Handbook of Non-Woven Filter Media

by Irwin Hutten

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Three years ago, I met with Geoff Smaldon of Elsevier Science Ltd. in Detroit, Michigan and we came to agreement on the scope of a book that I agreed to author for Elsevier. “The Handbook of Nonwoven Filter Media” is the result of that agreement. When I undertook this project, I accepted it as a “labor of love” that would fit in with my retirement. What I never anticipated is how much labor there would be to love. A good part of my life for the past 3 years has been devoted to the writing and preparation of the “Handbook”.

The intent of this book was to provide the reader with a fundamental understanding of nonwoven filter media. It provides basic information on how it is made and how it is used. The book is technical in nature. It does not provide marketing or economic information on nonwoven filter media. There are consultants out there whose role is to provide detailed information on filtration markets and it is not the intent of this discourse to undermine the efforts of these people.

Economics is an ever-changing phenomenon. Nonwoven filter media are global products from global industries. World economics is in such a change of flux that any attempt to offer cost and price information even on a relative basis would be very short term and most likely be changed by the time this book was published.

The sources and applications of nonwoven filter media are very broad. The technology is never ending. A complete book could be written on almost every category. This “Handbook” introduces the reader to those categories that I considered significant and justified in writing about.

A guided tour of the “Handbook” starts off with definitions of filtration and separation, nonwovens, and nonwoven filter media in Chapter 1. These definitions were necessary to set the scope of the book. In addition to the filtration of particulate matter from a fluid stream other forms of separation phenomena are included. Among these are adsorption, electrostatic and electrokinetic effects, coalescence, diffusion, osmosis and reverse osmosis, and others.

The definition of nonwoven filter media includes paper or wet lay media specifically designed for filter media applications. This was necessary because paper filter media is the largest tonnage of global nonwoven filter media. It would have been quite awkward to have a satisfactory discussion of nonwoven filter media without including the wet laid forms.

In addition to the definitions, Chapter 1 further classifies nonwoven filter media based on forming process. The two major categories of nonwovens are dry formed and wet laid. The dry formed processes include air laid, dry laid, spunbonded (which
includes solution spun), melt-blown, and electrospun. The wet laid process is not sub
classified.

The mechanisms and theory of nonwoven filter media are presented in Chapter 2.
The theoretical presentation is classical and does not venture into more modern
computerized tools to theorize filter media. Computational Flow Dynamics (CFD) is
mentioned and some examples given. Not discussed are recent computerized presen-
tation techniques, such as three dimensional graphic modeling, animated fluid
flow, and particle separation displays. The theory includes the Monte Carlo tech-
niques of Piekars and Clarenburg[72] to demonstrate web fiber structure and how
poles are defined.

Chapter 3 is an attempt to explain the broad range and variety of the properties of
nonwoven filter media and the broad range and variety of their properties. The
intent is to relate the properties to the use of the medium and provide guidance in its
choice. The properties not only include classical engineering properties such as
strength and rigidity, but also properties such as permeability and pore size that
relate to filtration performance.

To truly understand nonwoven filter media, one must understand how it is made.
Chapter 4 discusses the raw materials of nonwoven filter media and Chapter 5
describes the processes by which nonwoven filter media are made. The raw materials
are subdivided into polymers, fibers, resins, and additives (finishes). The processes of
Chapter 5 not only include the forming processes by which nonwoven filter media is
classified, but also the downstream converting and finishing operations. For example,
the needle punching and/or hydroentanglement of carded webs are well described.

Since so much of nonwoven filter media is used in a pleated cartridge or pleated panel
form, the various pleating processes are detailed.

The test methods pertinent to nonwoven filter media are discussed in Chapter 6.
The methods are presented in a way to help the reader understand the property
being tested. For example in the section on strength properties, the stress–strain
curve is presented to help the reader identify and understand the relationship of
each of the strength properties to the medium. While many of the tests described are
medium sheet tests, also discussed are some of the pertinent filtration tests where
the medium is tested as part of a filter.

Applications of nonwoven filter media are broken down into Liquid Filtration
(Chapter 7), Air Filtration (Chapter 8), and Engine Filtration (Chapter 9). Engine fil-
tration is concerned with filters for automobiles, heavy duty vehicles, off-the-road
equipment, and rotating machinery. It includes both air and liquid filtration and is of
sufficient market size to justify its own chapter.

I felt it was important to identify those organizations that are involved in develop-
ing, coordinating, promulgating, revising, amending, reissuing, interpreting, certi-
fying, regulating, or otherwise maintaining standards that are related to filtration
and filter media. This was done in Chapter 10. The list is by no means complete, but
does present a representative spectrum of those organizations involved. Many of the
worldwide standards applicable to nonwoven filter media are tabulated. Included is
the Table of Contents for the very recent (2005) INDA–EDANA harmonized test
methods for the nonwovens industry[199].
In the world of nonwovens, words are everything. A number of words are bandied about that have different meanings to different people. Sometimes they are used in the wrong context. For example, many people use the word porosity when they mean permeability. These two words are related to each other; however, they are two different properties of nonwoven filter media. Another example is a number of words describing the distribution of particles in a fluid. Included are words such as sol, aerosol, emulsion, latex, dispersion, suspension, and solution. In many cases they are used interchangeably and wrongfully. The primary purpose of the Glossary is to provide the reader with meanings of words that he may not be familiar with, and to provide specific definitions to confusing words.

In the writing of this book my literature search consisted of over 200 references, most of which are listed in the bibliography. The bibliography references are numbered more or less in the order in which they appear in the book. In the text they are identified by a superscript number enclosed in parenthesis.

The literature search was handicapped by my location in Georgia which was 100 miles away from the nearest technical library at the Georgia Institute of Technology (Georgia Tech) in Atlanta, Georgia. Fortunately, the Internet provided a wealth of information—much of it free. Most purchased articles were obtained through the Internet services of Nerac. The American Filtration and Separation Society was kind enough to provide me with copies of its conference proceedings for the 10 previous years.

The following books were of great help:

*Encyclopedia Britannica*

It is amazing as to how often this book had to be consulted.

A “Handbook” like this could not be written without the assistance of a lot of people. In acknowledging these people, I will first mention a small group of personal friends whose help and assistance were very important to me. These are Dr. Norman Lifshutz.
Mary Pierce, Tim Young and Bob Murphey, Hollingsworth & Vose, Dr. Larry Wadsworth, University of Tennessee, Joseph Israel and Michael Madden, Donaldson Company and Ed Homonoff, Edward C. Homonoff and Assoc.

There is a larger group of associates who went beyond the envelope in order to provide me with consultation and information and help me with copyright permissions; some of these people I know very well and some I have never even met other than telephone and email communication. Included in this group are Suzanne Sower, AFSS, Mary Beth Cornell, TAPPI, Ian Butler, INDA, Dr. Roy Broughton, Auburn University, Dr. Randall R. Bresee and Chris Eash, TANDEC (University of Tennessee), Hans-Georg Geus, Reicofl, Holly Hill, Kaydon, Dr. Jim Fredericks, IPST, Christine Murray, PGI, Dr. Leonard Bensch, Pall Corporation, Dr. Pius Trautmann, MANN+HUMMEL, Pat Svoboda, Evanite, Neville Bugli, Visteon Corp., James Hanson, MTS Publications, Alan Veeck, NAFA, Ron Cox and Stephanie Earley, Kimberly-Clark, Jeff Riggi, Glens Falls Interweb, Tom Burke, KX Industries, Kristine Graham, Donaldson Company John Scrivener, Frazier Isruments, LeGrande Crook, J.D. Hollingsworth on Wheels, Tom Savage, W.I. Gore and Associates, Ben Russell, Metso Paper, Dr. Ernest Mayer, Dupont, and Digvijai Singh, a2z Filtration Specialties.

In addition to the above, there were a large number of people who took the time from their work to make some form of contribution to the "Handbook". This might have been an advisory discussion, help with copyright permission approval, providing me with contacts and/or providing me with technical information from their organization. For this help I acknowledge the following:

I must acknowledge the assistance I received from the personnel at Elsevier who worked with me from beginning to end. Geoff Smaldon was indeed a most pleasant and satisfactory contact for most of this time. It is unfortunate that he retired before the “Handbook” was completed. Jonathon Simpson, his successor helped me nurture the “Handbook” to publication. There were several people who helped me through the editing and proof stages. These were Lyndsey Dixon, Charlotte Dawes, Debbie Clark, and Lisa Jones. Charon Tec (A Macmillan Company) and its team was responsible for the typesetting.

It would be very unfair not to mention my family who were so very patient and understanding with me throughout the writing of this “Handbook”. I have dedicated the “Handbook” to my wife Susan, but other family members also helped out. This included our sons Ethan and Scott Hutten, Scott’s wife Laura Hutten and of course, grandson baby Lucas Hutten.

Whatman: Gary Pelletier
Elsevier: Geoff Smaldon, Jonathon Simpson,
Charlotte Dawes, Lisa Jones
Table of Contents

Preface, Pages xiii-xvii

Chapter 1 - Introduction to Nonwoven Filter Media, Pages 1-28

Chapter 2 - Filtration Mechanisms and Theory, Pages 29-70

Chapter 3 - Properties of Nonwoven Filter Media, Pages 71-102

Chapter 4 - Raw Materials for Nonwoven Filter Media, Pages 103-194

Chapter 5 - Processes for Nonwoven Filter Media, Pages 195-244

Chapter 6 - Testing of Nonwoven Filter Media, Pages 245-290

Chapter 7 - Liquid Filter Applications, Pages 291-324

Chapter 8 - Air Filter Applications, Pages 325-367

Chapter 9 - Engine Filtration, Pages 369-392

Chapter 10 - Standards for Nonwoven Filter Media, Pages 393-414

Nomenclature, Pages 415-422

Glossary, Pages 423-443

References, Pages 445-455

Index, Pages 457-473
CHAPTER 1

Introduction to Nonwoven Filter Media

1.1 Introduction

Nonwoven filter media in their simplest forms are random fiber structures, usually in sheet form, that are used to separate one or more phases from a moving fluid passing through the media. Filtration is generally perceived as the removal of particulate phases from the moving fluid by entrapping the particulate matter in the tortuous structure of the filter medium. However, the discussion to be presented in this book will also include other forms of separation where a nonwoven is used as the separating media. This will include adsorption, absorption, extraction coalescence, electrostatic effects, and antimicrobial activity.

To define the scope of this handbook it is necessary to define filtration and separation, nonwovens, and filter media.

1.2 Filtration and Separation Defined

INDA, the Association of the Nonwovens Fabrics Industry (Butler1) explains filtration as follows:

"Filtration is a mechanism or device for separating one substance from another. Filtration may be used to separate contaminants from a fluid or separate value-added materials, such as minerals, chemicals, or foodstuffs in a process operation."

Separations can be broadly classified into six categories:

5. Gas–liquid separations.

Except for “solids–solids separations” each of these separation processes will be discussed in more detail in later sections of this book. Solid–solid separations are achieved by screening larger solid particles from a solid mixture containing smaller particles. In certain cases, the separation can also be achieved by magnetic separation. The author is unaware of any significant use of nonwoven media in solid–solid separations; therefore, this form of separation is outside the scope of this book and will not be discussed. Applications of nonwoven in the other forms of separation have been identified and will be discussed within the scope of this book.

The author will use the Encyclopedia Britannica(2) definition of a fluid as follows:

“any liquid or gas or generally any material that cannot sustain a tangential, or shearing, force when at rest and that undergoes a continuous change in shape when subjected to such a stress.”

It should be noted that by this definition, both gases and liquids are considered as fluids.

Separations are not limited to the filtration of solid particles from a fluid by entrapment within the matrix structure of the medium. Other forms of separation are mentioned in the introductory statement above and further discussed in Section 1.3.

Note that in the brief description of Nonwoven filter media (refer to Section 1.1 above), the fluid is moving and passes through the medium. This implies a driving force to force the fluid. Usually this force is a pressure differential induced by gravity, a vacuum, capillary action, a pump, a compressor, a fan, or a blower. Other forms of driving forces may also apply. For example, a thermal gradient may cause the fluid to pass through a media going from hot to cold. The driving force may be a concentration gradient forcing diffusion. A teabag is an example of a “diffusion filter”. Hot water extracts soluble taste components from the tea leaves contained within the bag. The soluble taste components then diffuse through the tea bag media into the greater body of hot water. In some cases, voltage potentials may force the flow of electronic charged particles to the filter surface. In air filtration this may be caused by electrostatic effects. In water filtration this could be the result of electronic or electrokinetic effects involving a Zeta potential.

1.3 Nonwovens Defined

Table 1.1 lists definitions of nonwovens from various sources. There has been a great deal of difficulty and controversy in the attempt to define nonwovens. A large part of this is due to the desire to differentiate nonwovens from paper. An early definition in The Manual of Nonwovens by Krcma in 1971(3) (Table 1.1, Number 1) failed to make this distinction.

Later definitions excluded paper from the definition of nonwovens, but did not set up any criteria for differentiating nonwovens from paper. Batra et al.(4) developed a structure-based definition as listed in Number 8 of Table 1.1. The definition listed is
### Table 1.1 Definitions of Nonwovens

<table>
<thead>
<tr>
<th>Number</th>
<th>Source</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><em>Manual of Nonwovens</em></td>
<td>“nonwoven 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 oriented 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 them with a mechanically bound or chemically bonded textile product.”</td>
</tr>
<tr>
<td>2</td>
<td><em>Annual Book of Standards, 1989, ASTM International</em></td>
<td>“nonwoven fabrics” A structure produced by bonding or interlocking of fibers, or both, accomplished by mechanical, chemical, thermal, or solvent means and the combination thereof. The term does not include paper or fabrics that are woven, knitted, tufted, or those made by wool or other felting processes.</td>
</tr>
<tr>
<td>3</td>
<td><em>Man-Made Fiber and Textile Dictionary</em></td>
<td>Nonwoven fabric: An assembly of textile fibers held together by mechanical interlocking in a random web or mat, by fusing of the fibers (in the case of thermoplastic fibers), or by bonding with cementing medium such as starch, glue, casein, rubber, latex, or one of the cellulose derivatives or synthetic resins. Initially, the fibers maybe oriented in one direction or may be deposited in a random manner. This web or sheet of fibers is bonded together by one of the methods described above. Normally, crimped fibers are used which range in length from 0.75 to 4.5 inches. Nonwoven fabrics are used for expendable items, such as hospital sheets, napkins, diapers, and wiping cloths, as the base material for coated fabrics, and in a variety of other applications. They have also been used for semi-disposable items and for permanent items such as in underlinings and similar end uses.</td>
</tr>
<tr>
<td>4</td>
<td>“Nonwovens: Theory, Process, Performance, and Testing,” Chapter 2: Nonwoven Terminology</td>
<td>Nonwoven: A manufacturing sheet, web, or batt of directionally oriented fibers, made by bonding or entangling fibers through mechanical, thermal, or chemical means. They exclude paper and products which are woven, knitted, tufted, or felted by wet milling. The fibers may be of natural or man-made origin.</td>
</tr>
<tr>
<td>5</td>
<td><em>The Dictionary of Paper, Fourth Edition</em></td>
<td>Nonwoven fabric: A cloth like material made of fibers longer than those normally used in papermaking which, instead of being woven on a loom, is formed by felting on a line mesh screen from an air or water suspension with or with out binders.</td>
</tr>
<tr>
<td>6</td>
<td><em>Nonwoven Fabrics, Handbook (INDA)</em></td>
<td>Nonwoven: A sheet, web, or batt of natural and/or man-made fibers or filaments, excluding paper, that have not been converted into yarns, and that are bonded to each other by any of several means.</td>
</tr>
</tbody>
</table>

**Notes**

To distinguish nonwovens from papers, a material shall be defined as a nonwoven if:

- More than 50% by mass of its fibrous content is made up of fibers (excluding chemically digested vegetable fibers) with a length to diameter ratio greater than 300; or
- More than 30% by mass of its fibrous content is made up of fibers as in “a” above and meeting one or both of the following criteria:
  - Length to diameter ratio more than 600.
  - The density of the fabric is less than 0.4 g/cc.

(Continued)
<table>
<thead>
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<th>Number</th>
<th>Source</th>
<th>Definition</th>
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| 7      | ISO 9092: 1988 (extract) from EDANA web site\(^{(6)}\) | Nonwoven: 
A manufactured sheet, web or batt of directionally or randomly orientated fibres, bonded by friction, and/or cohesion and/or adhesion, excluding paper (see note) and products which are woven, knitted, tufted, stitch-bonded incorporating binding yarns or filaments, or felted by wet-milling, whether or not additionally needled. 
The fibers may be of natural or man-made origin. They may be staple or continuous filaments or be formed in situ. 

Note: 
To distinguish wet laid nonwovens from wet laid papers, a material shall be regarded as a nonwoven: 
- if more than 50% by mass of its fibrous content is made up of fibers (excluding chemically digested vegetable fibers) with a length to diameter ratio greater than 300; or 
- if the conditions in 1) do not apply, then if the following conditions are fulfilled: 
  - more than 30% by mass of its fibrous content is made up of fibers (excluding chemically digested vegetable fibers) with a length to diameter ratio greater than 300 
  - and 
  - it's density is less than 0.40 g/cm\(^3\) 

Reproduced with permission of EDANA, Brussels, Belgium |
| 8      | A New System for Classifying Nonwovens, TAPPI Press\(^{(5)}\) | Structure-based definition of nonwoven: 
- Fiberweb structures: Includes all textile sheet structures made from fibrous webs, bonded by frictional/mechanical restraints and/or covalent bonds obtained through the use of resins, thermal fusion, or formation of chemical complexes. Here, fibers or filaments are bonded so that the average bond-to-bond distances are greater than 50-100 times the fiber diameter giving textile-like qualities of low bending and low in-plane stiffness. 
- Net-like structures: Structures formed by extruding one or more fiber-forming polymers in the form of a network or film. The film may then be uniaxially or biaxially oriented to fibrillate into a net-like structure. 
- Multiplex structures: This class of fabrics combine and utilize characteristics of several primary and/or secondary structures, at least one of which is a recognized nonwoven textile structure, into a single unitized structure. 

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that as reported by Hansen\textsuperscript{11}. Batra et al. excluded paper by specifying the fiber length between bond points.

Both INDA\textsuperscript{11} (Table 1.1, Number 6) and EDANA\textsuperscript{60} (Table 1.1, Number 7), whose definition is based on ISO 9092:1988, apply criteria based on fiber $L/D$ (length/diameter ratio), and bulk. Both definitions exclude chemically digested vegetable fiber content.

In effect a nonwoven is differentiated from paper if:

1. 50\% of its mass is composed of fibers whose $L/D$ is 300 or greater (chemically digested vegetable fibers excluded)

or

2. INDA – 30\% of its mass is composed of fibers whose $L/D$ is 600 or greater (chemically digested vegetable fibers excluded) or 30\% of its mass is composed of fibers whose $L/D$ is 300 or greater and its density is less than 0.4 g/cm$^3$ (chemically digested vegetable fibers excluded).

EDANA – 30\% of its mass is composed of fibers whose $L/D$ is 300 or greater (chemically digested vegetable fibers excluded) and its density is less than 0.4 g/cm$^3$.

Note that INDA and EDANA differ in that INDA allows a nonwoven to be defined as such if it contains 30\% by mass of fibers having an $L/D$ ratio of 600 or higher, whereas EDANA makes no allowance for the higher $L/D$ ratio fibers.

Nonwovens are generally perceived as being formed by a dry form process where aerodynamics, mechanical devices, and spinnerettes are used to form the web. On the other hand, paper is formed from a water medium using a wet lay or paper machine process. There are wet lay products that satisfy the INDA and/or EDANA definitions and are recognized as nonwovens. This includes glass fiber paper media (including glass microliber paper), and wet laid substrates with high percentages of synthetic long fibers such as those of nylon and polyester. Wet laid media made from inorganic fibers such as carbon, ceramic, and metal might also satisfy the definition provided they meet the bulk requirement of less than 0.4 g/cm$^3$.

The INDA and EDANA definitions allow for the use of natural fibers, however, if they are chemically digested, they cannot be counted as long fibers. This exclusion eliminates certain types of wet laid long fiber media normally perceived as being nonwoven. An example would be teabag paper made from chemically digested abaca (Manila hemp) and/or sisal. There are long natural fibers that are not chemically digested and used to make nonwoven webs, mats, and batts that satisfy the INDA and EDANA definitions. Examples are cotton, wool, sisal, hemp, abaca, and certain forms of kenaf. Indeed these fibers have the historical significance of being the origins of nonwoven materials. There is a reviving interest in natural fibers for nonwoven webs, because they are biodegradable and relieve environmental concerns about their disposal. In addition, during times of global oil crisis and/or shortages, natural fibers may present economical alternatives to petrochemical based synthetic fibers. The development of nonwovens from natural fiber sources are also motivated by the economics of synthetics derived from petrochemical sources.
Some forms of wood pulp are not chemically digested (e.g. groundwood), however they are very short fibers and do not meet the $L/D$ ratio requirements for nonwovens. The wood pulp fibers used for making paper normally have an $L/D$ ratio of less than 200/1.

Some dry formed products do not necessarily satisfy the definitions of nonwoven. Examples are the absorbent webs and other products produced on an air laid machine. These webs are formed from hammer milled wood pulps and adsorbent materials that have very low $L/D$ ratios. They generally have a minimal amount of long fibered synthetics depending on product design and application.

