The ability of a filter medium to hold the material removed from suspension without becoming blocked, i.e. without an unacceptable increase in pressure drop across the filter. The higher the dirt-holding capacity for a given dust load, the longer the time interval between cleaning or replacement.

Disc
A piece of filter medium cut (or stamped) out in the form of a circle, for insertion in a suitable holder. May also be used of two circular pieces of medium, sealed together around their periphery and to a central feed or offtake system. Also refers to the use of flat circular pieces of metal (or plastic) stacked one above the other to provide a filtering surface at the gaps between their outside edges. (See also capsule, lenticular)

Dispersion
A mixture of solid particles or liquid droplets in a continuous liquid or gaseous phase, usually implying a uniform distribution.

Droplet
A small particle of liquid.

Dry laid
Fibres or filaments produced in the air (or an inert gas) and settled onto a collecting surface, usually in random orientation, are said to be dry laid. (See also wet laid)

Dust
A fine dispersion of solid particles in a gas is called a dust, although there are no precise dimensional limits below which the solid must be. Many dusts are dangerous (either by inhalation or as an explosion risk) and gas cleaning is the corresponding process solution.

Edge filter
A filter element fabricated from a number of machined or stamped components, such that the edges of the components together create the filter medium – such as an array of discs, or of rings, or of bars, or of wire, or of ribbon spirally wound.

Electret
A fibre made in such a way that it has an intrinsic electrostatic charge, and can thus be used to capture particles more effectively if they too carry a charge.

(Filter) element
A single item of filtering medium, in any one of a number of shapes or structures, designed to fit in a (usually standardized) housing, from which it is removable for cleaning (or disposal). May be a cartridge, bag, pocket, etc.

Electrodialysis
Dialysis under the additional driving force of an electric potential between two electrodes.

Equivalent pore size
The calculated effective pore size of a piece of porous material as a result of one of a number of test methods.

Expanded metal
Sheet metal mechanically expanded into a regular diamond-shaped mesh.

Extrusion
The forcing of a molten substance through machined holes, under controlled pressure, to produce continuous forms, shaped according to the cross-section of

the holes. In the case of filter media, this mainly refers to the use of spinnerets to produce fine filaments or fibres of thermopolymers.

Fabric
A continuous piece of material made from fibrous or filamentous substances, by weaving or knitting, or as a non-woven material made by felting or some similar process.

Fabric filter
A term used to cover all those large filter installations, used for the cleaning of exhaust and process gases, comprising multiple elements in a single housing, which elements can be bags, pockets, cartridges, etc. (See also baghouse)

Felt
A mass of natural or synthetic fibre, laid down usually in a random fashion, and then carded to give some orientation to the fibres. Usually made in a multitude of thin webs. Natural fibres have sufficient mutual adhesion to provide strength to the felt, but synthetic fibres usually require further processing of the felt to give it the required tensile strength.

Fibre
A piece of natural or synthetic material, which has a small diameter (measured in hundredths of a millimetre, if not in micrometres), and is very long in relation to its diameter. Among natural fibres, cellulose from softwood trees is the shortest, and some wools are the longest.

Fibrillated, fibrillation
The processing of fibrous, filamentous or flat sheet material to create a very fine structure of open area and microfibrous protrusions, to give an effectively much smaller diameter material. Also refers to the microstructure of natural fibre that enables it bond naturally in felts.

Fibrous
Any material that is made up of fibres, natural or synthetic.

Filament
A very long, effectively continuous, single strand of any material. Among natural materials, only silk exists as a filament, but synthetic materials can be spun into filaments whose length is governed only by the size of the molten polymer reservoir.

Filter
In the present context, a filter is the mechanical device that achieves the required separation by filtration, and that holds the filter medium.

Filter aid

A granular solid added to a filter feed solution to bulk out the suspension and make it more easily filterable. The filter aid of course then contaminates the separated solids, so can only be used for situations where the solids are a waste material, or where the filter aid can easily be removed in a subsequent process. (See also precoat)

Filter medium

The porous material in a filter that does the actual filtering.

Filtrate

The fluid leaving a filter, after removal of suspended material. (See also permeate)

Finishing process

Refers to those processes applied to medium material after its basic structure has been formed, to consolidate it or to modify its surface, such as calendering, coating, singeing.

Flash spun

Material made as for meltblown, but from a mixture of solvent and polymer, so as to produce finer fibres.