The author understands the importance of having a distinction between nonwovens and paper. However, there is a great deal of gray area in the distinction. In addition, there is a great deal of cross lapping in the market place and in the technology of filter medium products. Nonwoven and paper products compete with and/or complement each other in many filter and separation applications. Many composite structures contain both nonwoven and paper components. Several filter medium manufacturers produce both nonwoven and paper media and do not differentiate their products by the nonwoven definition. Almost every nonwoven conference that includes sessions on nonwoven filter media will have discussions and presentations concerning paper media. Although, the title of this book is the *Handbook of Nonwoven Filter Media*, the author finds it awkward and difficult to present an adequate discussion of the topic without including paper structures. Therefore for purposes of this book the author accepts the definition of nonwoven as proposed by INDA (Table 1.1, Number 6) arbitrarily modified to include:

"Any wet laid structure, including paper, whose specific purpose is to be a medium in a filtration and/or separation application."

### 1.4 Definition of Filter Media

The *Filtration Dictionary and Glossary* (Wakeman[11]) defines filter medium as “any permeable material used in filtration and upon which, or within which, the solids are deposited.” Sutherland and Purchas[12] argue that this definition is not broad enough. The glossary in their handbook defines filter medium as “The porous material in a filter that does the actual filtering.” In Chapter 1 of their handbook they broaden the definition as follows:

“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 Purchas and Sutherland definition is consistent with the purposes of this handbook, because it allows for other possible separation processes other than simple particle entrapment. Examples of other types of separation media are as follows:

#### 1.4.1 Adsorbent media

Filter media containing adsorbents remove liquid and soluble contaminants from fluid streams by surface adsorption, i.e. the contaminants are attracted to the surfaces
of the medium and held their by physical chemical effects. Activated carbon is a common adsorbent used in filter media. In liquid filtration it is used to remove hydrocarbons and bad taste contaminants from drinking water. It is also used to remove toxic and obnoxious chemicals from air such as in gas masks and respirators. In military affairs adsorbents such as activated carbon are used to protect both military personnel and civilians from the toxic effects of chemical agents. Other adsorbent materials used in filter media include activated alumina, zeolites, ion exchange resins, and baking soda (sodium bicarbonate). Adsorbent media are gaining widespread use in automotive cabin air filters where they are effective in removing vile odors and emission fumes. In recent years adsorbents have become a significant medium in HVAC (heat, ventilation, air conditioning) systems in the workplace and in the home.

1.4.2 Absorbent media
Whereas an adsorbent medium removes contaminants from a fluid stream by surface effects, an absorbent medium removes the contaminants by absorbing them into the porous structure of the medium; much as a sponge soaks up water from a wet surface. Nonwovens are often used with absorbent structures, to contain the absorbent material and to act as a transport layer for fluid to flow to the absorbent material. However, absorbent structures such as diaper fluff, hygienic pads, and wipes are not considered as filter media, because there is no separation involved. On the other hand, some materials are selective. Polyolefins, although hydrophobic, have an affinity for oil and are often used to absorb oil from water. Polyolefin materials are often used to control oil spills at sea.

Very often absorbency is an undesired quality in a filter medium. The tendency of cellulose media to absorb water tends to soften and weaken the filter structure and shorten filter life. In addition, the absorption of moisture causes fiber swelling and interference with filtration performance.

1.4.3 Coalescing media
Coalescence is a process by which a filter medium can remove immiscible liquid particles from a liquid or gas stream. This includes dispersed hydrocarbons from water, oil mists from air, moisture and vapor from air, and moisture from aviation fuel. The phenomenon is a particulate filtration, in that it requires a matrix of fine fibers to trap the liquid particles and hold them on the fibers. An additional effect is required. Provision has to be provided for the transport of the entrapped liquid particles so that they can be removed from the media as a separate stream, either by a flotation or gravity settling mechanism.

1.4.4 Electro-filtration
Filter media and/or fibers for filter media can be electrostatically charged to enhance their filtration properties. Although it can be argued that electrostatic media still removes particles by filtration, the author considers this a different type of separation because a different technology is introduced. Charged fibers and/or filter media are often referred to as electrets. Electrets are dielectric materials that exhibit an
external electric field in the absence of an applied field. When used in air filtration applications, they can greatly increase initial filtration efficiency and reduce pressure drop. Electrostatic media has become an important entry into air filtration markets.

Electrokinetic filtration is used in liquid applications. The medium is given a positive electronic charge that enables it to attract the mostly anionic particles in a polar fluid stream. Cuno Incorporated, (a 3M Company) markets an electrokinetic media identified as “Zeta Plus®”.

1.4.5 Antimicrobial media

Antimicrobial filter media contains an agent to protect the filter by inhibiting the growth of bacteria, fungi, and yeast. In some cases the antimicrobial action is also intended to prevent the migration of biological microorganisms into the filtrate or filtered product. The antimicrobial agent can be applied to a medium as a finishing step or it can be incorporated into the fiber.

1.4.6 Extraction

Extraction is a phenomenon that is not built into a filter medium, but rather the medium serves as a structural support for the extraction process. A coffee filter is a good example. Hot water extracts the soluble coffee taste components from the coffee grinds supported in the coffee filter medium. The coffee rich water passes through the medium, however the grinds are retained. Teabag and tea filters act in a similar manner.

1.4.7 Filter support

There are applications where a medium does not do the filtering but acts as a support structure for the medium that does. Certain types of nonwoven media such as melt-blown and electrospun media are generally too thin and weak to provide for their own structural integrity. They require a stronger material such as a woven fabric, spunbond, needle punch felt, or cellulose web to provide mechanical strength for the application. Very often metal mesh materials are used for this purpose.

In many applications membrane filters are supported by a nonwoven structure. Membrane filter media are not considered within the scope of this “Handbook”, however the nonwoven support structures are within the scope.

In many cases, a medium used to provide mechanical support to a filter medium also participates in the filtration process. Often the support layer is a prefilter layer for the more efficient filter medium it is supporting, resulting in a gradient density filter medium – a filter medium composed of two or more layers; each layer being successively more efficient than the previous layer.

1.4.8 Composite structures

The supported filter media discussed in Section 1.4.7 above are examples of composite structures. Robert Murphey, of Hollingsworth & Vose Co. defines composites as
"Two or more different web technologies that are combined to optimize the characteristics of a filter medium." Composites provide the opportunity to bring more than one separation process into one medium. They are further discussed in Section 1.7.3.

1.5 Nonwoven Filter Media Defined

Combining the discussion points of Sections 1.2–1.4 the following definition of a nonwoven filter medium emerges:

A nonwoven filter medium is a porous fabric composed of a random array of fibers or filaments and whose specific function is to filter and/or separate phases and components of a fluid being transported through the medium or to support the medium that does the separation. The fabric is a sheet-like structure produced in lengths long enough to be wound into rolls. Although the random fiber structure is the backbone of the web, it may contain other components that are part of the forming process including (but not limited to) particulate fillers (clays, calcium, adsorptive powders, etc.), sizing agents, wet strength agents, antimicrobial additives, plasticizers, dyes and pigments, softening agents, and wetting agents.

It is implicit in the definition that the fibers and filaments be bonded in some form or fashion. The formed fabric may be bonded as it is formed. An example is the hydrogen bonding of cellulose fibers in webs formed by the wet lay process. Nonwoven webs may also be bonded by a process downstream of the fabric former that is either in-line or off-line with the forming process. The downstream bonding process may include any of the following: fiber entanglement either by needle punching, by hydroentanglement or by stitch bonding; water-based latex treatment; solvent-based resin treatment; and thermal bonding. As long as the web is a random fiber structure to be used for filtration and/or separation, the specific bonding process is not critical to the definition.

The fabric may be exposed to other chemical and mechanical treatments to enhance its properties. Examples are coatings and finishes, flame retardants, antimicrobial agents, water repellents, dyes, and softening agents. It may also be exposed to downstream mechanical conversions such as creping, corrugating, embossing, slitting and rewinding, pleating, bag making, sheeting, dye cutting, and stamping as necessary for the end use filter and/or separator application.

1.6 What Is Not a Nonwoven Filter Medium

The definition of nonwoven filter media above defines the scope of this handbook. Among the many types of filter media that are not within the scope of this book are:

- Woven filter media
- Screens (metal, plastic, etc.)
- Sintered metals – except when the source is a nonwoven medium of metal fibers
- Sand bed filters
- Membrane filter media
- Cake filters
Membrane filter media are not considered as nonwovens; however they are often supported by a nonwoven substrate and/or preceded by a nonwoven prefilter medium. Such applications of nonwovens will be part of the scope of this handbook. In addition, nonwoven media are sometimes used as support structures for bed filters. These applications of nonwoven media will also be included.

### 1.7 Classification of Nonwovens by Process

Nonwovens are best classified by process, because each process produces a unique class of nonwovens utilizing different raw materials and/or different forms of the same raw materials. There are two major process groups for forming nonwovens; dry formed and wet laid. A simple distinction between the two groups is that in dry formed processes the webs are formed in an air medium, whereas in the wet lay process the webs are formed in water.

There are five major dry formed processes:

1. Air laid
2. Dry laid (carding operations)
3. Spunbonded
4. Melt-blown
5. Electrospun.

Wet laid processes are similar to the processes for making paper, and the machines for producing wet laid webs, particularly filter paper, are referred to as paper machines. Highly porous filter papers and webs formed from long fibers require specially designed paper machines. They are often referred to as wet lay machines.

Table 1.2 shows various filter applications, the types of filter medium products, the process, conversion factors, and types of fibers. The interesting thing about Table 1.2 is that almost every type of media can be used in almost every application.

Following are short descriptions of each process. More detailed descriptions will be found in Chapter 5.

### 1.7.1 Dry formed processes

#### 1.7.1.1 Air laid

Air laid structures, mostly formed from cellulose fluff pulp, are generally used for absorbent materials such as diaper fluff or personal hygienic pads. The fluff pulp is hammer milled into individualized fibers, which are then air conveyed to a moving belt or forming wire to be formed into a fabric. Short cut or staple synthetic fibers such as polyester, polypropylene, Nylon, Rayon, etc. can also be fed into forming area. Super absorbent polymers (SAP), such as carboxy methyl cellulose (CMC) are often incorporated. Composite structures can also be formed. The air laid former
<table>
<thead>
<tr>
<th>Forming Process</th>
<th>Application</th>
<th>Medium Type</th>
</tr>
</thead>
</table>
| **Dry Laid**   | Industrial air filter (bags) | 1. Needle-punch and spunlace  
2. Membrane w/felt support |
|                | Industrial fume | Needle punch and spunlace – heat and chemical resistant |
|                | Air dust | Glass microfiber |
|                | Paint spray booth | High loft mat |
|                | Furnace and ventilation | 1. High loft  
2. Mat from polyester, cotton, hogs hair, coir, filament glass, fibrillated film and/or etc. |
| **General ventilation** | | 1. High loft panel or mat  
2. Monofilament glass mat  
3. Phenolic treated glass mat |
| **Vacuum bag** | | Needle-felt, electrostatic |
| **Air Purifier** | | Needle-felt, electrostatic |
| **Turbine and rotating machinery (bag)** | | 1. Needle-felt or spunlace  
2. Nanofiber w/felt support – electrostatic  
3. Membrane w/felt support |
| Milk filter | | Resin bonded |
| Beverage – beer and wine (bag) | Needle-felt |
| Belt filters | | Scrim reinforced needle felt – chemical and mechanical finishes |
| Roll filters | | Chemical bonded, needle punched, or spunlace |
| **Spunbond** | Cartridge dust filter | Polyester and nylon |
| Furnace and ventilation | Panel filters – polyester, nylon, and/or polypropylene |
| **Residential ventilation – panel** | | Gradient density |
| **Respirator** | | Activated carbon layer |
| **Cabin air filtration** | | Activated carbon layer |
| **Turbine and rotating machinery (cartridge)** | | Pleated |
| Milk filter | | Polyester |
| Beverage – beer and wine (bag) | Polyester |
| Beverage – beer and wine (cartridge) | Pleated |
| Swimming pool filter | Pleated – antimicrobial |
| Roll filters | Rolls slit to size |
| **Melt-Blown** | Residential ventilation (panel and pocket filters) | Composite w/support substrate |
| Surgical face mask | Laminated composite |
| Respirator | Composite |
| Vacuum bag | Composite w/resin treated paper |
| Micron rated filter bag | Composite w/needle-felt |
| Depth filter | Pleated |
| Pleated cartridge | Melt-blown w/support medium |
| **Electrospun** | Ventilation filters - panel | Nanofiber – Cellulose support |
| Cabin air filtration | Nanofiber – Cellulose or synthetic fiber support |

(Continued)
<table>
<thead>
<tr>
<th>Forming Process</th>
<th>Application</th>
<th>Medium Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum cleaner</td>
<td>Nanofiber – Cellulose support</td>
<td></td>
</tr>
<tr>
<td>Turbine and rotating machinery (bag)</td>
<td>Nanofiber – needle-felt or spunlace felt support</td>
<td></td>
</tr>
<tr>
<td>Wet Laid</td>
<td>Cartridge dust filter</td>
<td>Resin treated paper</td>
</tr>
<tr>
<td></td>
<td>Clean room filters and prefilters (pleated and mini-pleat)</td>
<td>Resin bonded glass microfiber (ASHRAE, HEPA, and ULPA)</td>
</tr>
<tr>
<td></td>
<td>Clean room filters and prefilters (pocket)</td>
<td>Glass microfiber (ASHRAE, HEPA, and ULPA)</td>
</tr>
<tr>
<td></td>
<td>Work station filters</td>
<td>Resin bonded glass microfiber (ASHRAE, HEPA, and ULPA)</td>
</tr>
<tr>
<td></td>
<td>Ventilation, high efficiency, pleated</td>
<td>Resin bonded glass microfiber (sometimes anti-microbial)</td>
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<tr>
<td></td>
<td>Surgical face mask</td>
<td>Laminated glass microfiber</td>
</tr>
<tr>
<td></td>
<td>Respirator</td>
<td>1. Glass microfiber laminate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Impregnated with activated carbon</td>
</tr>
<tr>
<td></td>
<td>Vacuum bag</td>
<td>1. Resin treated paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Melt-blown/resin treated paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Nanofiber/cellulose support</td>
</tr>
<tr>
<td></td>
<td>Vacuum cleaner cartridge</td>
<td>Glass microfiber – HEPA</td>
</tr>
<tr>
<td></td>
<td>Air purifier</td>
<td>4. Glass microfiber – ASHRAE or HEPA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Glass microfiber/synthetic blends</td>
</tr>
<tr>
<td></td>
<td>Automotive air intake</td>
<td>Resin treated cellulose</td>
</tr>
<tr>
<td></td>
<td>Heavy duty air</td>
<td>Resin treated cellulose</td>
</tr>
<tr>
<td></td>
<td>Turbine and rotating machinery (cartridge)</td>
<td>1. Resin treated cellulose</td>
</tr>
<tr>
<td></td>
<td>Cigarette filter wrap</td>
<td>2. Glass microfiber</td>
</tr>
<tr>
<td></td>
<td>Teabag</td>
<td>Treated cellulose</td>
</tr>
<tr>
<td></td>
<td>Coffee filter</td>
<td>Abaca fiber – sometimes thermo-bond fiber – high wet strength</td>
</tr>
<tr>
<td></td>
<td>Milk filter</td>
<td>High wet strength paper</td>
</tr>
<tr>
<td></td>
<td>Beverage - beer and wine (cartridge)</td>
<td>1. Resin treated cellulose</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Cellulose – synthetic blend</td>
</tr>
<tr>
<td></td>
<td>Cooking oil</td>
<td>Sheeted – sometimes diatomaceous earth</td>
</tr>
<tr>
<td></td>
<td>Swimming pool</td>
<td>Pleated – resin treated cellulose antimicrobial</td>
</tr>
<tr>
<td></td>
<td>Laboratory</td>
<td>1. Wet strength – cellulose</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Wet strength – high purity cellulose</td>
</tr>
<tr>
<td></td>
<td>Industrial filter paper</td>
<td>3. Glass microfiber</td>
</tr>
<tr>
<td></td>
<td>Filter sheets</td>
<td>Wet strength cellulose, sometimes creped - sheeted and/or die cut</td>
</tr>
<tr>
<td></td>
<td>Filter presses</td>
<td>Cellulose, D.E. filled, cationic charge</td>
</tr>
<tr>
<td></td>
<td>Engine oil filter</td>
<td>Industrial filter and/or filter sheets</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1. Resin treated cellulose</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Resin treated blend of cellulose, polyester, and sometimes microglass fiber</td>
</tr>
<tr>
<td></td>
<td>Fuel filtration</td>
<td>Resin treated blend of cellulose, polyester fiber and glass microfiber</td>
</tr>
</tbody>
</table>

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Table 1.2 (Continued)

<table>
<thead>
<tr>
<th>Forming Process</th>
<th>Application</th>
<th>Medium Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel filter coalescer</td>
<td></td>
<td>Resin treated blend of cellulose and glass microfiber</td>
</tr>
<tr>
<td>Fuel filter coalescer separator</td>
<td></td>
<td>Resin treated cellulose with Teflon or silicone treatment.</td>
</tr>
<tr>
<td>Composites</td>
<td>Industrial air filter (Bags)</td>
<td>1. Membrane w/felt support</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Scrim reinforced needle-felts and scrim reinforced spunlace felts</td>
</tr>
<tr>
<td>Composites</td>
<td>Industrial fume</td>
<td>PTFE membrane w/felt support</td>
</tr>
<tr>
<td></td>
<td>Cartridge dust filter</td>
<td>Needle punch and spunlace felt membrane support</td>
</tr>
<tr>
<td></td>
<td>Residential ventilation (panel and</td>
<td>1. Melt-blown composite</td>
</tr>
<tr>
<td></td>
<td>pocket filters)</td>
<td>2. Electrospun composite</td>
</tr>
<tr>
<td></td>
<td>Surgical face mask</td>
<td>3. SM or SMS composites (spunbond/melt-blown)</td>
</tr>
<tr>
<td></td>
<td>Respirator</td>
<td>1. Laminated melt-blown composite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Laminated glass microfiber</td>
</tr>
<tr>
<td></td>
<td>Vacuum Bag</td>
<td>1. Electrospun nanofiber w/wet lay support</td>
</tr>
<tr>
<td></td>
<td>Air purifier</td>
<td>Glass microfiber or glass microfiber/synthetic blends w/cellulose or synthetic fiber support</td>
</tr>
<tr>
<td></td>
<td>Automotive cabin air</td>
<td>1. Melt blown composites – electrostatic</td>
</tr>
<tr>
<td></td>
<td>Turbine and rotating machinery (bag)</td>
<td>2. Electrospun nanofiber composites</td>
</tr>
<tr>
<td></td>
<td>Belt filters</td>
<td>Felt supported nanofibers – electrostatic</td>
</tr>
<tr>
<td></td>
<td>Micron rated bags</td>
<td>Scrim reinforced needle-felt</td>
</tr>
<tr>
<td></td>
<td>Reverse osmosis prefilter</td>
<td>Laminated melt-blown/cellulose composite</td>
</tr>
</tbody>
</table>

often has an in-line bonder for applying latex binder. If the web produced contains a considerable amount of long synthetic fibers, the web can be Spunlaced (hydroentangled). Figure 1.1 is a flow diagram of the air laid pilot machine at MTS Testing Laboratories in Kalamazoo Michigan. The machine utilizes a Dan–Webb former produced by Dan–Webb in Aarhus, Denmark.

Although air laid webs are bulky structures that would appear to be likely candidates for filter media, the author is unaware of any major filtration market area that utilizes this type of media.

1.7.1.2 Dry laid webs and felts
1.7.1.2.1 Forming of dry laid webs
Dry laid forming is the process for forming many of the carded webs and felt materials used in filtration. The process has been well described by Crook[13]. A more
detailed discussion is also found in Chapter 5, Section 5.1.2.1. Both carded webs and felts are produced on similar types of equipment. High loft webs used in HVAC systems are usually thermo-bonded. In some cases they are chemically bonded. Felts produced by the layering of carded webs are usually much heavier in grammage. Needle punched felts are a major media source in filtration markets. Woven fabrics and needle punched felts are the largest source of filter media for baghouse filter operations. In recent times some applications have replaced needle punched felts with spunlace (hydroentangled) versions. Lately, baghouse operations have started switching to cartridge filters in place of felt and woven media bag filters.

Dry laid webs are differentiated from air laid webs by the nature of raw materials and the way they are handled by process. Air laid webs are primarily composed of cellulose wood pulp fibers and possibly a partial content (up to 20%) of staple fibers. Wipes and absorbent pads for hygienic products are important production items of the air laid process. On the other hand, longer staple fibers are the majority fiber source for dry laid structures. Very often, these are crimped fibers. In air laid processes
Introduction to Nonwoven Filter Media

Notes: Fiber bales in this line consist of polyester and rayon. Optomix® is a bale opening machine. MTO is a Micro-Tuft Opener that reduces fiber tuft size. FS/52 is a fiber accumulator. Flockfeed is used for additional fiber opening. Condenser is a barbed roll that accepts opened fiber and delivers it into the air stream for processing downstream toward the web former.

Figure 1.2. Dry laid nonwovens line layout. Reproduced with permission of TAPPI, Atlanta, Georgia, USA. p. 155.

Hammer mills and aerodynamic action are utilized to separate, individualize, and disperse the fibers and form them into a web. Dry laid processes also utilize aerodynamic action to form webs, however a considerable amount of mechanical processing is also utilized to individualize, disperse, and orient the fibers and to form them into webs.

Figure 1.2 is a layout of a typical dry-laid line. The core of the dry laid process is the card or a related machine called the garnett. Both consist of a series of rolls containing barbed point surfaces. The barbed points on the surfaces are obtained by coating the rolls with spirally wound saw-tooth wire often referred to as metallic clothing. The saw-tooth points are engineered to have specified heights, pitches, and angles. Fiber is carded when it passes between two or more metallic coated surfaces moving at different speeds and having their points in opposite directions. A combing action takes place that parallelizes the fiber. One of these surfaces is the main cylinder; the other is a smaller worker roll or a stationary plate with a barbed surface. Other types of rolls perform various other functions in the process. These includes stripping rolls that help breakdown fiber tufts, likerin rolls that feed fiber to the main cylinder from the feed bin, and doffer rolls that remove the fiber from the main cylinder. There are also condensation and randomizing rolls that serve to cross orient and randomize the fiber. A detailed discussion of card rolls and their purposes is presented in Chapter 5.
In addition to cards and garnetts a dry-laid line will include bale opening machines, blending machines, and machines to feed the cards (or garnetts). There may be two or more cards, each one forming a separate layer combined with the previously formed layers. The layering allows for different properties between layers, such as fiber orientation. It also allows for different fiber compositions in each layer. Another method for building layers is cross layering. Cross layering is accomplished by folding formed webs that are delivered by a conveyor into a lapper, which continuously transfers the web unto an apron operating at right angles to the cross layering motion. This is a way to obtain thick webs for heavyweight felted materials.

The process requires a device for forming the final web. This could be the output of the cards or garnetts. There are also air laid formers that form webs from carded fibers coming from the cards. A very popular such former is the Rando Webber® produced by Rando Machine Corporation. This machine is further discussed in Chapter 5.

It should be noted that the Rando Webber® is often used to form dry laid webs directly from bale opening equipment. Although cards are not used, the product is still considered a dry laid fabric, rather than an air laid fabric because the forming action of a Rando Webber® tends to be mechanical rather than aerodynamic. This is because barbed surfaces such as rolls and aprons are used to distribute the fiber unto the moving forming fabric.

### 1.7.1.2.2 Bonding of dry laid webs
Following is a brief review of the various methods to bond carded webs. More detailed discussions will be found in Chapter 5.

#### 1.7.1.2.2.1 Needle punch
Needle punching is a process by which fibers are entangled and mechanically interlocked by puncturing the web with a series of barbed needles. The density and strength of the web can be regulated by the strokes per minute of the web, the advance rate of the web, and the degree of penetration of the needles. Needle punched webs are one of the more popular filter media for dust collection systems (baghouse and cartridge).

#### 1.7.1.2.2.2 Hydroentanglement (spunlace)
Hydroentanglement bonds webs in a manner similar to needle punching, except that very high velocity water jets, instead of needles, are used to entangle the fibers. In recent years, spunlaced webs have developed as an alternative to needle punched webs in air filtration applications.

#### 1.7.1.2.2.3 Stitch bonding
Stitch bonding is a mechanical method of consolidating fiber webs by using knitting elements with or without yarn to interlock the fibers. In brief, a yarn is stitched through the fabric in a way that can impart very interesting properties. Quilted fabrics are often made this way. For example Lycra® will impart stretch properties such as in Ace bandages. Stitch bonded webs are used in filter applications such as vacuum bags.
1.7.1.2.2.4 Thermal bonding

Webs containing low melting thermoplastic material can be thermal bonded to consolidate the web. Usually the low melting material is fibers or bicomponent fibers, however thermoplastic powders are used in some applications. Following are some forms of thermal bonding:

Calendering or embossing: The heated web is squeezed between two rolls (either smooth or patterned) which forces intimate contact of the molten fibers with other fibers in the web. Often the rolls themselves are heated. If the rolls are smooth (calendering), the web is uniformly bonded. If the rolls are patterned, an embossed web results where bonding is most intense in the dense areas of the embossed structure. Spot bonding is accomplished in this manner. Embossing results in a soft bulky web, because the areas between the bond points are unbonded. Figure 1.3 is an illustration of a pattern bonded filter medium produced by Fiberweb™.

Through air bonding: The web is thermally bonded by passing the web through an air dryer or heater. The results are a bulkier and loftier web. High loft filter media are produced in this manner.

Ultrasonic bonding: This relatively new technology utilizes high intensity ultrasonic energy to melt and form bonds from thermoplastic fiber. The ultrasonic bonding is like stitch bonding in that it takes place along narrow lines in the web. It is also a way of producing quilted structures.

1Synergex™ and Fiberweb™ are trademarks of Fiberweb™.
Hot melt bonding: A hot melt thermoplastic is extruded unto the web and while still in the molten stage, penetrates and bonds the web.

1.7.1.2.2.5 Chemical bonding
Chemical bonding involves the use of a chemical binder or resin to bond the web. Water-based latex binders are the most commonly used resin binders for dry laid webs. Application of a latex binder to a web requires a drying process to follow the application. Additional heat may be necessary to cure the resin. Following are ways of applying the latex:

- Saturation
- Spray bonding
- Print bonding
- Spot bonding
- Froth binder application
- Curtain coating.

The process methods of applying latex binder to a nonwoven filter media are discussed in more detail in Chapter 5, Sections 5.1.2.3.5 and 5.2.3.2.

1.7.1.3 Spunbonded
There are several spunbonded systems all of which can be represented by the generic of Figure 1.4 as described by Malkan and Wadsworth\(^{(14)}\). The process involves the extrusion of molten polymer to a die block. The die block consists of a polymer flow control assembly and a spinnerette. The spinnerette is a block of metal having several thousand drilled holes. Molten polymer forced through the spinnerette is formed into filament fibers. The spun fibers are rapidly cooled and drawn by a succession of air streams through a venturi. Downstream of the venturi the filaments pass through a distributing chamber which effects fanning and entangling of the filaments. The randomness of the web is greatly affected by turbulence of the air in the distributing chamber. The entangled fibers are then deposited by suction unto a moving foraminous belt. The movement of the belt and the suction below the belt enhances calendar or embossing roll to achieve thermo-bonding. Finally, the bonded web is rolled up on a wind-up stand.

Polymers generally used in the spunbond process are polyester (Reemay\(^{®}\)), nylon (Cerex\(^{®}\)), polyethylene (Tyvek\(^{®}\)), and polypropylene (Typar\(^{®}\) and Tekton\(^{®}\)). Polyurethane and rayon have also been successfully spun into spunbonded webs. The trade names mentioned are those that were identified with the materials when originally introduced. Currently, there are at least 80 different trade names for spunbonded filter media.

Other manufacturers of spunbond systems are Kohle and Mineraloltechnik GmbH of Gernay (Docan System) and Carl Freudenberg Co. of Germany (Lutravil System).

A variation of the spunbonded process is flash spinning. A solvent solution of high-density polyethylene is extruded through the spinnerette and the solvent quickly evaporated causing the filaments to form a highly fibrillated form before they are deposited
on a screen. The web is thermally bonded with a calender roll to form a strong fabric. It is by this process that the polyethylene spunbonded known as Tyvek® is produced. Tyvek® in itself is generally too dense to be used as a filter medium, however a variation to this is a series of filter grades, marketed by DuPont, known as SoloFlo®.

1.7.1.4 Melt-blown
Melt-blown webs are formed directly from a molten resin. They are similar to spunbonded webs in that thermoplastic polymers are extruded through a spinning die, to form filaments. They are different from spunbonded webs in that high velocity, heated air, injected near the die tips, converges with the filaments to attenuate them to very fine diameters. The attenuated filaments are quenched with cool air and collected on a moving collector screen. The attenuated filaments are generally 1–4 μm in diameter and form a very uniform web at low grammages. Figure 1.5 is diagram of the typical melt-blown process.

Polypropylene and polybutyl terephthalate are the most frequently used polymers used for producing melt-blown webs.
The principal difference between melt-blown and spunbonded webs is that the
melt-blown process produces a webs composed of finer filaments. Melt-blown webs
are generally softer and weaker than spunbonded webs. Melt-blown webs are often
used in a composite or laminated form combined with a supporting web or material
to provide strength and stability. Butler\textsuperscript{14-2} estimated that two-thirds of melt-blown
consumption is used in composite form. The largest volume composite structures
are spunbonded/melt-blown structures. More will be said about composite struc-
tures in Section 1.7.3 below and in Chapters 3 and 5.
The fine fiber structure of melt-blown webs makes them ideal candidates for high
efficiency filter media, both in liquid and air filtration applications.

1.7.1.5 Electrospun process
In 1934 Anton Formhals\textsuperscript{15} was the first inventor to patent an electrospinning phe-
nomenon. Electrospinning is a process that produces nanofiber webs by applying a
high voltage charge to a polymer solution or melt and using the charge to draw the
solution from the tip of a capillary to a grounded collector. Voltages range from 5 to
30 kV, sufficient to overcome the surface tension forces of the polymer. The free sur-
face of the charged polymer produces very fine jets of liquid that are rapidly drawn
to the grounded collector. The effect causes substantial drawing of the rapidly solid-
ifying fibers as they approach the grounded collector. The highly attenuated fibers
collect on a moving surface passing over the grounded collector and form an inter-
connected web of small filaments. The fiber diameters for filtration purposes are in
the range of 0.25 μm. The webs are of very fine thickness (on the order of 1 μ or less)
and have limited mechanical properties. The moving surface on which they are
collected is usually a substrate that will provide strength and stability for subsequent
processing. Very often the substrate will be a nonwoven chosen specifically for the fil-
tration application. Figure 1.6 is a schematic of the process. Figure 1.7 is a scanning
electron microscopic (SEM) image of a nanofiber web on a polyester substrate.
Currently, air filtration applications are the significant markets for electrospun nanofiber webs. This includes engine air intake filters, turbine air filters, pulse filters for dust collection systems, and vacuum bag filters. A good discussion on the air filtration applications is provided by Graham et al.\textsuperscript{116}
1.7.2 Wet laid

Essentially all filter media that are identified as “paper” filter media, are made by the wet laid process. The wet lay process is essentially a paper machine process. A considerable amount of nonwoven that satisfies the INDA definition is produced by the wet lay process. The wet lay process produces most glass fiber media used in filtration. Wet lay machines are known to form webs up to 5 m wide and at speeds exceeding 300 m/min. They generally handle short fibers of 6 mm or less, however commercial products from the wet lay process have been produced with fibers as long as 35–50 mm. In addition to wood pulp and natural fibers, the wet lay process can also handle fibers of polyester, nylon, rayon, glass, Kevlar®, Nomex®, graphite, and any other material whose fiber can be reasonably dispersed in water. The largest filter product volume from the wet lay process is resin bonded filter media. This is the type that is usually pleated into cartridge filter elements.

1.7.2.1 Forming of wet lay webs

Figure 1.8 is a diagram of the wet end of a typical wet laid process line. The wet end is a process for dispersing fiber into aqueous slurry called stock and feeding it to the headbox of the web former. The headbox is a device to feed the diluted stock to a forming screen where it is formed into a wet sheet. The dry end of the wet lay machine consists of a combination of mechanical and thermal devices to remove moisture and dry the sheet into a nonwoven or paper media.

Just as the card is the core of the dry lay process, the headbox is the heart of the wet lay process. Paper, some nonwovens and microglass fiber media are formed by a
traditional type of paper machine headbox called the Fourdrinier headbox. Filter media made from long synthetic fiber and difficult to disperse furnishes are produced on headboxes specially designed for this purpose. Two of the most common are the Rotoformer® headbox and the inclined wire headbox. Glens Falls Interweb (GFI) in Glens Falls, New York manufactures both. The Rotoformer® forms the sheet on a wire covered rotating drum. The inclined wire headbox (trade named by GFI as the Delta Former®) forms the sheet on the incline of the wire as it passes through the pond. Voigt-Dorries in Germany also manufactures inclined wire formers under the trade name Hydroformer®. These machines operate at much lower stock consistencies than do traditional paper machines. Chapter 5 describes in greater detail the operation of wet lay headboxes.

After the wet lay sheet is formed, mechanical and thermal devices remove water and dry the sheet. Mechanical devices include wet presses, foils, and suction slots. Most water is removed by thermal drying. The thermal devices are usually hot air dryers, hot air ovens, and steam heated dryer cans. Infrared and microwave drying technologies are also utilized. Usually, wet lay drying systems use a combination of these devices.

1.7.2.2 Bonding of wet laid nonwovens
Wet laid nonwoven webs can be bonded by adding a bonding agent to the fiber slurry before formation (wet end or beater addition) and/or by passing the web through a resin applicator after formation. Bonding can also be achieved by incorporating thermal bonding fibers in the fiber furnish.

1.7.2.2.1 Beater addition
Beater addition or beater ad is the papermaker’s term for adding additives and resins to the fiber stock slurry. Several types of resins or chemical agents can be added to the fiber slurry or stock to enhance the strength of the web after it is dried. Most often, these are cationic agents that use ionic chemistry to be attracted to the negatively charged anionic fibers. If the additive is a latex binder, a complex system of retention aids is used to retain the latex particles on the fiber surfaces. Similar types of chemistry can also be used to retain solid fillers such as clays and activated carbon powder. Cationic wet strength agents are frequently used to give the medium enough strength to be transported through the wet lay machine and through subsequent aqueous treatments. They also make the medium strong enough for aqueous filtration applications. Sheeted filter media used in plate and frame industrial filtration applications are often referred to as high wet strength filter paper. Coffee filter paper is another example of filter medium bonded with a wet strength agent.

1.7.2.2.2 Resin application to the web
Most wet laid nonwovens used for filter medium applications are resin bonded after the web is formed. The resin treatment is intended to provide the desired structural properties so that the web can be converted to the end use filter application and have the integrity to stand up to the hostile challenges of the filtration environment.

Resin can be applied to the web either in-line with the wet lay machine or off-line in a separate operation. Either way, the most common form of resin applicator is the
size press. There are many versions of size presses. Two versions, the vertical size press and the horizontal size press are discussed in Chapter 5, Section 5.2.3.2 and diagrammed in Figure 5.29.

1.7.2.2.3 Thermal bonding fibers
Binder fibers can be included in the fiber furnish. This includes polyvinyl-alcohol-type fibers such as Kuralon®, vinyon (polyvinyl chloride fiber) and other low melting thermal bonding fibers. In more recent times, bicomponent fibers have come into vogue for this purpose. An established technology is sheath-core fibers with a low melting sheath.

1.7.2.3 Converting processes for wet lay webs
A number of converting processes are applied to wet lay media as necessary for their end use filtration performances. Included are corrugating, rewinding, slitting, creping, sheet cutting, die cutting, pleating, bag making, and other operations that alter the mechanical structure and geometrical surface of the web. In addition to resin, there are other chemical treatments that add to web properties. Among them are flame retardants, water repellents, extenders, surfactants, adsorbents, and antimicrobial agents. The various converting operations for filter media will be discussed in Chapter 5.

1.7.3 Composite structures
There are many, many examples of composite filter media including web supported membranes and electrospun media. Many needle felts are reinforced with a scrim to provide structural integrity in the filtration application. Kimberly-Clark has pioneered the SMS (spunbond/melt-blown/spunbond) process and variations thereof. Composite structures can combine layers of different density media to form gradient density media. Some structures are designed to provide different separation modes in a single filter media. For example, automotive cabin air filters often combine a nonwoven particulate filter layer with an activated carbon layer to remove odors and fumes.

Following are some of the purposes of composite structures:

1. One or more layers provide mechanical support for the layer or layers doing the filtering.
2. One layer serves as a prefilter layer for the layer doing the final filtering.
3. The different layers are organized in a way to provide gradient density depth filtration. Each layer has a different bulk and filtration efficiency to develop a gradient density medium, i.e. as the fluid and contaminants move through the medium, each layer provides a higher level of efficiency to remove smaller and smaller particles.
4. Different separation technologies are combined into one filter medium. In the example mentioned above for cabin air filters, an activated carbon layer is

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2 Kuralon® is a trade name of Kuraray Co., Inc. Japan.
combined with one or more nonwoven layers, whereby the nonwoven layers
do particulate filtration and the activated carbon layer separates molecular
contaminants by adsorption.
5. The outer layers serve as a containment to inhibit medium migration, dust-
ing, and particle fallout from the inner layers.

It should be noted that for a medium to fit the definition of a composite structure it
must be "layerized". For example, there are technologies for combining activated car-
bon particles into the fibrous structure of a single web. Although such a web may
combine the technologies of particulate filtration and adsorption, it is not a compos-
ite structure. Likewise, in such cases where additional properties are applied to the
web by the use of coatings or impregnants (examples are flame retardants or water
repellents), the structure remains a single layer structure and is not a composite.

Not all the layers of a composite are necessarily nonwovens. One or more of the
layers could be a membrane material, a woven material, or a plastic or metal mesh
material to provide structural support. Figure 1.9 illustrates the cross-section of a
filter medium that contains a stainless steel mesh for structural support.

![Figure 1.9. Nonwoven filter medium reinforced with a stainless steel scrim.](image)
Reproduced with permission of Städtisches Textilforschungsinstitut e.V. Chemnitz, Germany.

Needless to say, the combination possibilities for nonwoven composite structures
are endless.

Just as there are numerous combinations for composite structures, there are also
numerous ways for them to be combined. Some examples are:

1. Laminating: Two or more layers are unwound from unwind stands and combined
   into a composite structure. The layers are bonded to each other by adhesive appli-
   cation, thermal bonding, or by inherent Van der Waals or electrostatic forces.
2. Fiber entanglement: It occurs between layers by needle punching or hydro-
   entanglement.
3. **Multilayer forming:** This can be done in wet lay processes as well as dry formed processes.

4. **Combined process forming:** Kimberly-Clark’s SMMS (spunbond/melt-blown/melt-blown/spunbond) technology is a good example of combining different layers by different processes to form a composite structure.

5. **Using one layer:** As a collector for forming the other layer(s).

A more detailed discussion of the composite processes will be found in Chapter 5.

### 1.8 The Challenges of Nonwoven Filter Media

In Table 1.3 Mayman and Homonoff \(^{[17]}\) have identified over 10 major filtration segments and 36 sub-segments. It can be seen that filtration provides an important function in protecting life, materials, equipment, and the environment.

<table>
<thead>
<tr>
<th>Air filtration segments</th>
<th>Liquid filtration segments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Building/indoor air quality</strong></td>
<td><strong>Commercial</strong></td>
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<tr>
<td></td>
<td><strong>Residential</strong></td>
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<tr>
<td></td>
<td><strong>Institutional</strong></td>
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<tr>
<td><strong>Transportation</strong></td>
<td><strong>Automotive</strong></td>
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<td></td>
<td><strong>Heavy duty</strong></td>
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<tr>
<td><strong>Industrial processes</strong></td>
<td><strong>Power generation</strong></td>
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<tr>
<td></td>
<td><strong>High temperature dust collection</strong></td>
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<tr>
<td></td>
<td><strong>Ambient/mid-range temperature dust collection</strong></td>
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<tr>
<td><strong>Personal protection</strong></td>
<td><strong>Industrial face mask</strong></td>
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<tr>
<td></td>
<td><strong>Medical face mask</strong></td>
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<tr>
<td></td>
<td><strong>Respirators</strong></td>
</tr>
<tr>
<td><strong>Vacuum cleaner bags</strong></td>
<td><strong>Machining and metalworking</strong></td>
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<tr>
<td></td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td><strong>Electronics and equipment</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Medical (including devices)</strong></td>
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</tbody>
</table>

Reproduced with permission of Angelika Mayman and Ed Homonoff.
The two of the most important reasons for filters and separators are:

1. Remove undesirable contaminants from a fluid stream.
2. Recover the contaminant because it has value.

The two reasons may very well overlap. For example, contaminants may be recovered from a stream, not so much as to clean up the stream but rather to dispose of the contaminant in some manner other than with the stream. For example, sludge is recovered from sewage streams so that it can be incinerated or land filled.

Very often protection is the goal of a filter. The purpose may be to protect an inside environment from the contamination of an outside environment or to protect the outside environment from contaminants of the inside environment. To illustrate, high efficiency particulate air (HEPA) filters were first developed for nuclear processing facilities to provide a barrier against any radioactive dust or contaminants leaking to the outside world. Now they are just as likely to be used in clean room applications where the goal is to prevent even the minutest amount of contaminant from the outside world to enter the workplace.

The fluid stream to be filtered may be liquid or gas. For gas filters the fluid is most often air. There are other applications where gases other than air are filtered. Examples are process filters for gaseous fuels such as natural gas and propane, and specialized filters for the manufacture of special gases such as oxygen, nitrogen, helium, hydrogen, etc. However the needs for nonair filters are quite small compared to the demands for air filtration. On the other hand, the markets for liquid filtration can be substantially divided into filtration of aqueous fluids and the filtration of hydrocarbon fluids. Hydrocarbon fluids include fuels, engine lubricants, hydraulic fluids, cooling fluids for metal working operations, and edible oils.

Elaflherakis defines an “ideal” filter as follows:

- Removes all contaminants, regardless of size.
- Has no restriction, $\Delta P = 0$.
- Has infinite dust holding capacity, lasts forever.
- Is infinitely small, takes up no space.
- Costs nothing, price = $0.00$.

Obviously, within all these idealisms there has to be some room for compromise. It becomes apparent that to design a filter and a medium for that filter one has to consider:

1. The properties of the fluid being filtered, including its viscosity, temperature, and its chemical properties such as corrosiveness.
2. The properties of the contaminant including its particle size and concentration.
3. The desired performance of the filter:
   (a) Filtration efficiency
   (b) Flow resistance
   (c) Filter life
   (d) Size.