Foam

A dispersion of gas bubbles throughout a liquid. If the liquid then sets solid, a very light material is produced, but one of little use to filtration, because the pores do not interconnect. If, however, the foam is reticulated by a chemical or thermal process that breaks down the bubble walls then a useful filter medium can be created. (See also reticulated)

Fouling

The gradual deterioration of a membrane filter's performance, because of the deposition on the surface and within the pores of fine, sometimes slimy materials.

Glass

A synthetic semi-solid material, which can be melted and spun into fibres that make a very good medium for papers for filtration.

Harvesting

The recovery of solid materials from suspension in a fluid, where the recovered solid is valuable, and is the purpose of the filtration.

Heel

A layer of cake that is necessarily left on the surface of a filter medium after the bulk of the cake has been removed, usually because the removal mechanism would damage the medium if it got too close. (See also cake)

Hollow fibre

Filter medium produced in the form of minute tubes, which are bundled together to allow sufficient filter area to be built into a sensibly sized filter.

(Filter) housing

That part of a filter that provides the containment for the process fluid, and which holds the filter medium securely.

Hydroentanglement

The consolidation of a felt by the passage through it of fine jets of water at high speed.

Hydrophilic

Used of filter media through which water flows easily (i.e. the medium surface is easily wetted).

Hydrophobic

Used of filter media through which water does not flow easily (i.e. the medium surface is not wetted).

Impermeable

Cannot be penetrated by any fluid, particle, or molecular or ionic species.

Ion exchange

The transfer of ionic species between solution in a liquid and attachment to a suitably formed resin. A mixed bed (of anion and cation exchange resins) can remove all ions from water.

Knitted, knitting

A knitted fabric is produced by the interlocking of a series of loops made from one or more yarns, with each row of loops caught into the preceding row. Loops running lengthwise are called wales, those running crosswise courses.

Lamination, laminated

Layers of material, laid one on top of another, and then usually bonded together. The most common is a coarse substrate, to which a fine coating layer is laminated.

(Filter) leaf

A filter leaf is formed by fixing two (normally rigid) pieces of filter medium close together (but not touching), and sealing their periphery. Two or more leaves are then mounted one above the other and sealed into a central collecting tube. The whole assembly is placed in a vessel full of slurry under pressure, the filtrate goes into the space between the pieces of media, and then into the central tube. The leaves may be held horizontally or vertically (with cake removal easier in the vertically mounted case).

Lenticular
Lens-shaped, and only convex in form. Used of filter capsules, and such devices when mounted as a stack in a cylindrical housing.

Looped wedge wire
One form of wire format used in wedge wire screens.

Machine direction
A direction in a roll material-making machine that is parallel to the flow of the material (the warp in a weaving loom). (See also cross (machine) direction)

Macrofiltration
A term increasingly being used for all filtration processes down to about 5μm (the start of microfiltration).

Mean pore size
The average diameter of all the pores passing through a filter medium, used the same as effective pore size.

Media migration
See Shedding.

Meltblown
Polymeric filaments, extruded from a spinneret, are broken up by jets of air, and laid down on a moving belt as a mass of fibres. The fibres may also be laid down on a moving core as a cartridge element.

Membrane
Originally implying a thin, microporous or semi-permeable plastic sheet, now applied to any media that are capable of removing particles to below 0.1 μm, whether they be organic or inorganic, flexible or rigid.

Mesh
A geometrically regular material, used for precise sieving, made from wire or plastic filaments by weaving to carefully controlled dimensions.

Metal edge filter
An edge filter where the components are made of metal, a common usage in the automotive sector.

Microfibre
A general term covering the very fine fibres and filaments made by extrusion processes.

Microfiltration
A term defining a range of filtration processes, which cover the size range 5 μm down to 0.1 μm (between macrofiltration and ultrafiltration).

Molecular sieve

A material with extremely fine pores, capable of the adsorption of molecular species, such as water.

Monofilament

A single filament used as the yarn to weave fabrics or meshes.

Moulded

In this context, refers to the formation of media into shapes by moulding – the resultant format may be held in shape by a bonding resin, or by thermal treatment.

Multifilament

A yarn made of a number of filaments, twisted as required.

Nanofiltration

A filtration region fairly recently separated between reverse osmosis and ultrafiltration, both in size of species separated, and in operating pressure.