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The first thing a filter has to do is filter the contaminants in the fluid. If the contaminant is a particulate material, it can be sure to come in a broad range of particle sizes. Figure 1.10 illustrates the particle size range of several types of particles and airborne contaminants. The medium designed for removing larger particles such as pollen, spores, larger bacteria, and dust will be different than the medium for smaller particles such as viruses, tobacco smoke, and fumes. Generally, the smaller the particle, the finer is the fiber in the medium to filter it, and the higher will be the cost. It is established that electret medium produced from electro-charging techniques can enhance the filtration of fine particles. In liquid filtration, cationic charged media has been established as an effective way of improving liquid filter performance.

The nature of the medium changes even more severely when the particles are in the molecular size range. In this size range are the gas contaminants in air and the soluble components in a liquid. Media to remove molecular contaminants have to be designed with capabilities for ultrafiltration, nanofiltration, reverse osmosis, and/or adsorption. Figure 1.10 illustrates the particle size range of several air-borne contaminants in air.

![Figure 1.10. The sizes of contaminants in air.](image)

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2.1 Filtration Mechanisms

2.1.1 Types of filtration mechanisms

Sutherland and Purchas\textsuperscript{12} describe four fundamental filtration mechanisms: surface straining, depth straining, depth filtration, and cake filtration. Following is a brief description of each one:

Surface straining: The particle is larger than the pores and simply cannot pass through. Particles smaller than the pore diameters pass through the medium and are not separated. This type of separation is generally not associated with nonwoven fabrics but rather with media that has uniform pore openings. Examples are woven mesh fabrics, screens and membrane materials where the openings are uniform in diameter.

Depth straining: This applies to felts and nonwoven materials that are relatively thick compared to pore diameters, and where the pore diameters are quite variable in their length. The particles penetrate the pores until they reach a necking point where the diameter becomes smaller than the particle and at this point the particle is trapped in the pore.

Depth filtration: Depth filtration is different from depth straining. It involves mechanisms for removing a particle from a fluid even though the particle may be smaller than the diameter at any point in the pore structure. The mechanisms for doing this are discussed in Section 2.1.2.

Cake filtration: Cake (or surface) filtration involves the capture of particles on the surface (or near the surface) of a filter medium so that the build-up of particulate matter into a layer of filter cake, participates in the filtration process. Surface modified needlefelts and other media used in baghouse dust collection systems operate in this manner so that pulsing or reverse flow cleaning operations would allow for easy removal of the cake and reuse of the filter media. In some chemical operations this is important because the cake has value and its recovery is the intended purpose of the filtration. In many operations where a filter aid such as diatomaceous earth is used, the filter cake becomes the filter medium and the nonwoven serves as the support. Plate and frame filter presses often operate in this manner.
2.1.2 Mechanisms of particle capture

Most theories concerning nonwoven filter medium are based on a depth filtration effect. This is more complicated than simple screening or sieving where the particle is simply bigger than the hole in the medium and cannot get through. Depth filtration and separation theories are more concerned with other mechanisms for particle capture. These are:

1. **Inertial impaction** occurs when the particle inertia is so high that it has sufficient momentum to break away from air streamlines and impact the fiber.
2. **Interception** occurs when a particle does not have sufficient inertia to break away from the streamline, however comes close enough to the fiber so that natural forces will attach the particle to the fiber. For mathematical treatment, Lastow and Podgorski\(^{(19)}\) define interception as follows “A particle is intercepted by a particle when the distance from the center of mass of the particle to the fiber surface is equal or less than the radius of the particle.”
3. **Diffusion** is based on the Brownian (zig zag) motion of very small particles (<0.5 μm). This random and probabilistic motion will cause a particle to vary from the streamline and possibly engage a fiber.
4. **Electrostatic attraction** is based on an electric or electrostatic charge on the particle and/or fiber that will force the particle to be diverted from the streamline and attracted to the fiber.

Figure 2.1 is a classic illustration of the various mechanisms.

![Figure 2.1. Mechanisms of particle capture.](image-url)
The dominant capture mechanism is related to particle size. Very small particles exert Brownian motion and are subject to capture by diffusion. Large particles have more momentum. They are more likely to break loose from the fluid streamlines and be captured in accordance with the inertia mechanism. For small particles, there is a particle size in the range of 0.04-0.4 μm, that is too large for substantial diffusion effects and yet too small to have sufficient momentum for inertial effects. Particles of this size are the most difficult to capture by a filter medium. They are referred to as the "most penetrating particle size" (MPPS). Efficiency ratings in EN 1822-1, the European standard for HEPA and ULPA media, are based on MPPS.

There are numerous examples of MPPS in the literature. Figure 2.2 is an example chosen from a presentation by Goldsmith. The high efficiency filter medium was a synthetic fiber web. The challenge contaminants include three different oil aerosols, latex spheres, and a commonly used solid particulate, potassium chloride (KCl). Figure 2.2 shows that the MPPS is different for each contaminant. The MPPS is also velocity related and will decrease in size as the velocity is increased. This is indicated by the representation of Spurny (p. 14) in Figure 2.3. Note that the MPPS at 50 cm/s is smaller than the MPPS at 10 cm/s. Also note that the range of particle sizes in Spurny's display is of smaller diameters than the range in Goldsmith's presentation.

The suggestion from Spurny's Figure 2.3 is that in addition to an MPPS there is also for a small particle size a velocity of maximum penetration. Note that Spurny includes the inertia mechanism with the interception mechanism. Ramskill and Anderson reviewed the theories of Irving Langmuir and noted that he had assumed that the inertial effect was not significant. In their paper, the diagram of Figure 2.4 demonstrates the three mechanisms and suggests that inertial effects are more significant than Langmuir previously supposed. Ramskill and Anderson provided data to support this contention. Davies supported this contention with his data. The diagram of Figure 2.4 suggests that for small particles below the velocity of maximum penetration, diffusion dominates.

1 See Chapter 8, Section 8.3.2.1 for a discussion of EN1822-1.
Figure 2.3. Most penetrating particle size separation mechanisms.
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Figure 2.4. Qualitative picture of filtration mechanisms.
the separation process. Above this velocity the competing process of inertia begins to dominate. Note that Ramskill and Anderson have the interception mechanism independent of velocity.

2.1.3 Reentrainment and medium migration

It is rational to think that as the velocity of a particle increases, its momentum will make it more vulnerable to capture by the fibers of a nonwoven media. In real life testing, this effect is confounded by the effects of reentrainment and medium migration. Reentrainment is the result of particles that originally attach to the fiber surfaces being blown free by the "wind" forces of the fluid flowing through it. Medium migration is the release of "fines" or small fibers and particles in the medium structure that were there as residue from the manufacturing process. They also confound efficiency measurements and the cleanliness of the exiting stream. The tendencies of reentrainment and medium migration tend to increase with increasing fluid velocity.

2.1.4 Membrane processes

The mechanisms discussed in Section 2.1.2 are generally applied to air and aerosol filtration. Processes for fine filtering and/or separation of contaminants in liquid fluids are microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. These are generally membrane processes, although very high efficiency nonwovens composed of fibers in the nanofiber category are often used for microfiltration and ultrafiltration purposes. Following is a description of the membrane separation processes.

2.1.4.1 Microfiltration
Microfiltration is used for the filtration of particles and finely suspended solids down to less than 0.1 μm (100 nm). The process operates at relatively low pressures (1–4 bars – 100–400 kPa). Liquid clarification and sterile filtration are two applications of microfiltration.

2.1.4.2 Ultrafiltration
Ultrafiltration starts to bridge the gap between particulate filtration and molecular filtration. The particle size filtration range is roughly from 0.004 μm to 0.1 μm (4–100 nm). Ultrafiltration rejects finer particulates such as viruses and molecules of basis weight greater than 10,000. Process pressures are in the range of 5–10 bar (500–1,000 kPa). Ultrafiltration applications include separation of macromolecular solutions.

2.1.4.3 Nanofiltration
Nanofiltration is a form of reverse osmosis (see Section 2.1.4.4) for the separation of molecules in the 300–1,000 molecular weight range and for larger ions such as Ca$^{2+}$ and Mg$^{2+}$. The size range for particle and molecule separation is approximately 0.0012–0.012 μm (1.2–12 nm). The pressure range is 20–40 bar (2,000–4,000 kPa).
The separation of small organic compounds and selected salts from solutions, are applications of nanofiltration.

2.1.4.4 Reverse osmosis
Reverse osmosis is not so much a particulate separation process as it is a process to separate ions from water. It utilizes a membrane that is under very high pressure, 30–60 bar (3,000–6,000 kPa) and impermeable to most molecular species in the solution. The back pressure must be sufficient to overcome the natural osmotic pressure of the solution, so that water will flow from the high salt concentration side of the membrane to the dilute side. The size range of the molecules to be separated is approximately from 0.0015 μm (1.5 nm) to less than 0.0005 μm (0.5 nm). A major application of reverse osmosis is the desalinization of brackish water.

2.1.4.5 Membrane process summary
Figure 2.5 is a summary of the major membrane separation technologies.

2.2 Filtration Theory

2.2.1 Flow dynamics
Nonwoven filter media are porous media and the theories concerning flow through porous media apply. There are two major avenues of theory concerning nonwoven filter media: channel theory and cell model theory. A variation of cell model theory is drag model theory. The original channel theory was based on filtration through nonfibrous packed beds such as sand. Often referred to as the capillary tube model, it assumes that the media is a bundle of cylindrical tubes passing from one surface of the media to the other surface, and not necessarily perpendicular to the surfaces. Channel theory can be applied to nonwoven filter media used in liquid filtration, particularly if the medium is a tight structure with a high packing density.

Much of cell model and drag model theories were developed for fibrous air filter media. They are based on flow past a single fiber and the organization of fibers that compose the media. They are best applied to open structures of low packing density. For nonwoven media, the fibers are represented as cylinders. Cell model theory assumes an array of circular cylinders, each cylinder contained in a cell of fluid surrounded by cylindrical envelopes. Each cylinder with its fluid and envelope is treated as a cell. Drag model theory, the variation of cell model theory, analyzes the drag on each envelope.

Cell model theory is applicable to liquid filtration. Wakeman and Tarleton\(^2\) discuss the cell model work of Happel\(^{25}\) and Happel and Brenner\(^{26}\) in regards to liquid filtration where the medium is an assemblage of spheres. They report that the Happel Model\(^2\) closely agrees with channel theory and is superior at low packing densities.

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\(^2\)The work of Happel in developing cell model theory for fiber or cylinder structures is presented in Section 2.2.3.3.
Figure 2.5. Summary of membrane liquid filtration processes.
The criterion is the packing density or solidity of the medium, i.e. the volume of solids in the medium per unit volume of medium. Schaeffer\(^{(27)}\) summarizing the comments of several investigators, indicated that channel theory would apply to solidities greater than 0.2. Cell model theory and/or drag model theory is preferred for solidities less than 0.2. Cell model theory is most commonly used for the theoretical development of air filtration.

### 2.2.2 The equations of motion and continuity

The equations of motion and continuity are the fundamental equations from which filtration theory is derived. The simplified and abbreviated explanations below are based on Bird, Lightfoot, and Stewart\(^{(28)}\). Chapter 3 of this classic textbook contains a comprehensive teaching of the two equations for isothermal systems including the equation of mechanical energy.

#### 2.2.2.1 The equation of continuity

The equation of continuity is simply a mass balance of a fluid flowing through a stationary volume element. It states that the rate of mass accumulation in this volume element equals the rate of mass in minus the rate of mass out. In vector form the balance is as follows:

\[
\frac{\partial \rho}{\partial t} = -(\nabla \cdot \rho \nu)
\]

\(\rho\) is the density, kg/m\(^3\);
\(t\) is the time variable, s;
\(\nu\) is the velocity vector, m/s;
\((\nabla \cdot \rho \nu)\) is the vector operator indicating the divergence of the mass flux \(\rho \nu\).

Note that \(\nabla\) has the units of reciprocal length, m\(^{-1}\).

#### 2.2.2.2 The equation of motion

In the case of an incompressible fluid, Equation (2.1) simplifies to the equation of motion.

\[
(\nabla \cdot \nu) = 0
\]

Analogous to the equation of continuity, the equation of motion is a momentum balance around a unit volume of fluid. It states that rate of momentum accumulation equals the rate of momentum in minus the rate of momentum out plus the sum of all the other forces acting on the system. Its vector form is:

\[
\rho \frac{D\nu}{Dt} = -\nabla p - [\nabla \cdot \tau] + \rho g
\]

\(\rho\) is the density, kg/m\(^3\);
\(t\) is the time variable, s;
\[ \rho \frac{D\mathbf{v}}{Dt} \] is the rate of momentum accumulation per unit volume, kg/m²/s²;

\( \nabla p \) is the pressure force on the element per unit volume, Pa (Pa = kg/m/s¹²);

\( [\nabla \cdot \tau] \) is the viscous force on the element per unit volume, kg/m²/s²;

\( \tau \) is the shear stress tensor, kg/m²/s²;

\( \rho g \) is the gravitational force on the element per unit volume, kg/m²/s²;

\( g \) is the acceleration of gravity (9.807 m/s²);

\[ [\nabla \cdot \tau] \text{ can be revised in terms of the fluid viscosity } \mu, \text{ assuming constant } \mu \text{ and constant } \rho. \]

\[ [\nabla \cdot \tau] = \mu \nabla^2 \mathbf{v} \quad (2.4) \]

For the case of constant \( \mu \) and constant \( \rho \), Equation (2.3) becomes:

\[ \rho \frac{D\mathbf{v}}{Dt} = -\nabla p - [\mu \nabla^2 \cdot \mathbf{v}] + \rho g \quad (2.5) \]

Equation (2.5) is known as the Navier–Stokes equation. For the case of \( [\nabla \cdot \tau] = 0 \), Equation (2.5) reduces to:

\[ \rho \frac{D\mathbf{v}}{Dt} = -\nabla p + \rho g \quad (2.6) \]

Equation (2.6) is known as the Euler equation.

### 2.2.3 Flow through porous media: channel theory

#### 2.2.3.1 Darcy’s law

For flow through porous media the equations of continuity and motion may be replaced by:

\[ \varepsilon \frac{\partial p}{\partial t} = -(\nabla \cdot \rho \mathbf{v}_0) \quad (2.7) \]

\[ \mathbf{v}_0 = \frac{k}{\mu} \nabla p - \rho g \quad (2.8) \]

\( \varepsilon \) is the porosity or the void volume ratio, cm³/cm³ or m³/m³;

\( \mathbf{v}_0 \) the flow rate or superficial fluid velocity through the medium, m/s;
\( \mu \) is the fluid viscosity, Pa/s;
\( \nabla p \) is the pressure gradient across the medium, Pa/m;
\( \rho \) is the fluid density, kg/m\(^3\);
\( g \) is the gravitational constant, m/s\(^2\);
\( k \) is a property of the porous medium called the permeability constant \(^3\), m\(^2\).

Equation (2.8) is known as Darcy’s law. It is one of the fundamental equations concerning flow through a porous medium. In the case of a flat porous medium where the fluid flow is perpendicular to the surface of the medium, Darcy’s law reduces to:

\[
v_0 = \frac{k}{\mu} \frac{dp}{dz}
\]

Equation (2.9)

\( dp/dz \) (Pa/m) is the differential pressure gradient across the thickness or \( z \)-direction of the medium.

If the medium is a nonwoven fabric, Equation (2.9) can be further simplified to:

\[
v_0 = \frac{k}{\mu} \frac{\Delta p}{L}
\]

Equation (2.10)

where \( v_0 \) is the face velocity of the medium expressed as the volume flow per unit area of medium, m\(^3\)/m\(^2\)/s and \( \Delta p \) is the pressure drop (Pa) across the thickness, \( L \) (m) of the fabric.

It should be noted that \( v_0 \) and \( v_0 \) are the superficial velocities in vector and scalar form respectively. Bird, Lightfoot and Stewart\(^{28t}\ p. 151\) describe it as the volume rate of flow through a unit cross-sectional area of the solid plus fluid. It is averaged over a small region of space – small with respect to macroscopic dimensions in the flow system but large with respect to the pore size.

Darcy’s law was originally developed for flow through packed beds. It is limited to viscous flow and for Reynolds numbers less than 1. Wakeman and Tarleton\(^{24t}\) state that the dimensionless Reynolds number (Re) as calculated for packed beds is based on the particle size \( x \) (m) and usually determined from the mean volume to surface size ratio. The velocity component, \( v \), of the Reynolds number is based on the average fluid velocity in the porous structure of the packed bed.

\[
Re = \frac{\rho vx}{\mu}
\]

Equation (2.11)

\(^3\)The permeability constant as defined here is often referred to as the permeability. It is not quite the same as the air permeability test property (frequently referred to as the Frazier permeability) of nonwoven filter media as discussed in Chapter 6. The air permeability is actually the \( v_0 \) of Darcy’s law. The air permeability is directly related and proportional to Darcy’s permeability constant because all the other variables in the test are fixed. The air permeability and the permeability constant are directly related to the properties of the medium or porous structure.
In the case of nonwoven filter media, the pore structure is of sufficient small size that the concerns of high Reynolds number and related turbulence generally do not apply; therefore Darcy's law can be applied to nonwoven media.

2.2.3.2 The Hagen-Poiseuille equation

The Hagen-Poiseuille equation describes laminar flow through a cylinder:

\[ Q = \frac{\pi (P_0 - P_1) r_c^4}{8 \mu L} \]  

(2.12)

where

- \( Q \) is the volume flow rate through the cylinder (m³/s);
- \( r_c \) is the radius of the cylinder (m);
- \( P_0 \) is the pressure at the inlet side of the cylinder (Pa);
- \( P_1 \) is the pressure at the exit side of the cylinder (Pa);
- \( L \) is the length of the cylinder (m).

2.2.3.3 The Kozeny-Carman equation

\( k \), the permeability constant of Darcy's law (Equation (2.10)) is defined from the Kozeny-Carman equation.

\[ k = \frac{1}{KS_0^2} \frac{r_c^3}{(1 - \varepsilon_0)^2} \]  

(2.13)

\( K \) is the Kozeny constant that accounts for the tortuosity of the pore structure through the medium:

- \( \varepsilon_0 \) is the permeable porosity or void volume expressed as a decimal fraction of the total medium volume (m³/m³);
- \( S_0 \) is the effective surface area per unit volume of solid material (m²/m³).

The Kozeny-Carman Equation (Equation 2.13) is derived from the velocity form of the Hagen-Poiseuille Equation (2.12).

\[ u' = \frac{\pi (P_0 - P_1) r_c^2}{8 \mu L} \]  

(2.14)

where \( u' \) is the average velocity through the cylinder (m/s).

The following explanation of Kozeny's and Carman's derivation is based on Wakeman and Tarleton (24) (pp. 19–21). The assumptions are based on a packed bed that is a bundle of capillary tubes whose orientation is at 45° to the surface of the medium and 45° to the flow approaching the medium. It is assumed that the flow energy lost by the fluid when it contacts the capillary surface is similar to the energy
lost by the flowing fluid when it is in contact with the actual internal surfaces of the medium. A hydraulic diameter, \(D_h\) (m), and a hydraulic radius \(r_h\) (m) are defined as:

\[
D_h = 2r_h = 4 \times \frac{\text{flow cross sectional area}}{\text{wetted perimeter}} \times \frac{\text{length of flow path}}{\text{length of flow path}}
\]

\[
= 4 \times \frac{\text{volume of voids in bed}}{\text{total surface of particles forming bed}} \times \frac{\text{length of flow path}}{\text{length of flow path}}
\]

\[
= 4 \times \text{voids ratio} \times \frac{\text{volume of the particles}}{\text{surface of particles}}
\]

\[
D_h = 4 \frac{\varepsilon_0}{S_0(1 - \varepsilon_0)} \quad (2.15)
\]

For a straight circular pipe \(D_h\) and \(D_c\) (\(D_c = 2r_c\)) are identical, however in real media, pores are not perfect cylinders. Their lengths are not straight lines, but rather follow tortuous paths. The length of the tortuous pore path through a porous medium is \(L_e\) (m). \(L_e\) divided by the thickness of the medium, \(L\), is the tortuosity factor.

\[
\frac{L_e}{L} = \text{tortuosity factor} > 1 \quad (2.17)
\]

If \(u'\) from Equation (2.14) represents the velocity through a cylindrical pore, then \(v\) the velocity through a tortuous pore (m/s) is related to \(u'\) by:

\[
v = u' \frac{L_e}{L} \quad (2.18)
\]

If we let \(L = L_e\) and \(v = u'\), Equation (2.14) becomes:

\[
v = \frac{(P_0 - P_L)D_h^2}{32\mu L_e} \quad (2.19)
\]

\(v\) is related to \(v_0\), the superficial velocity of Darcy’s law as follows:

\[
v = u' \frac{L_e}{L} = \frac{v_0 L_e}{\varepsilon_0 L} \quad (2.20)
\]

Combining Equations (2.16) and (2.20) into Equation (2.19) gives:

\[
v_0 = \frac{\varepsilon_0^3(P_0 - P_L)}{k_0 \mu S_0^2 (1 - \varepsilon_0)^2 L \left(\frac{L}{L_e}\right)^2} \quad (2.21)
\]
$k_0$ is a factor that depends on the shape and size of the cross-sectional areas of the pores. It has the value of 2 if the pores are perfect circles, however for rectangular, annular, and elliptical shapes $k_0$ has values ranging from 2 to 2.5. One of the assumptions was that the capillary flow through the medium is at 45° to the medium surface. Then $(L_e/L)^2 = 2$. $K$, the Kozeny constant of equation (Equation (2.13)) becomes:

$$K = k_0 \left( \frac{L_e}{L} \right)^2 = \text{Kozeny Constant} \quad (2.22)$$

Based on $k_0 = 2.5$ and $(L_e/L)^2 = 2$, the value for $K$ will be 5. Substituting into (Equation (2.21)) gives the Kozeny–Carman equation.

$$v_0 = \frac{\varepsilon_0^3 (P_0 - P_L)}{5\mu S_0^2 (1 - \varepsilon_0)^2 L} \quad (2.23)$$

The Kozeny–Carman equation applies to substrates whose solidity ($\chi_0 = (1 - \varepsilon_0)$) is $>0.2$ or $\varepsilon_0 < 0.8$. It should be noted that the author has chosen to use $\varepsilon_p$, the permeable or extra-fiber porosity rather than $\varepsilon$ the true porosity and $\chi_0$ the apparent solidity rather than $\chi$, the solidity based on nonporous solid materials in the web. This is because much of the void space in a nonwoven medium may not be available to permeable airflow. For example, cellulose fibers such as cotton, wood pulp, and vegetable fibers have internal cellular structures. That is why they are called cellulose. In a filter medium, these internal cells contained within the walls of the fiber may contribute to the void volume of the medium, but may not be part of the permeable void space where significant flow occurs. $\varepsilon_0$ is the void volume outside the fiber structure. For solid and nonporous fibers such as glass and many synthetic polymer fibers it would appear that $\varepsilon_0 = \varepsilon$. However, Jena and Gupta (13) also identified blind pores and closed pores that may exist outside the fiber walls of filter media. Jena and Gupta noted that although blind pores will not permit fluid flow, they may adsorb fluids, capture small particles, and participate in reactions.

Lindsay (12) discussed this problem for water in pulp mats. He refers to the fiber cell structure that is not available to fluid flow as being swollen fiber. He defined $\varepsilon_{\text{rel}}$ as the fraction of total pore space open to flow. Lindsay’s measurements indicated that $\varepsilon_{\text{rel}}$ ranged from as low as 45% up to 70%.

Lindsay defined $\varepsilon_0$ in terms of $\alpha$ and $c$:

$$\varepsilon_0 = 1 - \alpha c \quad (2.24)$$

$\alpha$ is the volume of swollen fiber per unit mass of fiber in the medium (m$^3$/kg); $c$ is the mass concentration of fiber per unit volume of medium (kg/m$^3$).

---

*See Chapter 6, Section 6.7 and Table 6.4 for further discussion of Lindsay’s work.*
Substitution of Equation (2.24) into the permeability constant of the Kozeny–Carman equation (2.13) and rearrangement yields:

\[
(kc^2)^{1/3} = \left(\frac{1}{5.55S^2}\right)^{1/3} (1 - \alpha c)
\]  
(2.25)

\(S\) is the flow exposed surface of the fibers per unit mass (m²/kg), commonly called the specific surface area.

\[S = \alpha S_0\]  
(2.26)

Equation (2.25) is a classic equation used for pulp mats. Note 5.55 is used here as the value of the Kozeny constant \(K\). One feature of this equation is that it provides for an experimental way of determining \(\alpha\) and \(S\) in fibrous webs under various degrees of compression, by using experimental techniques to develop the plot of \((kc^2)^{1/3}\) vs. \(c\). \(\alpha\) can be determined from the slope and \(S\) from the intercept.

### 2.2.4 Flow through porous media: cell model theory

#### 2.2.4.1 Davies equation

The Kozeny–Carman equation (2.23) was based on liquid flow through flat beds of filter medium such as sand. Davies\(^{33}\) developed the following relationship for the flow of air through fibrous pads\(^5\).

\[
\frac{\Delta P d_t^2 A}{\mu Q L} = 64(1 - \varepsilon)^{1.5}[1 + 56(1 - \varepsilon)]^3
\]  
(2.27)

\(Q\) is the flow volume from Darcy’s law \((Q = \nu_0 \times A)\), Equation (2.10) (m³/s);

\(L\) is the thickness of the fibrous pad (m);

\(\Delta P\) is the pressure across the pad (Pa);

\(A\) is the filter area (m²);

\(d_t\) is the mean fiber diameter (m);

\(\mu\) is the fluid viscosity (Pa/s);

\(1 - \varepsilon\) is the solidity or packing density \((\chi = (1 - \varepsilon)) \) (m³/m³).

Davies development was based on flow past a single fiber and Darcy’s law. He asserted that a “unique relationship must exist between \(\chi\), the packing density and the dimensionless group”:

\[
\frac{\Delta P d_t^2 A}{\mu Q L}\]  
(2.28)

\(^5\)Note that Davies uses \(\varepsilon\) and \(\chi\) instead of \(\varepsilon_0\) and \(\chi_0\). Davies defines \(\chi\) as “the ratio of the volume of all the fibres to the volume of the filter”. If one presumes that the volume of fibers includes all the void space inside the surfaces of the fibers, than \(\chi = \chi_0\). By this presumption the porous volume of the filter does not include the void space inside the surfaces of the fibers, then \(\varepsilon = \varepsilon_0\). For purposes of continuity with previous authors, \(\varepsilon\) and \(\chi\) will be used in remainder of this discussion to symbolize porosity and solidity.
Davies gathered data on a number of filter pads (Figure 2.6) and found their scatter best fit the model as proposed in Equation (2.27). He noted that the scatter related to clumps, fiber orientation, and type of fiber, but not to the fiber length. He also noted that the equation is only valid to Reynolds numbers ($Re$) up to 1.

For solidities where $\gamma = (1 - \varepsilon) > 0.2$, Davies determined that:

$$\frac{\Delta p d_{f}^{2}}{\mu v \varepsilon L} = 70(1 - \varepsilon)^{1.5}[1 + 52(1 - \varepsilon)]$$

gives better agreement with experimental results. $\nu$ is the mean velocity inside the filter and $d_f$ is the effective fiber diameter in contrast to $d_e$, the mean fiber diameter.
He identifies the Reynolds number as $Re = \frac{v d_f}{\mu}$ where $v$ is a mean internal velocity within the depth of the filter medium. Note that Davies theory is based on flow past a single fiber and therefore is dependent on fiber diameter $d_f$. This is in contrast to the Kozeny–Carman equation, which is developed from pore size considerations of cylindrical openings through the medium.

2.2.4.2 Langmuir's theory

Prior to Davies work several pioneering investigators (Albrecht\textsuperscript{34}, Sell\textsuperscript{35}, and Kaufman\textsuperscript{36}) investigated flow patterns around parallel arrays of cylinders. Albrecht was the first to employ a single cylinder model. His work is considered as pioneering. Further progress had to be made in order to consider the interference effects of adjacent fibers. Langmuir\textsuperscript{37} in an ingenious approach assumed an array of parallel cylinders parallel to the direction of flow. Each cylinder, representing a fiber was surrounded by a hexagon-shaped void space that bordered with the similar void space of the adjacent fibers. The honeycomb arrangement is depicted in Figure 2.7.

![Figure 2.7. Langmuir's cylinder model.](image)

Langmuir\textsuperscript{37} then assumed that each hexagon could be approximated by a circle whose area was equal to the hexagon. This reduced the problem to flow through a coaxial cylinder, the inner cylinder being the fiber perimeter and the outer cylinder being the fluid boundaries to the adjacent cylinders. In the classic solution to this problem (see Bird, Lightfoot, and Stewart\textsuperscript{28} (p. 51)), the velocity profile from inner cylinder to outer cylinder is parabolic. The boundary layer velocities at both the inner and outer cylinder walls are zero. Langmuir changed this by assuming a maximum velocity at the outer cylinder wall, which in reality was the assumed fluid boundary of the flow around each cylinder. Langmuir also assumed that the pressure gradient was only along the axis ($x$) of each cylinder, and that the velocity was a function of the radial distance ($r$).
from the axes. Langmuir also assumed there were no inertial effects. The resulting equation was:

\[
\frac{dp}{dx} = \mu \left( \frac{1}{r} \frac{dv}{dr} + \frac{d^2v}{dr^2} \right)
\]  
(2.29)

Note that in Equation (2.29) the shearing force equals the pressure force, so that no acceleration or deceleration takes place in the direction of the axis (x). Double integration of Equation (2.29) gives the velocity profile from the fiber surface to the outer cylinder wall.

\[
v = \frac{1}{2\mu L} \left[ b^2 \ln \left( \frac{r}{a} \right) - \frac{1}{2} (r^2 - a^2) \right]
\]  
(2.30)

where

- \( L \) is the length of the cylinder model (m);
- \( r \) is a radial position from the fiber axis (m);
- \( b \) is the radius of the outer cylinder (m);
- \( a \) is the radius of the fiber (m).

The volumetric flow rate \( Q \) (m\(^3\)/s) is obtained by the integration of Equation (2.30) as follows:

\[
Q = \int_0^{b} \int_0^{a} vr \, dr \, d\theta
\]  
(2.31)

where

- \( r \) (m) and \( \theta \) (rad) are radial components.

This gives:

\[
Q = \frac{2\pi \Delta P a^4}{4\mu L \chi^2} \left[ -\ln \chi + 2\chi - \frac{\chi^2}{2} - \frac{3}{2} \right]
\]  
(2.32)

\( \chi \) the solidity or the “fraction of the filter volume occupied by the fibers” (m\(^3\)/m\(^3\)) is:

\[
\chi = \left( \frac{a}{b} \right)^2
\]  
(2.33)

Langmuir continued with his analysis by defining a function, \( \phi \) as being the reciprocal of the portion of Equation (2.32) that is bracketed.
\[
\varphi = \frac{1}{-\ln \chi + 2\chi - \frac{\chi^2}{2} - \frac{3}{2}} \tag{2.34}
\]

Langmuir\(^{(37)}\) drew an analogy between the Hagen-Poiseuille equation for flow through a cylinder and Ohm’s law for electrical resistance, and developed the following expression:

\[
Qp = \frac{p_a (P_0 - P_L)}{R} \tag{2.35}
\]

\(Q\) is the cylinder flow volume from Equation (2.32);
\(p\) is the pressure at any point in the cylinder, Pa.
\((P_0 - P_L)\) is the pressure drop, Pa.
\(p_a\) is the average pressure in the cylinder \((P_0 - P_L)/2\), Pa.
\(R\) is the resistance to flow and has the units of Pa/s/m\(^3\).

\[
R = R_0 (1 + (\Delta L/L)) \tag{2.36}
\]

\(L\) is the length of the cylinder (m);
\(\Delta L\) is an end correction for the fluid entering the cylinder m;
\(R_0\) is the Hagen-Poiseuille resistance of the flow within the cylinder, Pa/s/m\(^{-3}\).

\[
R_0 = \frac{8\mu L}{\pi r^4} \tag{2.37}
\]

Combining Equations (2.32), (2.34), (2.35), and (2.37), Langmuir developed the resistance of his model as:

\[
R = 4\mu L \varphi a^2 \tag{2.38}
\]

\(A\) is the total area of the filter, m\(^2\).

Langmuir\(^{(37)}\) recognized that his model did not represent real filter media because:

- The fibers of an actual filter have their axis approximately parallel to the surface of the media.
- The fibers are not parallel to one another but cross at all angles and their distribution in space is far less than in the model.

A correction factor was applied based on the flow of ellipsoids through fluids. The model was a prolate ellipsoid. A prolate ellipsoid is obtained by rotating an ellipse around its long axis so that the three-dimensional shape is something like an egg. If \(a\) is the long axis of the ellipsoid and \(b\) is the diameter at its center or thickest part, the ratio \(a/b\) approximates the \(L/D\) (length/diameter) ratio of a fiber. Langmuir
calculated that the force $F_T$ to move an ellipsoid with its long axis transverse to the flow was greater than the force $F_L$ to move the ellipsoid when its long axis was parallel to the direction of flow. The force ratio $F_T/F_L$ increased as $a/b$ increased, however it was asymptotic to 2 as $a/b$ approached infinity. By relating this rational to fibers of a filter medium, Langmuir argued that the flow resistance of transverse fibers should never be more than two times the resistance of parallel fibers as calculated by his model and more likely to be in the neighborhood of 1.4. Accordingly the correction factor $B$ was introduced to Equation (2.38).

$$R = 4B\mu \varphi/\lambda a^2 \quad (2.39)$$

### 2.2.4.3 Happel and Kuwabara models

It should be noted that Langmuir was studying aerosol filtration and based his model for a gas fluid. He developed the model for flow through a filter medium based on fibers parallel to the flow, and then justified a correction factor $B$ for fibers transverse to the flow. Happel and Kuwabara both solved the problem for the transverse flow situation. Both solutions were based on two concentric cylinders being used to represent a model of a fluid flowing through an assemblage of cylinders. Note in Figure 2.8, that the starting point for this model is very similar to Langmuir's model.

The solidity of the cell in Figure 2.8 is:

$$\chi = \left(\frac{a}{b}\right)^2 \quad (2.40)$$

Note that Equation (2.40) is identical to Langmuir’s Equation (2.33). If there are $N$ such cells in the filter domain then Equation (2.40) is the solidity of the entire model.

![Figure 2.8. Happel-Kuwabara cell model.](image_url)

7 Using Happel’s theory as discussed in Section 2.2.4.3, Davies showed that Langmuir’s estimate of 1.4 for the transverse to parallel resistance ratio of fibers is low. Davis calculations showed the number to range from 1.43 to 2.0.
For this discussion, we will follow Happel’s (38) development and then note the differences between Happel’s model and Kuwabara’s model.

Happel made the following assumptions:

1. There is no slippage at the cell boundaries, a and b.
2. The mean free path of gas molecules is very small compared to the dimension a of the inner cylinder.
3. The cross-sectional shape of the cell is represented by a circle whose area is the same as the cross-section of the actual cell geometry. In effect, the outer boundary of the cell at b is a cylinder.

Happel started with the equations of motion and utilized the stream function $\psi$.

$$v_r = \frac{1}{r} \frac{\partial \psi}{\partial \theta} \quad \text{and} \quad v_\theta = -\frac{\partial \psi}{\partial r} \quad (2.41)$$

$v_r$ and $v_\theta$ are the velocity components (m/s) at the radial coordinates $\theta$ (rad) and $r$ (m), based on the axis of the inner cylinder being $r = 0$.

He then assumed that the system could be represented by the biharmonic equation:

$$\nabla^4 \psi = 0 \quad (2.42)$$

The general solution to Equation (2.42) is:

$$\psi = \sin \theta \left[ \frac{1}{8} Cr^3 + \frac{1}{2} Dr \left( \ln r - \frac{1}{2} \right) + Er + F \right] \quad (2.43)$$

$C$, $D$, $E'$, and $F$ are constants obtained from boundary conditions.

In order to develop the boundary condition constants, Happel assumed that the cylinder in Figure 2.8 was moving and the fluid envelope was standing still. This would give the same, but negative, result as if the fluid envelope were moving and the cylinder standing still. This allowed for the following boundary assumptions at the surface of the cylinder where $r = a$:

$$u = v_f \quad (2.44)$$

$$v_r = v_f \cos \theta \quad (2.45)$$

$$v_\theta = v_f \sin \theta \quad (2.46)$$

$u$ and $v_f$ are the velocity and superficial velocity of the cylinder respectively (Figure 2.9).
At the outer cylinder of Figure 2.9, where \( r = b \), Happel\(^{181} \) assumed there is no shearing stress, \( \sigma_{r\theta} = 0 \), and there is no radial velocity component, \( v_r = 0 \). Yuan\(^{40} \) derived the equations of motion in cylindrical coordinates and gave the following relationships for normal (\( \sigma_{rr} \)) and shearing stress (\( \sigma_{r\theta} \)):

\[
\sigma_{rr} = -p + 2\mu \varepsilon_{rr} - 2/3 \mu (\nabla \cdot \mathbf{v})
\]

(2.47)

\[
\sigma_{r\theta} = \mu \gamma_{r\theta}
\]

(2.48)

\( \varepsilon_{rr} \) is a normal strain;
\( \gamma_{r\theta} \) is a shearing strain.

It has already been noted in Equation (2.2) that for a viscous incompressible fluid, the equation of continuity is equal to zero.

\[
(\mathbf{N} \times \mathbf{v}) = 0
\]

(2.49)

Happel\(^{181} \) assumed that if \( v_r = 0 \), then:

\[
\varepsilon_{rr} = \frac{\partial v_r}{\partial r} = 0
\]

(2.50)

Accounting for Equations (2.49) and (2.50) in Equation (2.47), reduces it to:

\[
\sigma_{rr} = -p
\]

(2.51)
The shearing strain $\gamma_{r\theta}$ is:

$$\gamma_{r\theta} = \frac{\partial v_\theta}{\partial r} - \frac{v_\theta}{r} + \frac{1}{r} \frac{\partial v_r}{\partial \theta}$$  \hspace{1cm} (2.52)$$

If Happel's assumption that $\sigma_{r\theta} = 0$ is accepted, then combining Equation (2.52) into Equation (2.48) gives:

$$\frac{\partial v_\theta}{\partial r} - \frac{v_\theta}{r} + \frac{1}{r} \frac{\partial v_r}{\partial \theta} = 0$$  \hspace{1cm} (2.53)$$

Equation (2.53) along with $v_r = 0$ becomes the boundary conditions for Happel's development.

At this point, it would be useful to compare Kuwabara's boundary condition. Like Happel, Kuwabara assumed $v_r = 0$ at the outer cylinder where $r = b$. In contrast to Happel, Kuwabara assumed no vorticity at the outer cylinder. As a result, his boundary equation is:

$$\frac{v_\theta}{r} + \frac{\partial v_\theta}{\partial r} - \frac{1}{r} \frac{\partial v_r}{\partial \theta} = 0$$  \hspace{1cm} (2.54)$$

By comparing Equation (2.54) to Equation (2.53), it will be noted that the only difference is a sign change for two of the terms, however this creates significant differences in the resultant equations. Both Happel and Kuwabara were identical to each other and to Langmuir in their solutions of flow parallel to the cylinders (Equation (2.39)). Their models for flow transverse to the cylinders are as follows:

Happel\(^{\text{38}}\):

$$\frac{\Delta p d_f^2}{\mu v_0 L} = \frac{32 \chi}{-\ln \chi - (1 - \chi^2)/(1 + \chi^2)}$$  \hspace{1cm} (2.55)$$

Kuwabara\(^{\text{39}}\):

$$\frac{\Delta p d_f^2}{\mu v_0 L} = \frac{32 \chi}{-\ln \chi + 2\chi - \chi^2/2 - 3/2}$$  \hspace{1cm} (2.56)$$

Note that Equations (2.55) and (2.56) are presented in the dimensionless arrangement (Equation (2.29)) of Davies\(^{\text{23}}\). The difference between the Happel and Kuwabara models raises the question as to which is the most accurate. Kirsch and Fuchs\(^{\text{41}}\) using spheres, 20–30 $\mu$m in diameter and equal in density to the surrounding fluid determined velocities that were more in agreement with Kuwabara\(^{\text{39}}\) than Happel. Brown\(^{\text{42}}\) states that "Of the two theories Kuwabara's is found to give better agreement with experiment and is probably even now the most popular model of air flow through nonwoven media."
flow through a filter." The denominator in the Kuwabara equation (2.56) divided by 2 gives the Kuwabara hydrodynamic factor \( K_u \). Several investigators in subsequent theory development have used this factor.

\[
K_u = -\frac{1}{2} \ln \chi - \frac{3}{4} + \frac{\chi^2}{4}
\]  
(2.57)

2.2.4.4 Advances in cell model theory

There have been several updates on the theories offered by Kuwabara and Happel. Pich\(^{143,144}\) modified Kuwabara's model by assuming there was some slippage at the surface of the inner cylinder. The resulting equation in Davies' dimensionless terms is:

\[
\frac{\Delta P d_f^2}{\mu u_0 l} = \frac{32 \chi (1 + 1.996 Kn)}{-\ln \chi + 2 \chi - \chi^2/2 - 3/2 + 1.996 Kn (-\ln \chi + \chi^2/2 - 1/2)}
\]  
(2.58)

\( Kn \) is the Knudsen number.

\[
Kn = \frac{2 \lambda}{d_f}
\]  
(2.59)

\( \lambda \) is the mean free path of the gas molecules, m;

\( d_f \) is the fiber diameter, m.

Pich claims his equation to be valid for conditions where \( \lambda \) is very small compared to the diameter of the fiber \( d_f \). The applicable region is \( Kn < 0.25 \). Grafe and Graham\(^{145}\) have noted that at low fiber diameters (0.5 \( \mu m \)) slip flow should be considered.

Brown\(^{142}\) mentions that the strength of cell model theory is its simplicity. It assumes that finding the airflow around a single circular fiber is typical of the filter as a whole. Brown notes that in a real medium not all fibers are perpendicular to the flow nor are they of uniform diameter. In addition the fiber cross-section is not necessarily circular. He also notes that the packing density varies through the medium. Brown acknowledges that there is no existing theory that deals with all of these problems, however a number of refinements exist. Myagi\(^{146}\) used a complex variable approach to treat the filter as a single infinite row of uniformly spaced parallel fibers. According to Brown, this approach gave results comparable to cell theory, provided that the packing distance between successive layers of the rows was equal to the inter-fiber distance within a row.

Kirsch and Fuchs\(^{147,148}\) explored a fan model approach. This approach consists of successive planes of parallel fibers; however the fibers in each plane were rotated at some arbitrary angle with respect to the parallel fibers in the previous plane. The fan model was based on a perfect homogeneous dispersion of fibers. In real filters the fibers are not so homogeneously dispersed. The fan model predicted higher resistance than real filters, therefore an inhomogeneity factor was introduced to bring the real filter in alignment with the fan model (Fuchs et al.\(^{149}\)).