Napping

A finishing process for fabrics that raises short fibres above the surface of the medium

Natural (fibres, filaments)

Materials derived from animal or vegetable sources: cellulose, cotton, silk and wool in filtration terms, although flax/linen, jute and other fibres are used.

Needlefelt

A felt that has been stabilized and strengthened by needling.

Needling

The processing of felts (and some other non-woven materials) by rapid puncturing of the material with a set of barbed needles.

Non-woven

Any textile fabric made by methods other than weaving and knitting.

Osmosis

The passage of a solvent (usually water) from a dilute solution to a more concentrated solution through a semi-permeable membrane, the driving force being the difference in osmotic pressure across the membrane.

Panel

A flat pad of filter media, held in a simple frame, that may be square or rectangular in shape. Used mainly for air conditioning applications, and sometimes called a cassette.

Paper
A medium made by wet laying of cellulose or glass fibres.

Particle
A small granule of solid material, the basic component of dusts or other suspensions.

Pathogen
Any body capable of transferring disease to humans. Especially bacteria and viruses.

Penetration
The passage of a particle or droplet through a filter medium. The degree of penetration measures the efficiency of the filter.

Perforated, perforation
Usually means sheet material (metal or plastic) in which holes are machined, by drilling or punching. Used for coarse filtration.

Permeable, permeability
Open to the passage of specific components of a mixture. Permeability is a measure of the degree of openness.

Permeate
The clear liquid passing through a membrane, either by diffusion through the body of the material, or passage through continuous pores. (See also filtrate)

Permeation
Processes that operate by separation at a barrier, usually referring to the microscopic scale.

Pervaporation
A membrane separation process for one liquid from another, by passage of one component as vapour through the membrane, with a vacuum maintained on the downstream side.

Plain weave
The simplest form of weaving: over one yarn, then under one, for the entire material.

Plastic
Specifically, any deformable material, but used generically of all synthetic polymeric materials.

(Filter) plate
May refer to a component of a plate-and-frame filter press, which holds the filter medium and the formed cake, or may be an equivalent word to 'leaf', i.e. a rigid structure made from sheets of filter media, sealed at their periphery.

Pleat, pleated

A fold in a piece of filter medium, usually occurring in series, to make a concertina effect, then mounted flat, as in a panel, or made into a cylinder, as part of a filter cartridge. The effect of pleating is greatly to increase the filter area within a given vessel volume.

Pocket

A form of bag, which has a flat oval cross-section (rather than circular), and a rectangular external shape. Often used mounted side by side with others in a panel frame for air conditioning use.

Polishing

A final filtration stage, to remove traces of suspended material left in the fluid by previous processing.

Polymer

One of a wide range of synthetic materials, formed by condensing monomers into long-chain molecules.

Pore

A singe hole passing through a filter medium, by which the fluid crosses it, and which is small enough in diameter not to let pass any material above a certain size, dictated by the pore diameter.

Porous, porosity

Any material through which fluid will flow under pressure. The porosity is a measure of the freedom of this flow.

Precoat

Granular or other particulate material fed into a filter to create the initial cake upon which the main filtration then takes place. (See also filter aid, cake filtration)

Prefilter

A term for the first filter in a series of filtration stages, which is actually no different from the same duty performed on its own. Often used of the filter needed ahead of a membrane process, used to prevent ingress of coarse material that would block the flow channels rather than the medium itself.

Pressure filter

Any filter needing the imposition of a positive pressure upstream, as distinct from gravity- or vacuum-driven filters.

Pyrogen

Any of a group of materials that, upon ingestion by an animal, cause a rise in body temperature.

Rapid sand filter
A deep-bed filter with down flow of fluid at a relatively fast rate, cleaned by backflushing, which expands the bed of sand to release the captured solids.

Recovery
A general term referring to the removal of suspended solids (usually) from a liquid; it implies that the solids are wanted, not wastes.

Resin, resin bonded
An adhesive used to bond together the particles or fibres of a filter medium. May be added as a solid in the medium formation stage, or injected as a liquid, in either case being set at higher temperatures.

Retention
Used in a similar way to 'capture' to refer to the entrapment or the holding back of suspended material by a filter medium.

Reticulated (foams)
Foams that are impermeable as made can be rendered permeable by chemical or thermal methods that erode the cell walls to create pores through the material - the process is reticulation.