The assumption that the distance between layers of a filter medium is the same as the inter-fiber distance within a layer is not necessarily true. In a depth filter, successive
arrays of parallel fibers are the simplest approach for developing a theoretical model. Two such arrays are depicted in Figure 2.10. The cylinders represent segments of parallel fibers perpendicular to the direction of flow. Each vertical row of cylinders represents a layer of filter media. $2L$ is the distance between parallel fibers within a layer. $2e$ is the distance between layers. Two structures are represented. The channel structure assumes that the fibers in each layer line up directly behind the fibers of the layer in front of it. The staggered model represents the case where the fiber alignment from layer to layer is staggered. Brown(42) illustrated four structures: the channel and three versions of the staggered structure.

The parameters are the scale, the packing fraction, and the ratio between inter-fiber spacing to inter-layer spacing. If there is stagger between successive layers than a fourth parameter is required describing the extant of stagger. Brown(42) mentions four approaches:

1. Extension of cell model to account for adjacent fibers: In this approach the solution of the biharmonic equation (Equation (2.42)) requires a series solution of higher order than the simple cell model solution of Equation (2.43). The radial components vary continuously. They cannot be simply defined by the cell radius and fiber radius of the cell model. Sangani and Acrivos(50) are one set of investigators who used this approach. They used their methodology to obtain an exact numerical solution on the creeping flow field in arrays of high and low porosities.

Referring to a personal communication with Majid Zia of the University of Rhode Island, Kahn(51) reports that Zia had compared Sangani and Acrivos’ solution to the streamlines and radial velocities of the Kuwabara solution and determined that disagreement between the two solutions increases with increasing solidities, particularly near the upstream cell boundary and at increasing radial distances from the fiber surface. Zia did note that calculated drag for filter solidities up to 0.4 were near identical. Above 0.4 the difference increased rapidly. Kahn also notes that for $\chi \leq 0.2$ the pressure drop associated with inline and staggered arrangements of parallel cylinders are almost identical, however for

![Figure 2.10. Arrays of parallel fibers.](image)
increased solidities the drag for inline arrays is considerably higher than for staggered structures.

2. **Numerical methods**: Finite difference methods are a way of breaking down complex differential equations into meshes of simultaneous equations. Each point in the mesh is solved one by one to approximate the analytical solution. Fardi and Liu\(^\text{52}\) used this approach to solve the simplified components of the Navier–Stokes equations along with the equation of continuity for the fluid velocity. Numerical analysis will give very good results provided appropriate boundary conditions are applied at the surface.

3. **Variational method**: Helmholtz’s principle is used to find the flow pattern that gives rise to the lowest rate of dissipation of energy by viscous drag. The periodic symmetry or the fiber array is exploited by the use of a Fourier series. Brown\(^{153,54}\) conducted calculations using the variational model and determined that although the pressure drop is not sensitive to fiber arrangement when the inter-fiber and inter-layer distances are equal, the structure behaves very differently when they are not. If the distance between layers is less than the distance between fibers, then the effect of compression may be simulated. In addition, the structure behaves differently depending on whether the successive layers are channeled or staggered.

4. **Boundary element method**: Brown\(^{52}\) mentions Hildyard et al.\(^{155}\) as one set researchers that used the boundary element method. In this method, the biharmonic equation is split into two equations by way of vorticity resulting in two integral equations. The problem is then reduced to the solution of simultaneous equations. Brown reports that flow patterns and pressure drops obtained by this method are similar to that obtained by the variational method.

### 2.2.4.5 Drag model theory

Drag model theory is based on the drag on an object moving through a fluid. The drag equation is:

\[
F = \frac{1}{2} \rho u^2 AC_d
\]  
\[\text{(2.60)}\]

where:

- \(F\) is the drag force (N);
- \(\rho\) is the density of the fluid (kg/m\(^3\));
- \(u\) is the velocity of the object moving through the fluid (m/s);
- \(A\) is the reference area of the object (m\(^2\));
- \(C_d\) is the drag coefficient (dimensionless).

If the object is a fiber represented by the unit length of a long cylinder transverse to the flow, then:

\[
F = \frac{1}{2} \rho u^2 d_t C_d
\]  
\[\text{(2.61)}\]

\(d_t\) is the fiber diameter (m).
Note that in Equation (2.61) the reference area \( A \) of Equation (2.60) is the cross-section of the unit length cylinder \((d_f \times \text{unit length})\).

Applying Lamb's solution for an isolated fiber:

\[
F = \frac{4\pi\mu u}{2.0022 - \ln Re}
\]  

(2.62)

where \( Re \) is the Reynolds number:

\[
Re = \frac{ud_f \rho}{\mu}
\]  

(2.63)

The Lamb drag coefficient for Equation (2.61) is:

\[
C_d = \frac{8\pi}{Re(2.022 - \ln Re)}
\]  

(2.64)

The problem with Lamb's equation is that it is for an isolated fiber and does not consider the interference effect of other nearby fibers in the filter medium network. Some investigators such as Langmuir, Irving, Happel, and Kuwabara, discussed above, dealt with this by organizing fibers into parallel arrays and placing a fluid cell envelope around each fiber. Boundary conditions were established at each cell border to allow for the interaction of the adjacent cell.

Other investigators such as Chen established drag coefficients by using neighboring fibers as boundaries. Chen assumed that at low Reynolds number, the ratio of inter-fiber distance \((d_b)\) to fiber diameter \((d_f)\) is inversely proportional to the square root of the solidity \((\chi)\). White, a previous investigator had determined that the drag coefficient of a cylinder moving in a tank could be correlated by the following equation:

\[
\frac{C_d \cdot Re}{2} = \frac{k'}{\ln k'' \cdot \frac{d_b}{d_f}}
\]  

2.65

\( k' \) and \( k'' \) are constants of the equation.

Chen used White's Equation (2.65) for his own model. Chen's model was a screen formed from a square matrix of fibers. The in-plane distance between fibers in both the \( x \) and \( y \) directions was \( d_b \). Each screen formed a separate layer in the filter. \( d_b \) was also the distance between layers.

The drag equations developed from Chen's model were as follows:

\[
\frac{C_d \cdot Re}{2} = \frac{k_4}{\ln k_5 \cdot \sqrt{\chi}}
\]  

(2.66)
\[ \Delta P = \frac{4}{\pi \ln k_5} \left( \frac{k_4}{\chi^{0.5}} - \frac{1 - \chi}{(d_L)^2} \right) \mu \nu_s L \]

(2.67)

\( k_4 \) and \( k_5 \) are constants of the equation:

\( \Delta P \) is the pressure drop across the filter (Pa);

\( \mu \) is the fluid viscosity (Pa/s);

\( \nu_s \) is the superficial velocity through the filter (m/s);

\( L \) is the thickness of the filter (m);

\( (d_L)^2 \) is the surface average fiber diameter (m).

Experiments by Chen\(^{(57)}\) indicated that the drag coefficient term, \( C_{dn}/2 \cdot Re \), is constant over a broad range of Reynolds numbers (\( Re = 10^{-3} \) to \( Re = 10^{-1} \)). Chen also determined the best-fit data for the constants \( k_4 \) and \( k_5 \) as \( k_4 = 6.1 \) and \( k_5 = 0.64 \).

Khan\(^{(51,59)}\) developed a screen model approach which he termed an “offset screen model”. The model consisted of two layers of parallel fibers. The parallel fibers in the first layer were perpendicular to the fibers in the second layer. The layout is pictured in Figure 2.11. Each layer of area \( L \times L \) is composed of \( N \) equally spaced fibers in the

\[ \text{Figure 2.11. Kahn offset screen model.} \]

Reproduced with permission of the American Filtration and Separation Society.
first layer and \( M \) equally spaced fibers in the second layer and perpendicular to the fibers in the first layer. Kahn defined an anisotropy parameter as being:

\[
R_{pa} = \frac{M}{N} \tag{2.68}
\]

Kahn related the anisotropy parameter to the orientation of fibers in real media. He claimed that his model accounted for structural properties: fiber size, solidity, and anisotropy. It also calculated a three-dimensional flow field. Kahn argued that his model predicted pressure drop very well and that particle capture efficiencies compared well with experimental data, except in domains where diffusion, interception, and inertial mechanisms were of equal importance. He also showed that anisotropy affects pressure drop only for solidities greater than 0.2.

2.2.4.6 Computational fluid dynamics

The advent of the computer and the increasing availability of mathematical software tools have enabled the filter scientist to find more sophisticated ways to theorize the filtration process. One such tool, computational fluid dynamics (CFD) is becoming an increasingly important tool in the design and modeling of filtration flow systems. CFD is a software tool that allows for the simulation of fluid flow dynamics in a number of situations including flow through porous media. The simulation is accomplished by solving the Navier–Stokes equations (see Section 2.2.1 above) for the conservation of mass, momentum, and energy for a fluid. These are differential equations that can be approximated by discrete formulations that are solved in finite, rather than infinitesimal volumes. Because of the approximation, it is often necessary to employ empirical methods for phenomena, which are not sufficiently resolved for a given level of discretization. Fluid turbulence and porous media effects are two quantities that can be modeled by CFD.

There has been numerous of publications using of CFD for various filter applications. Some examples are as follows:

1. “Application of computational fluid dynamics to air induction system design” Chen et al.\(^{(60)}\) – presents a methodology for applying CFD tools to the design of and analysis of automotive air induction and filtration systems.
2. “Simulating the deep-bed loading and soot cake growth in a DPF Using a 3-D CFD model” Yi and Egalia\(^{(61)}\) – a detailed three-dimensional CFD model simulates the soot loading process in a diesel particulate filter (DPF).
3. “Numerical analysis of air filtration and pulse jet cleaning in a dust collector” Lo et al.\(^{(62)}\) – The CFD technique is employed to examine pressure changes across pleated filter cartridges during pulse jet cleaning in a dust collector.

2.3 Particle Filtration

The theoretical discussion to this point has been mostly concerned with the theories of flow through porous media. It is necessary to understand the flow behavior
through a nonwoven filter medium in order to develop theories for the separation of particles in that flow. Most of the following discussion will be based on the separation of particles in gas streams, particularly air-borne particles.

2.3.1 Single fiber theory

Single fiber theory was developed for filtration of aerosol particles from an air stream. The following explanation will be mostly based on that offered by Davies (23).

Consider a filter element, of length $\delta x \text{ (m)}$ in a fibrous filter of unit cross-section and thickness $h \text{ (m)}$ in the $x$-direction. The filter is at right angles to the airflow as shown in Figure 2.12.

If $d_f$ is the fiber diameter (m) and $L_f$ is the length of fiber (m) in the unit thickness $\delta x$ of the filter pad, then the solidity or packing density of the element is:

$$\chi = \frac{\pi d_f^2 L_f}{4} = 1 - \varepsilon \quad (2.69)$$

where $\varepsilon$ is the porosity or fractional void volume of the web.

Now consider one fiber in that filter whose axis is transverse to the flow as indicated in Figure 2.13.

At some distance upstream of this fiber is a stream of width $y \text{ (m)}$, where all the particles in this stream are the ones that will strike the fiber, whose diameter is $d_f \text{ (m)}$. The single fiber efficiency is then:

$$E = \frac{y}{d_f} \quad (2.70)$$

Let $v \text{ (m/s)}$ be the velocity of the flow inside the filter:

$$v = \frac{v_0}{1 - \chi} \quad (2.71)$$

where $v_0$ is the face velocity of the filter (m/s).
Let $c_p$ be the particle concentration (particles/m$^3$) of the air stream approaching the element. Then $v_0 \times c_p$ is the particle rate (particles/m$^2$/s) approaching the filter. If the fiber cross-section to remove particles is $L_f \times d_f$ (m$^2$), then:

$$\delta c_p = -c_p E L_f d_f \delta x \quad (2.72)$$

and the rate of particulate removal is:

$$\frac{dc_p}{dx} = -c_p E L_f d_f \quad (2.73)$$

Integration of Equation (2.73) across the thickness $h$ yields:

$$\frac{n}{n_0} = \exp(-E L_f d_f h) \quad (2.74)$$

$n_0$ is the concentration of aerosol particles entering the filter (particles·m$^{-3}$); $n$ is the concentration of aerosol particles leaving the filter (particles·m$^{-3}$).

A filter is often characterized by its penetration, $P$ where $P = 1 - E$. Note that $n/n_0$ is not the efficiency of the filter but rather the fraction of upstream particles penetrating the filter (the penetration). In terms of efficiency, filter performance is generally defined as:

$$E = \frac{n_0 - n}{n_0} = 1 - \exp(-E L_f d_f h) \quad (2.75)$$
The value $\gamma = FL_d$ is referred to as the filtration index and has the units of $m^{-1}$. Expressing the penetration as a percentage, Equation (2.75) becomes:

$$P = 100 \frac{N}{n_t} = 100 \exp(-\gamma h) \quad (2.76)$$

If the fibers are cylindrical and of constant radius, combination of Equations (2.69) and (2.76) yields:

$$\gamma = \frac{4F\lambda}{\pi D_f} \quad (2.77)$$

Davies organized Table 2.1 to demonstrate the calculated relationship between $\gamma h$ and $P$.

<table>
<thead>
<tr>
<th>$\gamma h$</th>
<th>$P$ – percentage penetration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.9</td>
<td>0.0001</td>
</tr>
<tr>
<td>12.2</td>
<td>0.0005</td>
</tr>
<tr>
<td>11.5</td>
<td>0.001</td>
</tr>
<tr>
<td>10.9</td>
<td>0.005</td>
</tr>
<tr>
<td>9.2</td>
<td>0.01</td>
</tr>
<tr>
<td>7.6</td>
<td>0.05</td>
</tr>
<tr>
<td>6.9</td>
<td>0.1</td>
</tr>
<tr>
<td>5.3</td>
<td>0.5</td>
</tr>
<tr>
<td>4.6</td>
<td>1.0</td>
</tr>
<tr>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>2.3</td>
<td>10</td>
</tr>
<tr>
<td>1.61</td>
<td>20</td>
</tr>
<tr>
<td>0.694</td>
<td>50</td>
</tr>
<tr>
<td>0.511</td>
<td>70</td>
</tr>
<tr>
<td>0.223</td>
<td>80</td>
</tr>
<tr>
<td>0.105</td>
<td>90</td>
</tr>
</tbody>
</table>


### 2.3.2 Particle capture based on the Kuwabara flow model

#### 2.3.2.1 Justification for Kuwabara flow model

The Davies presentation in Section 2.3.1 is based on an isolated fiber. Davies acknowledged that the single fiber efficiency found this way is smaller than what would be calculated from an accurate theory, because the dispersion of fibers is imperfect. An accurate theory must allow for the proximity of other fibers.

Much of the current theory is developed from the Kuwabara and Happel cell models discussed above. These flow models consider the effects of adjacent fibers. The
Kuwabara model has been preferred because several investigators have argued that “it is more representative of the flow around the fiber in the case of low Reynolds numbers” (Bouland and Renoux\(^{(63)}\), p. 55).

2.3.2.2 Mechanisms of particle capture
In Section 2.1.2, the mechanisms of particle capture were discussed. These were inertia \(E_i\), interception \(E_r\), and diffusion \(E_d\). Electrostatic attraction is not included for this discussion. Many investigators either ignore inertial efficiency \(E_i\) or account for it with the interception efficiency \(E_r\) in the term, \(E_{ri}\). For fine particle filtration, Kowalski et al.\(^{(64)}\) argues that the inertia process “is not significant for normal filter velocities and microbial sizes, and is neglected in most filter models since interception satisfactorily accounts for it. Davies\(^{(23)}\), p. 72 introduced a combination term \(E_{DR}\) so that the total single fiber efficiency due to diffusion and interception in the Kuwabara flow field is:

\[
E_i = \gamma X E_d + E_r + E_{DR} X d_i v
\] (2.78)

Many investigators ignore \(E_{DR}\), so that Equation (2.78) reduces to:

\[
E = E_d + E_{DR} + E_r E_i
\] (2.79)

Figure 2.14 by Davies\(^{(23)}\) indicates the particle size domains for the various mechanisms of single fiber efficiency. The medium is a paper filter containing fibers 2 \(\mu\)m in diameter. The curves are based on Kuwabara flow theory as discussed in the following sections. For this particular filtration condition, diffusion \(E_d\) is the dominating mechanism for particles less than 0.1 \(\mu\)m in radius. Note that for particles in this range of <0.1 \(\mu\)m the single fiber efficiency decreases with increasing particle size. Interception, \(E_r\), first becomes notable at particle radii of 0.07 \(\mu\)m. At this point, the contribution of interception efficiency starts causing an increase in efficiency with increasing particle size as indicated by the turnaround in the curve of \(E_d + E_{DR} + E_r\). The effects of inertia, \(E_i\), do not show until particle size radius is in the range of 0.1–0.2 \(\mu\)m. Figure 2.14 suggests that at particles size radii of 0.5 \(\mu\)m and greater, particle inertia becomes the dominating efficiency mechanism.

2.3.2.3 Dimensionless numbers
Before we proceed further, several numbers are identified:

1. The Knudsen number \(Kn\): see Equation (2.59).
2. The Pedet number \(Pe\): This number accounts for the diffusivity of the particles in the flow field. It is defined as:

\[
Pe = \frac{\nu_0 d_f}{D_{AB}}
\] (2.80)

\(\nu_0\) is the face velocity of the filter, m/s;
\(d_f\) is the fiber diameter, m;
\(D_{AB}\) is the particle diffusion coefficient m\(^2\)/s.
$D_{AB}$ relates the movement of a particle $A$ in a binary mixture of $A$ and $B$. It is defined by the Einstein equation:

$$D_{AB} = \mu_p k_b T$$

(2.81)

$\mu_p$ is the particle mobility, $s/kg$;

$k_b$ is Boltzman’s constant\(^8\), $1.3805 \times 10^{-23}$ $\text{J}/\text{K}$;

$T$ is the Temperature, $K$.

The particle mobility, $\mu_p$, is determined from the Cunningham slip factor $C_k$:

$$\mu_p = \frac{C_k}{\pi n \mu_p}$$

(2.82)

\(^8\)The author has noted some slight inconsistencies in various sources reporting the value of the Boltzman constant. Kowalski et al.\(^{46}\) report the value as $1.3708 \times (10)^{-23}$ $\text{J}/\text{K}$. “Perry’s Chemical Engineers’ Handbook”\(^{170}\) reports it as $1.38048 \times (10)^{-23}$ $\text{J}/\text{K}$. Bird, Lightfoot, and Stewart\(^{28}\) report it as $1.3805 \times (10)^{16}$ $\text{erg}/\text{K}$ (one $\text{J} = 1 \times (10)^{10}$ $\text{erg}$). The *Encyclopedia Britannica*\(^31\) reports two values: $1.38062 \times (10)^{23}$ $\text{J}/\text{K}$ and $1.38622 \times (10)^{16}$ $\text{erg}/\text{K}$. The author can only assume that the latter Britannica value is the result of a typographical error. The author chose to list the values reported by Perry and by Bird et al. since these were the only two sources that were consistent with each other.
\( C_k \) is the Cunningham slip factor, dimensionless;
\( \eta \) is the absolute viscosity, N-s/m²;
\( d_p \) is the particle diameter, m.

The Cunningham slip factor accounts for the aerodynamic slip that occurs at the particle surface. It is defined as:

\[
C_k = 1 + \left( \frac{\lambda}{d_p} \right) \left( 2.492 + 0.84e^{-0.435d_p/\lambda} \right)
\]  

(2.83)

\( \lambda \) is the gas molecule free path, N-s/m². It is the same \( \lambda \) as used in the Knudsen number of Equation (2.59).

3. The Stokes number \( St \): The Stokes number “is a dimensionless group expressing the ratio of kinetic energy of a particle, traveling with the velocity \( v_p \) through air or another fluid, to the work done against it by viscous drag over a distance \( R \) (m) (Davies\(^{23}\)).” It is defined by:

\[
St = \frac{d_p \rho_p v_p}{9 \mu R}
\]  

(2.84)

\( d_p \) is the particle diameter, m;
\( \rho_p \) is the particle density, kg/m³;
\( v_p \) is the particle velocity, m/s;
\( \mu \) is the air or fluid viscosity, N-s/m = kg/m-s;
\( R \) is the viscous drag distance.

4. The Kuwabara hydrodynamic factor: This factor has been previously discussed in Section 2.2.3.3 and defined by Equation (2.57).

\[
Ku = -\frac{1}{2} \ln \chi - 3/4 + \chi - \frac{\chi^2}{4}
\]  

(2.85)

2.3.2.4 Results of various investigators
2.3.2.4.1 Diffusion and interception

Stechkina and Fuchs\(^{65}\) were the first to use the Kuwabara flow approach for diffusion (\( E_D \)). Their result was:

\[
E_D = 2.6 Ku^{-1/3} Pe^{-2/3}
\]  

(2.86)

Referring to Equation (2.78), Davies\(^{23}\) determined the following for diffusion and interception in the Kuwabara flow field.
Lee and Liu (66) used a boundary layer theory along with the Kuwabara flow field to combine the effects of interception and diffusion. They obtained the following equations:

\[ E = E_D + E_R \]  
(2.90)

\[ E_D = 2.6 \left( \frac{1 - \chi}{Ku} \right)^{1/3} Pe^{-2/3} \]  
(2.91)

\[ E_R = \left( \frac{1 - \chi}{Ku} \right)^{1/3} \frac{R^2}{(1 + R)} \]  
(2.92)

\[ R \] is the interception parameter \( \frac{d_p}{d_f} \).

Lee and Liu (67) then amended the equations to better fit with their experimental data.

\[ E_D = 1.6 \left( \frac{1 - \chi}{Ku} \right)^{1/3} Pe^{-2/3} \]  
(2.93)

\[ E_R = 0.6 \left( \frac{1 - \chi}{Ku} \right)^{1/3} \frac{R^2}{(1 + R)} \]  
(2.94)

Liu and Rubow (68) took into account Pich's (44) slip flow correction (Equation (2.58)) and applied two correction terms \( C_D \) and \( C_R \) to the equations of Lee and Liu:

\[ E_D = 1.6 \left( \frac{1 - \chi}{Ku} \right)^{1/3} Pe^{-2/3} C_D \]  
(2.95)
\[ E_R = 0.6 \left( \frac{1 - \chi}{Ku} \right)^{1/3} \frac{R^2}{(1 + R)} C_R \]  

(2.96)

where

\[ C_D = 1 + 0.388 Kn_f \left( \frac{(1 - \chi)Pe}{Ku} \right)^{1/3} \]  

(2.97)

\[ C_R = 1 + \frac{1.996 Kn_f}{R} \]  

(2.98)

Bouland and Renoux\textsuperscript{(63)} reported on the work of Payet\textsuperscript{(69)} and Payet et al.\textsuperscript{(70)} The work introduced a new correction of Equation (2.95) related solely to the mechanism of diffusion.

\[ E'_D = 1.6 \left( \frac{1 - \chi}{Ku} \right)^{1/3} Pe^{-2/3} C_D C'_D \]  

(2.99)

where

\[ C'_D = \frac{1}{1 + E'_D} \]  

(2.100)

2.3.2.4.2 Inertial impaction

Bouland and Renoux\textsuperscript{(63)} describe three flow regimes for inertial impaction based on the Reynolds number (Equation (2.63)):

1. Low Reynolds number (Re < 0.2) – Inertial forces are very low and the flow around the fiber is purely viscous. Disturbance of the streamlines due to the fiber starts well upstream.
2. High Reynolds number (Re > 1,000) – Inertial forces are dominant and the flow around the cylinder is considered as ideal, nonviscous, and nonrotational. This is a potential flow regime where streamlines come very close to the fiber before deviating strongly in order to get around it. Generally there are very few filter situations that operate at high Reynolds numbers of this order.
3. Intermediate range (1 < Re < 1,000) – The flow is considered as transitory.

Most theory has been concerned with the low Re domain where inertia effects are minimal. The Navier–Stokes equation from which most theory derives can be simplified in this region. In the transitory realm, transition flow requires a broader development of the equations.
Table 2.2  Values of $J/2 \text{Ku}$ for Equation 2.101

<table>
<thead>
<tr>
<th>$\lambda_1$</th>
<th>$d_e/d_i = 0.01$</th>
<th>0.02</th>
<th>0.05</th>
<th>0.10</th>
<th>0.20</th>
<th>-0.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005</td>
<td>0.000076</td>
<td>0.00294</td>
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<td>-</td>
</tr>
<tr>
<td>0.01</td>
<td>0.000090</td>
<td>0.00339</td>
<td>0.0208</td>
<td>0.0755</td>
<td>0.257</td>
<td>-</td>
</tr>
<tr>
<td>0.02</td>
<td>0.000110</td>
<td>0.00408</td>
<td>0.0255</td>
<td>0.0926</td>
<td>0.313</td>
<td>1.21</td>
</tr>
<tr>
<td>0.05</td>
<td>0.000157</td>
<td>0.00590</td>
<td>0.0365</td>
<td>0.134</td>
<td>0.440</td>
<td>1.78</td>
</tr>
<tr>
<td>0.1</td>
<td>0.000230</td>
<td>0.00852</td>
<td>0.0528</td>
<td>0.1923</td>
<td>0.624</td>
<td>2.36</td>
</tr>
</tbody>
</table>

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Davies\(^{(23)}\) reported on the work of Stechkina, Kirsch, and Fuchs\(^{(71)}\) for calculating collision efficiency. They determined that for Stokes numbers less than one the following model applies:

$$E_{RI} = E_R + \frac{J}{2\text{Ku}} St = E_R + E_I$$  \hspace{1cm} (2.101)

$E_{RI}$ is the combined single fiber efficiency term from $E_R$ and $E_I$; $St$ and $\text{Ku}$ are the Stokes number and the Kuwabara hydrodynamic factor from Equations (2.84) and (2.85), respectively; $J$ derives from a complicated integral.

Davies extracted from Stechkina et al.\(^{(71)}\) the tabulation scheme above (Table 2.2) for determining $J/2 \text{Ku}$.

### 2.3.3 Structure of fibrous filters

Several investigators have attempted to model the structure of a fibrous filter and thereby gain insight into the medium properties. A frequent approach is to use Monte Carlo techniques to simulate the random fiber structure of a nonwoven filter medium. One of the more classical presentations is the line model work of Piekaar and Clarenburg\(^{(7,21)}\) in 1967. Piekaar and Clarenburg simulated a nonwoven filter medium with a number of straight lines of equal length $l$, each line representing a fiber. All the lines were perpendicular to the direction of flow and multi-layered in the plane of the filter medium. Each layer has a thickness twice the mean fiber diameter, $2d$. A random number technique was used to assign a random orientation to each fiber. Figure 2.15 is a typical array containing a line density of 25 per unit area. Note there is both an inner square and an outer square. The inner square whose side is $l$ (the same as the fiber or line length) represents the area of consideration. The outer square has a side of length $2l$ and accounts for those fibers that extend beyond the inner square.

The random intersection of the lines in Figure 2.15 form a number of randomly shaped polygons, each polygon simulating a pore. The number of pores per unit
surface area of filter is a parameter of interest. Piekaar and Clarenburg\(^{(72)}\) expressed this as:

\[
n_p = \frac{n \cdot \bar{n}_v}{n_v}
\]  

(2.102)

where

- \(n_p\) is the number of polygons per unit of surface area;
- \(n\) is the mean number of vertices of a polygon;
- \(\bar{n}_v\) is number of polygons sharing one vertex per unit area of surface area.

Three types of intersections were identified as illustrated in Figure 2.16. Based on probabilities, the total number of interceptions per unit of surface area is:

\[
n = N(N - 1)P/2
\]  

(2.103)

where

- \(N\) is number of lines per unit surface area (25 in Figure 2.15);
- \(P\) is the probability that two lines intersect.
By analyzing the three types of line intersections of Figure 2.16 and their probabilities, Piekaar and Clarenburg derived the following expression for $n_p$.

$$n_p = \frac{2N(N - 1)P - 2N}{11}$$  \hspace{1cm} (2.104)

The value for $P$ was determined to be:

$$P = \frac{2}{\pi}$$  \hspace{1cm} (2.105)

In a previous assessment, Miles determined that $\bar{n}_v$, the number of polygons sharing one vertex is:

$$\bar{n}_v = 4$$  \hspace{1cm} (2.106)

This was confirmed by the Monte Carlo technique of Piekaar and Clarenburg as indicated in Table 2.3. The probabilistic outcomes were based on $N = 25, 37,$ and $49$. The values of $\bar{n}_v$ are $3.98, 3.96, \text{and } 3.93$, respectively, close enough to justify the 4 value of Equation (2.106).

The number of polygons per unit of surface area then simplifies to:

$$n_p = \frac{N(N - 1)}{\pi} - \frac{N}{2}$$  \hspace{1cm} (2.107)

It was mentioned above that Piekaar and Clarenburg conducted line model studies at $N = 25, 37,$ and $49$. They determined that the “polygon’s surface areas form a logarithmic-normal distribution, of which the geometric standard deviation is independent of the specific line density”. They also calculated hydraulic radii based on the ratio of the polygon surface area divided by the perimeter. Their sequel conclusion is that “the hydraulic radii form a logarithmic-normal distribution, of which the geometric standard deviation is independent of the specific line density”.

\[\text{Figure 2.16. Three types of line intersections. a: “normal” case – one vertex shared by 4 polygons; b: “normal-extreme” – one vertex shared by 3 polygons; c: “extreme-extreme” – one vertex shared by 2 polygons. Reproduced with permission of Elsevier Ltd, London, England, UK.}\]
Table 2.3  Percentage of polygons as a function of the number of lines

<table>
<thead>
<tr>
<th>Number of vertices</th>
<th>Number of lines per unit area, N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>38.9</td>
</tr>
<tr>
<td>4</td>
<td>35.1</td>
</tr>
<tr>
<td>5</td>
<td>16.9</td>
</tr>
<tr>
<td>6</td>
<td>7.6</td>
</tr>
<tr>
<td>7</td>
<td>1.6</td>
</tr>
<tr>
<td>Mean number of vertices per polygon ( \bar{n}_v )</td>
<td>3.98</td>
</tr>
</tbody>
</table>


Piekaar and Clarenburg related their results to the pore properties of actual filters. The mean surface area, \( \bar{s} \), of a polygon in the line model is:

\[
\bar{s} = \frac{l^2}{n_p}
\]  

(2.108)

Allowing for line thickness (fiber diameter), Equation (2.107) is corrected to:

\[
\bar{s}' = \left( \frac{l^2 - N\bar{d}}{n'_p} \right)
\]  

(2.109)

where

- \( \bar{s}' \) is the "corrected" mean surface area of a polygon;
- \( \bar{d} \) is the mean line width or simulated fiber diameter;
- \( n'_p \) is the total number of pores in a slice of thickness \( 2\bar{d} \) and a unit square \( l^2 \) after correction for line width \( \bar{d} \).

Miles(73) proved that for isotropic line arrays:

\[
\bar{s}' = \bar{s}
\]  

(2.110)

Hence, the important result that the mean pore surface area can be calculated from:

\[
\bar{s}' = \frac{l^2}{n_p}
\]  

(2.111)

and

\[
n'_p = \left(1 - \frac{N\bar{d}}{t}\right)\left[\frac{N(N-1)}{\pi} - \frac{N}{2}\right]
\]  

(2.112)

Piekaar and Clarenburg used a complicated integral to define a parameter \( \bar{s}_h \) as being the mean hydraulic surface area of the polygons of the line model.
\[
\bar{r}_h = 4\pi m^3_{hg} \exp(2 \ln^2 \sigma_{hg}) \cdot \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{l_2} \exp\left(-\frac{s^2}{2}\right) ds \quad (2.113)
\]

where

\[
s = \frac{\ln m_h - \ln m_{hg} - 2 \ln \sigma_{hg}}{\ln \sigma_{hg}}
\]

\[
l_2 = \frac{\ln M_h - \ln m_{hg} - 2 \ln \sigma_{hg}}{\ln \sigma_{hg}}
\]

\(m_h\) is the hydraulic radius:

\(m_{hg}\) is the geometric mean radius based on a log-normal hydraulic radius distribution:

\(\sigma_{hg}\) is the standard deviation radius based on a log-normal hydraulic radius distribution:

\(M_h\) is the maximal hydraulic radius.

Piekaar and Clarenburg determined that \(\sigma_{hg}\) is independent of line density and is to be considered as a constant. They determined the value of \(\sigma_{hg}\) to be 1.9.

A parameter \(\beta\) was defined as being the conversion factor from effective polygon area to real polygon area. It represents the deviation of the actual pore perimeter from the ideal pore perimeter, which is the perimeter of a circle.

\[
\beta \bar{r}_h = l^2/n_p
\]

(2.114)

From their Monte Carlo techniques Piekaar and Clarenburg determined the value of \(\beta\) to be 1.28 and confirmed it with a series of calculations based on a range of Johns Manville glass microfibers.

Piekaar and Clarenburg also identified \(\bar{s}_h\) a term which corrected for the mean line width or fiber diameter. They determined from their Monte Carlo methods that \(\bar{s}_h = \bar{s}_h\). Then:

\[
\bar{s}_h' = \frac{l^2}{\beta n_p}
\]

(2.115)

The argument made from Equation (2.115) is that it demonstrates that the filter property is equated to the properties of the mathematical line model.

Substituting Equation (2.113) into Equation (2.115), recognizing that \(\sigma_{hg}\) is independent of line density, and that \(\beta = 1.28\), gives the following expression for the mean hydraulic radius of the pores in a fibrous filter.
In summary, Piekaar and Clarenberg arrived at the following conclusions based on their line model work:

1. Pore surface area and hydraulic radii form logarithmic-normal distributions of which the geometric standard deviation is independent of line density.
2. The mean pore surface area can be calculated from the fiber length and the number of pores per unit area of filter medium (see Equation (2.114)).
3. The mean hydraulic radius can also be calculated from fiber length and the number of pores per unit area of filter medium per Equation (2.115).
4. The number of pores in a unit area of filter, $n_p$, can be determined from the line density, $N$, or number of fibers per unit area of filter medium in accordance with Equation (2.106).\(^9\)
5. The conversion factor from effective to real pore area is 1.28.

\(^9\)The fiber number per unit area for a filter medium can be calculated from the mean fiber diameter $\bar{d}$ and solidity $X$ as

$$N = \frac{8X}{\pi} \cdot \frac{l_\bar{d}}{d^2}.$$
3.1 Characteristics and Properties of Air Laid Webs

Air laid webs tend to be bulky structures designed for absorbency. The major markets are diaper padding, feminine hygiene pads, incontinence pads, wipes, and other applications where absorbency is a principle property. The absorbency properties are achieved by the use of specially produced high bulk wood pulp fibers known as fluff pulps, and by the use of superabsorbent polymers. Superabsorbent polymers can include superabsorbent powders such as carboxy methyl cellulose and superabsorbent fibers. Air laid webs can incorporate synthetic fibers for improved strength and resiliency. Bi-component sheath-core fibers are often used to provide for thermo-bonded structures. The products used for wipes are often latex and/or foam bonded. Spunlace (hydroentangled forms) of the web are becoming popular for the wipes market. Skyt\textsuperscript{(74)} has identified possibilities for combining the air laid process with other technologies to produce advanced composite structures. This includes multilayer combinations of air laid webs with dry laid (carded), melt-blown, spunbonded, and wet laid webs.

3.2 Characteristics and Properties of Dry Laid Webs

There are several forms of dry laid carded webs for filter media. Included are needle punch felts, hydroentangled felts, thermal bonded, resin bonded and high loft webs. PGI (Polymer Group, Inc.), Charlotte, North Carolina, USA produces a variety of dry laid webs as indicated in Table 3.1. The table differentiates the various products by bonding technology. It does not include needle punch felts that are used for filtration. It indicates the extent of technologies, polymers and fibers, products and applications that can be achieved with dry laid webs.

3.2.1 Needle punched felts

Needle punched felts produced from a wide variety of fiber materials have a broad range of properties, depending on application. The biggest use of needle punch filter felts are in baghouse type dust collection and fume systems. The traditional fibers
### Table 3.1 Carded web filter media of PGI

<table>
<thead>
<tr>
<th>Technology</th>
<th>Raw materials</th>
<th>Products</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>APEX® Spunlace</td>
<td>Polyester (PET), polyolefin (PE and PP), bicomponent, acetates (Rayon), polyaramid, polyphenylene sulphide (PPS), natural fibers (cotton, wool, wood pulp), blends</td>
<td>Spunlace</td>
<td>Dust filtration, liquid filtration, membrane support</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Durapex®</td>
<td>pool &amp; spa, dust bag</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aquapex™</td>
<td></td>
</tr>
<tr>
<td>Thermal Bond</td>
<td>Polyester (PET), polyolefin (PE and PP), bicomponent, acetates (Rayon), cellulose and blends</td>
<td>Klara®</td>
<td>potable water, coolant filtration, membrane backing,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ultraloft™</td>
<td>HVAC filtration, liquid filtration, air filtration,</td>
</tr>
<tr>
<td>Adhesive Bond</td>
<td>Polyester (PET), polyolefin (PE and PP), bicomponent, acetates (Rayon), cellulose and blends</td>
<td>Adhesive bond</td>
<td>Fuel, oil &amp; gas filtration, turbine in-take filtration, air filtration, specialty applications</td>
</tr>
<tr>
<td>Resin Bond</td>
<td>Polyester (PET), polyolefin (PE and PP), bicomponent, cellulose and blends</td>
<td>Resin bond</td>
<td>Coalescing filters, liquid filtration, air filtration, specialty applications</td>
</tr>
</tbody>
</table>

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For this type of fabric are wool, however the industry has converted much of this production to cotton–polyester and 100% polyester. Other more specialized fibers are used to provide needle punch felts with resistance to a broad spectrum of hostile environments. Often the requirement is for very high temperature resistance and resistance to some very corrosive chemicals. Several types of staple fibers may be used to provide the necessary heat resistance for high temperature applications. These include glass microfiber, polyphenylene sulfide (PPS), polyaramid fibers such as Kevlar® and Nomex®, and polyimide fiber (P84®). Ceramic, metal, and carbon fibers are used in applications where a very high degree of temperature and corrosion resistance is required.

In pulse jet filter bags and cartridges, needle punch filter media have to provide surface filtration and release properties so that the filter cake will readily fall off the media in the pulsing operation. Several possible finish treatments are used to enhance this. These include calendering, glazing, and singeing. Calendering is a treatment that smooths the web surfaces by passing the web through a set of high pressure nip rolls. The rolls may be gapped to provide for a uniform thickness. Glazing passes the web through a set of heated, high temperature, nip rolls that are rotating at slightly different surface speeds. The effect is to “iron” into the web a glazed glass-like surface. Singeing is an operation that burns off protruding surface fibers.
3.2.2 Hydroentangled webs

Spunlace and hydroentanglement are the most frequent terms applied to webs consolidated by high velocity water jets. Other terms are jet entangled, water entangled, and hydraulically needled. The product and process was first developed and patented by DuPont in the 1960s and 1970s. DuPont’s product entry into the market place was the product identified as Sontara®. Chicopee Nonwovens (now PGI) and Kendall (now part of Tyco Healthcare) also were early entries into hydroentangled products.

Hydroentanglement uses high speed jets of water to entangle the fibers for integrity enhancement. The entanglement is accomplished by applying the jets to the web as it is supported by a foraminous screen. The foraminous screen may be a porous belt, a patterned screen, or a perforated screen. The process of hydroentanglement is discussed in more detail in Chapter 5, Section 5.1.2.3.2.

Carded dry laid webs are common source of spunlace webs. However air laid, meltblown, spunbonded webs, and wet lay webs have all been hydroentangled. It provides the possibility of providing strength to a loosely bonded medium without the necessity of a thermo-bond or chemical binder. In addition to integrity, hydroentanglement can add depth and dimension to a filter medium structure. Hydroentanglement is one way of inter-bonding the different layers in a composite structure. This is done by proper choice of pattern or apertures in the support screen.

Kamath et al. indicates that air laid and carded webs are the most frequently used webs for hydroentanglement, however, there has been a trend toward wet laid precursor webs. C.E. White reports on hydroentanglement technology applied to wet laid precursor webs. He mentions that Dexter Corporation (now Ahlstrom), Windsor Locks, Connecticut uses the Unicharm® technology to produce fabrics from wet lay technology.

Spunlace or hydroentangled felts are becoming significant in the market place for baghouse filter media. They are also finding applications for other forms of filtration such as turbine intake filters and liquid bag filters. It will be noted from Table 3.1 above that PGI is a producer of Spunlace and proprietary imaged Spunlace webs for liquid and dust filtration.

3.2.3 High loft filter media

High loft filter media pictured in Figure 3.1 are carded or melt spun webs that are produced to be bulky and thick. Usually they are composed of polyester fiber, however other fibers are often utilized. This includes natural fibers such as hogs hair and coconut fiber. High loft webs can be obtained by thermo-bonding and less often by chemical or resin bonding. Sheath-core bi-component fibers with low melting sheaths are often used as the melt binder. Loft and thickness are accomplished by thru-air oven heating. The loft or thickness can be regulated or controlled to give mats with thicknesses greater than 3 mm (0.12 in.). High loft mats are used in residential furnace and air-conditioning systems and also in paint spray booths. In many applications the filters are the mats cut to a specific size. Either the supplier cuts the mats into custom sized sheets or the user buys the mat in roll or large sheet form and cuts the pads to the dimensions of his filter opening.
3.3 Characteristics and Properties of Spunbonded Webs

Malkan and Wadsworth\(^{14}\) identifies the following as being characteristics of spunbonded webs:

(a) Random fiber structure.
(b) Generally the web is white with high opacity per unit area.
(c) Most spunbonded webs have a layered or shingled structure, the number of layers increases with increasing basis weight.
(d) Grammages (basis weights) range between 5 and 800 g/m\(^2\), typically 10–20 g/m\(^2\).
(e) Fiber diameters range between 1 and 50 \(\mu\)m, but the preferred range is between 15 and 35 \(\mu\)m.
(f) Web thickness ranges between 0.1 and 4.0 mm, typically 0.2–1.5 mm.
(g) High strength-to-weight ratios compared to other nonwoven, woven, and knitted structures.
(h) Planar isotropic properties due to random lay down of the fibers.
(i) Good fray and crease resistance.
(j) High liquid retention capacity due to high void content.
(k) High in-plane shear resistance.
(l) Low drapeability.
Properties of Nonwoven Filter Media

Spunbonded webs can be produced from polyester (Reemay®), nylon (Cerex® and PBN-II®), polypropylene (Typar® and Tekton®), and polyethylene (Tyvek® and SoloFlo®).