Reverse osmosis
The first of the membrane processes, developed mainly for the desalination of brackish and salt water, this uses a membrane under high pressure to allow water to move through, and to hold back any dissolved material in a feed solution. The membrane is impermeable to ionic and most molecular species in solution. The applied pressure must be higher than the natural osmotic pressure of the solution.

Ribbon
A continuous strip of material wound flat in the form of a spiral, so that its outer edges may be used as a filter medium.

Rigidity
The stiffness of a filter medium material, as descriptive of one of its essential mechanical properties.

Rigidized media
Term used to describe a range of polymeric media formed by moulding into shapes resembling bags or pockets, but essentially rigid in their final form.

Ring stacks
A series of flat rings, with suitable indented spacers, stacked one above the other around a central core, so that the outer edges form a filter medium.

Rollgoods
Any material produced (and sold) in rolls, for conversion to suitably shaped filter medium; includes woven and non-woven materials.

Roving
A yarn treatment process, which imparts a slight twist to the yarn as well as compressing it.

Rupture strength
A mechanical property of a medium material, determined by standard tests. Used as equivalent to bursting strength and tensile strength.

Sand
A coarsely granular natural material, used commonly in deep-bed filters.

Satin weave
A complex weave pattern, designed to give a flat surface to at least one side of the material.

Screen
A woven or perforated medium, for relatively coarse separations, usually made with some precision as to the shape and size of the openings.

Screening
A filtration process employing coarse media, possibly for separation of a mixture of solid particles by particle size, or for prefiltration, wet or dry.

Scrim
A strong simple woven material, with yarns well separated, used within a felt to give it tensile strength.

Seam, seamless
The place(s) at which materials are joined to make non-flat media structures. The seam is a region where the porosity of the medium may be very different from the bulk of the medium, so possibly creating a weakness – hence the search for seamless construction of bags, etc.

Semi-permeable
Literally, permeable to some components of a mixture or solution, and not to others. All filter media can be thus described, but the term largely relates to membranes.

Shedding
The loss of particles of the filter medium to the downstream, clean fluid. This is obviously a feature to be avoided, and resistance to shedding becomes an important material parameter. (Also known as media migration.)

(Filter) sheet
A relatively stiff piece of filter medium, usually in the form of a rectangle, and wet laid like paper. Used for depth filtration.

Sieve
Usually refers to the device that holds a screen, and enables screening of solid particles to occur.

Sieve bend
A coarse, but high-flux filter, made from parallel wedge-wire bars, positioned across the direction of liquid flow, which is tangential to the filter surface.

Sifting
The process of separating solid particles by particle size, usually in the dry state.

Silk
A natural material, produced as a very long filament, which has to be untangled.

Singeing
The treatment of a material surface by a flame or contact with a very hot surface, to cause partial melting of the material, and hence to change the surface porosity.

Sintered, sintering
The bonding of powders, fibres or meshes by heating under pressure, to fuse the material at the points of contact. Originally used of metals and ceramics, but now also applied to polymeric materials.

Sleeve
A piece of filter medium formed as an open ended cylinder, which is slid over a cage or core to form a replaceable filter element.

Sliver
A loose, soft, untwisted rope-like strand of textile fibre, having a roughly uniform thickness. It is produced by the carding process, which separates raw fibres to prepare them for spinning.

Slow sand filter
A deep-bed filter, with downward flow at low velocity, with biological action also in the top layer, which is cut off to clean the filter.

Softening temperature
The temperature at which a complex material begins to melt, such that points of contact fuse together.

Solution
A uniform mixture of soluble materials in a solvent, which cannot be separated in a normal filter, but can with suitable membranes.

Spinneret
The working head of an extrusion process, in which a set of fine holes are machined (or a set of fine nozzles fitted), from which a molten material can be extruded under pressure as continuous filaments.

Spinning
A term with two quite different meanings in the present context: the production of yarn from a bundle of fibres, or the production of extruded filaments.

Spiral wound
The winding of a yarn, wire or filament on a core in a spiral fashion, such that successive layers overlie previous layers at an angle. Also refers to the formation of membrane media by setting up several layers of medium and spacers, which are then wound round a central core, so forming a spiral.

Spool wound
The winding of a yarn, wire or filament on a core in any regular fashion, to create a filter element (includes spiral wound).

Spun, spunbonded
The extrusion of molten polymeric materials as filament (melt spun), which filaments are then laid down on a moving belt, and further processed to ensure adequate bonding of the mass of filaments. The filaments may also be laid down on a rotating core to form a cartridge element.

Stability
A number of physical properties of a material that relate to its maintenance in use of its initial performance and design characteristics.

Stack
An array of a set of identical components – discs, rings, capsules – one above the other around a central former of some kind.

Staple (fibre)
Originally used of the naturally occurring fibres, now used of any fibre of the same sort of length (i.e. a few centimetres).

Strainer, straining
A coarse filter, often using a mesh or perforated plate screen as medium, and usually employed to strain out of a liquid flow any 'rogue' large particles, ahead of some other process unit where such particles would be harmful in some way.

Surface filter
A filter that operates entirely by the retention of suspended material on the surface of the medium. This mechanism is rarely found in practice, because all media are actually finite in thickness, and a small part of the retained solid penetrates into that thickness. Membranes come the closest to being exemplars of surface filtration. (See also depth filter)

Suspension
A fluid carrying particulate solids or liquid droplets, as a separate phase, dispersed uniformly throughout the fluid.

Synthetic (fibres, filaments)
Artificial, as opposed to occurring naturally. Usually refers to polymeric materials.

Tangential flow
Equivalent term to 'cross-flow'.

Tex
Unit for the measurement of fibre or filament fineness. Expressed as the weight in grams of 1000 m of the material (and so is dependent upon the material density). (See also denier)

Textile
Any natural or synthetic fibre or filament, or yarn, suitable for making up into fabric or cloth, including the made up materials as well. Covers woven, knitted and non-woven fabrics, as well as threads, cords, ropes, braids, lace, embroidery, and nets. Paper is not considered to be a textile, although some non-woven materials are made from fibres in the same way as paper.

Thermally bonded
The adhesion of fibres, powders, etc., by heating under pressure, so that softening occurs and the material fuses together at the points of contact.

Through-flow
Another term for the flow of fluid through the medium. (See also cross-flow, dead-end)

Track-etching
A process for the creation of membranes, involving irradiation of a polymer film, to create the initial pores, followed by chemical etching to enlarge the pores to the required size.

Tubular
In this context refers to media that are in the form of long rigid tubes of diameters in the region of 1 cm, with a fairly thin wall of filter medium.

Twill weave
A weaving process that produces the characteristic diagonal appearance to the fabric: over two, under one, staggered at each repeat along the warp.

Ultrafiltration
A membrane filtration process that deals with large molecules or colloidal materials; lying between microfiltration and nanofiltration in both degree of fineness of filtration and operating pressure.

Vacuum filter
A filter operated by vacuum as the driving force.

Voidage
The empty space within a filter medium: related to porosity.

Warp
The strands, whether yarn or filament, of a woven material, which run the length of the loom. (For materials that are not woven, but which come from a machine in a similar way, the term 'machine direction' may be used.) (See also weft)

Weave
The pattern by which the warp and weft yarns lie over and under one another.

Web
A thin array of fibres or filaments laid down in the first stage of production of a non-woven material. It may have a directional orientation, or a completely random structure.

Wedge wire
Wire whose cross-section is not round but pressed into a wedge shape.

Weft
The strands, whether yarn or filament, of a woven material, which run across the width of the loom. (The corresponding term to 'machine direction' is 'cross machine') (See also warp)

Wet laid
Wet laying involves the dispersion of relatively short fibres in water, followed by the distribution of the slurry over a porous belt of some kind, such that the water drains away, leaving the wet-laid fibres on the belt. (See also dry laid, paper)

Wet strength
The tensile strength of a fabric or paper when it is completely wet.

Wettability
The ability of a material to be wetted by water (or, in principle, any solvent), and so to allow water to flow though it in a porous form. (See also hydrophilic, hydrophobic)

Wire, wire wound
In addition to its use as a filament in woven meshes, wire can be wound round a core, usually in spiral fashion, to provide a filter element.

Wool
Natural fibres from animal coats, mainly sheep. Fine wool fibre ranges from 4 to 7.5 cm in length, coarse can be up to 35 cm.

Woven
Any material made on a loom from warp and weft threads, normally crossing at right angles.

Yarn, yarn wound
A continuous strand of fibres or filaments grouped or twisted together, and used to make woven fabrics. Can also be wound onto a cylindrical core or former to make a yarn-wound filter element.

Yield
Yield strength and yield point are mechanical properties of materials and may be important in defining the material performance.

Zeta potential
An electrostatic charge on a material that increases its particle retention performance.

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