Fiberweb™ in West Chester, Ohio is a major manufacturer of spunbond polyester for filtration purposes. Fiberweb™ manufactures the media under the trade name of Reemay®. Table 3.2 lists typical properties. Note that Reemay® is produced with straight fibers or crimped fibers and with round or trilobal cross-sections. The bulking effect of the crimped fibers is evident from the data. For example, straight fiber Grade 2040

<table>
<thead>
<tr>
<th>Style no.</th>
<th>Filament cross-section</th>
<th>Basis weight (gsm)</th>
<th>Thickness (mm)</th>
<th>Grab tensile (N) MX × XD</th>
<th>Trap tear (N) MD × XD</th>
<th>Mullen burst (kPa)</th>
<th>Pruefer air perm (l/m²/s)</th>
<th>Texest air perm (l/m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Straight fibers</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>T</td>
<td>14</td>
<td>0.13</td>
<td>41 × 32</td>
<td>14 × 14</td>
<td>62</td>
<td>7.110</td>
<td>7.750</td>
</tr>
<tr>
<td>2005</td>
<td>T</td>
<td>19</td>
<td>0.18</td>
<td>50 × 36</td>
<td>14 × 18</td>
<td>N/A</td>
<td>6.095</td>
<td>7.205</td>
</tr>
<tr>
<td>2006</td>
<td>T</td>
<td>20</td>
<td>0.18</td>
<td>45 × 36</td>
<td>18 × 21</td>
<td>89</td>
<td>5.995</td>
<td>6.909</td>
</tr>
<tr>
<td>2011</td>
<td>T</td>
<td>25</td>
<td>0.23</td>
<td>63 × 50</td>
<td>23 × 27</td>
<td>110</td>
<td>5.435</td>
<td>5.649</td>
</tr>
<tr>
<td>2014</td>
<td>T</td>
<td>34</td>
<td>0.25</td>
<td>95 × 77</td>
<td>27 × 32</td>
<td>151</td>
<td>4.470</td>
<td>4.369</td>
</tr>
<tr>
<td>2016</td>
<td>T</td>
<td>46</td>
<td>0.25</td>
<td>144 × 113</td>
<td>12 × 41</td>
<td>220</td>
<td>2.745</td>
<td>2.784</td>
</tr>
<tr>
<td>2024</td>
<td>T</td>
<td>73</td>
<td>0.30</td>
<td>279 × 212</td>
<td>41 × 50</td>
<td>358</td>
<td>1.575</td>
<td>1.641</td>
</tr>
<tr>
<td>2033</td>
<td>T</td>
<td>100</td>
<td>0.43</td>
<td>387 × 351</td>
<td>68 × 77</td>
<td>N/A</td>
<td>1.310</td>
<td>1.300</td>
</tr>
<tr>
<td>2040</td>
<td>T</td>
<td>136</td>
<td>0.51</td>
<td>563 × 450</td>
<td>63 × 86</td>
<td>681</td>
<td>965</td>
<td>885</td>
</tr>
<tr>
<td>2250</td>
<td>R</td>
<td>17</td>
<td>0.11</td>
<td>50 × 32</td>
<td>18 × 23</td>
<td>76</td>
<td>5.485</td>
<td>6.640</td>
</tr>
<tr>
<td>2275</td>
<td>R</td>
<td>25</td>
<td>0.15</td>
<td>68 × 63</td>
<td>27 × 32</td>
<td>117</td>
<td>4.410</td>
<td>4.699</td>
</tr>
<tr>
<td>2200</td>
<td>R</td>
<td>36</td>
<td>0.20</td>
<td>95 × 90</td>
<td>12 × 32</td>
<td>158</td>
<td>3.370</td>
<td>3.378</td>
</tr>
<tr>
<td>2214</td>
<td>R</td>
<td>46</td>
<td>0.23</td>
<td>144 × 135</td>
<td>41 × 45</td>
<td>193</td>
<td>2.645</td>
<td>2.631</td>
</tr>
<tr>
<td>2217B</td>
<td>R</td>
<td>58</td>
<td>0.28</td>
<td>171 × 162</td>
<td>54 × 54</td>
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<td>2.365</td>
<td>2.164</td>
</tr>
<tr>
<td>2295</td>
<td>R</td>
<td>100</td>
<td>0.46</td>
<td>338 × 320</td>
<td>108 × 108</td>
<td>509</td>
<td>1.270</td>
<td>1.245</td>
</tr>
<tr>
<td>7061</td>
<td>T</td>
<td>46</td>
<td>0.32</td>
<td>131 × 108</td>
<td>32 × 41</td>
<td>N/A</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td><strong>Crimped fibers</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>2410</td>
<td>T</td>
<td>39</td>
<td>0.36</td>
<td>68 × 50</td>
<td>32 × 36</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2415</td>
<td>T</td>
<td>53</td>
<td>0.41</td>
<td>108 × 81</td>
<td>41 × 50</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2420</td>
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<td>63</td>
<td>0.43</td>
<td>135 × 99</td>
<td>50 × 59</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>2430</td>
<td>T</td>
<td>81</td>
<td>0.48</td>
<td>198 × 153</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>2440</td>
<td>T</td>
<td>98</td>
<td>0.53</td>
<td>252 × 189</td>
<td>81 × 104</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2470</td>
<td>T</td>
<td>203</td>
<td>0.81</td>
<td>567 × 430</td>
<td>167 × 212</td>
<td>564</td>
<td>845</td>
<td>818</td>
</tr>
</tbody>
</table>

The following test methods are used to measure typical properties:

- Unit weight: ASTM D-3776
- Thickness: ASTM D-1777
- Grab tensile: ASTM D-4632
- Trap tear: ASTM D-1117
- Mullen burst: ASTM D-3786
- Air permeability: ASTM D-737

Note:
- 2000 Series Trilobal Fiber Diameter = 21 μ
- 2200 Series Round Fiber Diameter = 16 μ
- 2400 Series Trilobal Fiber Diameter = 23 μ

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Table 3.3 Kimberly-Clark Intrepid™ Filter Media

<table>
<thead>
<tr>
<th>Grade</th>
<th>353H</th>
<th>355H</th>
<th>411SP</th>
<th>612L</th>
<th>684L</th>
<th>854L</th>
<th>984L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>White</td>
<td>White</td>
<td>Gold/White</td>
<td>White</td>
<td>White</td>
<td>White</td>
<td>White</td>
</tr>
<tr>
<td>Basis weight, oz/yd²</td>
<td>1.65</td>
<td>2.2</td>
<td>2.75</td>
<td>3.25</td>
<td>3.25</td>
<td>4.0</td>
<td>3.40</td>
</tr>
<tr>
<td>Grammage, g/m²</td>
<td>56</td>
<td>75</td>
<td>93</td>
<td>110</td>
<td>110</td>
<td>136</td>
<td>115</td>
</tr>
<tr>
<td>Efficiency*, %</td>
<td>27</td>
<td>43</td>
<td>55</td>
<td>59</td>
<td>56</td>
<td>71</td>
<td>80</td>
</tr>
<tr>
<td>Permeability cfm/ft² @ 0.5&quot; H₂O ΔP</td>
<td>700</td>
<td>487</td>
<td>370</td>
<td>235</td>
<td>330</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>m³/s/m² @ 12.7 mm H₂O ΔP</td>
<td>3.58</td>
<td>2.47</td>
<td>1.88</td>
<td>1.19</td>
<td>1.67</td>
<td>0.66</td>
<td>0.37</td>
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<tr>
<td>Caliper</td>
<td>0.080</td>
<td>0.095</td>
<td>0.100</td>
<td>0.042</td>
<td>0.53</td>
<td>0.47</td>
<td>0.55</td>
</tr>
<tr>
<td>Stiffness, mg</td>
<td>2.0</td>
<td>2.4</td>
<td>2.5</td>
<td>1.1</td>
<td>1.35</td>
<td>1.2</td>
<td>1.4</td>
</tr>
</tbody>
</table>

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Reproduced from product data on Kimberly-Clark website: www.kcfiltration.com

has a grammage (basis weight) of 136 gsm and a thickness of 0.51 mm. Crimped fiber Grade 2440 is considerably lighter at 98 gsm and yet has the same or slightly more thickness at 0.53 mm. Also note that the spunbonded products can be spun with either round fibers or trilobal fibers. Fiberweb™ also manufactures Reemay Elite© as a membrane support medium, and Reemay Advantage© and Reemay Freedom© for swimming pool filtration. The Reemay Advantage© and Reemay Freedom© swimming pool media are treated with Microban® for antimicrobial product protection. Fiberweb™ also manufactures a composite filtration product under the trade name of Synergex®.

Typar®/Tekton® are the trade names of polypropylene spunbonded filter media marketed by Fiberweb™ Filtration. Typar® is the name used in North America, South America, Israel, and South Africa. Tekton® is the name used elsewhere in the world. Typical properties are listed in Table 7.6 in Chapter 7. Kimberly-Clark Worldwide Inc. produces a proprietary spunbonded composite from a patented spunbond process. Marketed as their Intrepid™ filter medium, it is a dual layer gradient density medium that is electrostatically charged. The thermally bonded medium contains two layers of polyolefin fibers that are not independently produced and laminated together but formed together at the same time. The medium is generally used in pleated air filter applications.

Cerex Advanced Fabrics manufactures and markets nylon spunbonded media for several purposes including filter media. Two such products are Cerex® and PBN-II®. Cerex® is autogenously bonded by exposing the web to a chemically activating gas phase that is later removed from the web. It is designed to be a flat, smooth, strong, crisp fabric. PBN-II® is thermally bonded with a cross-hatch bonding pattern. In contrast to Cerex®, the PBN-II® fabric is drapeable, conformable, and textile-like. Tables 3.4 and 3.5 are tabulations of the Cerex® and PBN-II® products, respectively. Note that the spunbonded nylon fibers are available in round or trilobal form.

Although not included in the family of spunbonded materials, spun glass is a continuous filament glass fiber spun into a nonwoven structure that is used for residential air filtration.
Table 3.4  Typical physical properties of Cerex® fabrics

<table>
<thead>
<tr>
<th>Filament geometry</th>
<th>Fabric weight&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Average thickness&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Grab tensile strength&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Trapezoid tear strength&lt;sup&gt;d&lt;/sup&gt;</th>
<th>Burst strength&lt;sup&gt;e&lt;/sup&gt;</th>
<th>Air permeability&lt;sup&gt;f&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>osy</td>
<td>gsm</td>
<td>mil</td>
<td>mm</td>
<td>lb</td>
<td>N</td>
</tr>
<tr>
<td>Round</td>
<td>0.25</td>
<td>8</td>
<td>2.6</td>
<td>0.07</td>
<td>7</td>
<td>31</td>
</tr>
<tr>
<td>Round</td>
<td>0.3</td>
<td>10</td>
<td>2.6</td>
<td>0.07</td>
<td>8</td>
<td>36</td>
</tr>
<tr>
<td>Round</td>
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<td>14</td>
<td>3.0</td>
<td>0.08</td>
<td>12</td>
<td>53</td>
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<tr>
<td>Round</td>
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<td>17</td>
<td>3.3</td>
<td>0.08</td>
<td>16</td>
<td>71</td>
</tr>
<tr>
<td>Round</td>
<td>0.6</td>
<td>20</td>
<td>3.6</td>
<td>0.09</td>
<td>20</td>
<td>89</td>
</tr>
<tr>
<td>Round</td>
<td>0.7</td>
<td>24</td>
<td>3.8</td>
<td>0.10</td>
<td>25</td>
<td>111</td>
</tr>
<tr>
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<td>0.85</td>
<td>29</td>
<td>4.4</td>
<td>0.11</td>
<td>30</td>
<td>134</td>
</tr>
<tr>
<td>Round</td>
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<td>34</td>
<td>4.8</td>
<td>0.12</td>
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<td>165</td>
</tr>
<tr>
<td>Round</td>
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<td>51</td>
<td>6.4</td>
<td>0.16</td>
<td>59</td>
<td>263</td>
</tr>
<tr>
<td>Round</td>
<td>2.0</td>
<td>68</td>
<td>7.9</td>
<td>0.21</td>
<td>78</td>
<td>347</td>
</tr>
<tr>
<td>Trilobal&lt;sup&gt;g&lt;/sup&gt;</td>
<td>0.25</td>
<td>8</td>
<td>2.6</td>
<td>0.07</td>
<td>7</td>
<td>29</td>
</tr>
<tr>
<td>Trilobal&lt;sup&gt;g&lt;/sup&gt;</td>
<td>0.4</td>
<td>14</td>
<td>3.4</td>
<td>0.09</td>
<td>12</td>
<td>52</td>
</tr>
<tr>
<td>Trilobal&lt;sup&gt;g&lt;/sup&gt;</td>
<td>0.045</td>
<td>15</td>
<td>3.6</td>
<td>0.09</td>
<td>13</td>
<td>60</td>
</tr>
<tr>
<td>Trilobal&lt;sup&gt;g&lt;/sup&gt;</td>
<td>0.5</td>
<td>17</td>
<td>3.8</td>
<td>0.10</td>
<td>16</td>
<td>71</td>
</tr>
<tr>
<td>Trilobal&lt;sup&gt;g&lt;/sup&gt;</td>
<td>0.85</td>
<td>29</td>
<td>4.5</td>
<td>0.11</td>
<td>27</td>
<td>119</td>
</tr>
<tr>
<td>Trilobal&lt;sup&gt;g&lt;/sup&gt;</td>
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<td>149</td>
</tr>
<tr>
<td>Trilobal&lt;sup&gt;g&lt;/sup&gt;</td>
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<td>51</td>
<td>6.9</td>
<td>0.18</td>
<td>47</td>
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</tr>
</tbody>
</table>

<sup>a</sup>ASTM D-3776-83; <sup>b</sup>ASTM D-1777-80; <sup>c</sup>ASTM D-5034-90; <sup>d</sup>ASTM D-1117-80; <sup>e</sup>ASTM D-3786-87; <sup>f</sup>ASTM D-737-75

<sup>g</sup>These are tentative typical properties based on one roll sampled from one production lot. Other basis weights available upon request.

Table 3.5  Typical properties of PBN-II® fabrics

<table>
<thead>
<tr>
<th>Filament geometry</th>
<th>Fabric weight&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Average thickness&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Grab tensile strength&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Trapezoid tear strength&lt;sup&gt;d&lt;/sup&gt;</th>
<th>Burst strength&lt;sup&gt;e&lt;/sup&gt;</th>
<th>Air permeability&lt;sup&gt;f&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>osy</td>
<td>gsm</td>
<td>mil</td>
<td>mm</td>
<td>lb</td>
<td>N</td>
</tr>
<tr>
<td>Round</td>
<td>0.3</td>
<td>10</td>
<td>3.9</td>
<td>0.10</td>
<td>7</td>
<td>31</td>
</tr>
<tr>
<td>Round</td>
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<td>14</td>
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<td>0.11</td>
<td>10</td>
<td>44</td>
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<tr>
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<td>58</td>
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<tr>
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<td>20</td>
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<td>0.36</td>
<td>76</td>
<td>338</td>
</tr>
<tr>
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<td>15.9</td>
<td>0.40</td>
<td>99</td>
<td>441</td>
</tr>
<tr>
<td>Round</td>
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<td>102</td>
<td>18.4</td>
<td>0.47</td>
<td>122</td>
<td>543</td>
</tr>
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<td>Round</td>
<td>4.0</td>
<td>136</td>
<td>21.8</td>
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<td>699</td>
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<tr>
<td>Trilobal</td>
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<td>8</td>
<td>4.2</td>
<td>0.11</td>
<td>5</td>
<td>21</td>
</tr>
<tr>
<td>Trilobal</td>
<td>0.3</td>
<td>10</td>
<td>4.7</td>
<td>0.12</td>
<td>7</td>
<td>30</td>
</tr>
<tr>
<td>Trilobal</td>
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<td>9.2</td>
<td>0.23</td>
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<td>115</td>
</tr>
<tr>
<td>Trilobal</td>
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<td>34</td>
<td>10.3</td>
<td>0.26</td>
<td>32</td>
<td>141</td>
</tr>
</tbody>
</table>

<sup>a</sup>ASTM D-3776-85; <sup>b</sup>ASTM D-1777-80; <sup>c</sup>ASTM D-5034-90; <sup>d</sup>ASTM D-1117-80; <sup>e</sup>ASTM D-3786-87; <sup>f</sup>ASTM D-737-75

3.4 Characteristics and Properties of Melt-Blown Webs

Malkan and Wadsworth\textsuperscript{14} identifies the following as being characteristics of melt-blown webs:

(a) Random fiber orientation.
(b) Low to moderate web strength.
(c) Generally, the web is highly opaque (high cover factor).
(d) Melt-blown webs derive their strength from mechanical entanglement and frictional forces.
(e) Most melt-blown webs are layered or shingled structures, the number of layers increases with increasing basis weight.
(f) Grammages (basis weights) range between 8 and 350 g/m\textsuperscript{2}, typically 20–200 g/m\textsuperscript{2}.
(g) Fiber diameters range between 0.5 and 30 \(\mu\)m, but the typical range is 2–7 \(\mu\)m.
(h) Microlifers provide high surface area for good insulation and filtration characteristics.
(i) The fibers have smooth texture and appear to be circular in cross-section.
(j) The fibers vary in diameter along a single fiber, as shown in Figure 3.2.
(k) Fibers are continuous in length.
(l) Fibers show thermal branching as indicated in Figure 3.3. It is not certain as to exactly what causes thermal branching, however it is caused by complexities in the extruded fiber–air stream as it approaches the collector plate. See Chapter 5, Section 5.14.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.2.png}
\caption{Variation in fiber diameter along a single fiber.}
\end{figure}

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Figure 3.3. Thermal branching of fibers in melt-blown webs.
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Table 3.6 LyPore® MB calendered typical properties

<table>
<thead>
<tr>
<th>Grade</th>
<th>Basis weight (gsm)</th>
<th>Thickness (mils)</th>
<th>Resistance (mm)</th>
<th>Frazier (CFM)</th>
<th>MFP (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA 9201</td>
<td>25</td>
<td>2.0</td>
<td>10</td>
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<td>8.5</td>
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<tr>
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<td>7</td>
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<td>13.5</td>
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<td>5.7</td>
<td>35</td>
<td>4</td>
<td>5.2</td>
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<tr>
<td>CA 9401</td>
<td>45</td>
<td>6.0</td>
<td>25</td>
<td>8</td>
<td>7.0</td>
</tr>
<tr>
<td>CA 9402</td>
<td>45</td>
<td>6.5</td>
<td>15</td>
<td>120</td>
<td>12.0</td>
</tr>
<tr>
<td>CA 9403</td>
<td>45</td>
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<td>7</td>
<td>35</td>
<td>15.0</td>
</tr>
<tr>
<td>CA 9600</td>
<td>65</td>
<td>4.2</td>
<td>750</td>
<td>&lt;0.5</td>
<td>2.0</td>
</tr>
<tr>
<td>CA 9601</td>
<td>65</td>
<td>4.9</td>
<td>120</td>
<td>1.2</td>
<td>3.0</td>
</tr>
<tr>
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<td>7.5</td>
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<td>3.5</td>
<td>5.0</td>
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<td>14.0</td>
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<td>CA 9800</td>
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<td>700</td>
<td>&lt;0.5</td>
<td>1.7</td>
</tr>
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<td>275</td>
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<tr>
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<td>6.7</td>
<td>100</td>
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</tr>
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<td>1.5</td>
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<tr>
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<td>750</td>
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<td>17.6</td>
<td>25</td>
<td>7.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

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Table 3.7 LyPore® MB uncalendered typical properties.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Micron rating (µ)</th>
<th>Basis weight (gsm/m²)</th>
<th>Frazier (cfm)</th>
</tr>
</thead>
<tbody>
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<td>CL 9007</td>
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<td>16.5</td>
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<tr>
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<td>329</td>
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</tr>
<tr>
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</tr>
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<td>129</td>
<td>120</td>
</tr>
</tbody>
</table>

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In most filter applications melt-blown webs are used as part of a composite structure in combination with spunbond or wet laid webs – but not always. Lydall Filter/Separation Group markets a line of 100% melt-blown polypropylene liquid filter media under their trade name of LyPore® MB. The media are available in calendered and uncalendered versions. Tables 3.6 and 3.7 are typical property tabulations of the calendered and uncalendered versions, respectively.

3.5 Characteristics and Properties of Wet Laid Webs

Wet laid filter media have a broad variety of properties and characteristics, depending on application, design, raw materials, and manufacturing process. The two fundamental types of media are base sheet filter media and resin treated filter media.

3.5.1 Base sheet

The author defines base sheet filter media as filter papers that are not resin treated or not yet resin treated downstream of the forming process. The term “raw stock” is also applied to this form of wet laid media. The definition includes paper that may later be resin treated either in-line or off-line. This discussion is concerned with base sheet that is sold as filter media without any post-formation resin treatment. Most base sheets are used in liquid filtration applications and are further discussed in Chapter 7. Examples are: many forms of laboratory filter papers, filter sheets, industrial filter paper for filter presses, coffee filter, and papers for the filtration of edible oils. These papers are produced from cellulose wood and vegetable fiber pulps, blends of synthetic and pulp fibers, and from glass fibers. Base papers may also contain diatomaceous earth, activated carbon, perlite clay, and other powder fillers. Several types of media used in industrial filter applications, such as filter presses, are creped to increase surface area for filtration. Filter sheets are designed for depth filtration and are produced at grammages much higher than other types of paper filter media. Special wet lay machines are used to produce this type of media. Filter media used for one shot disposable applications, such as laboratory filter papers, coffee filter, and
biological and medical filtration are produced at the low end of the grammage scale. Laboratory filter papers used for analytical purposes have to be composed of extremely pure materials so as not to contaminate the analysis. For example, ash content (non-combustible) is specified for many grades of laboratory filter papers.

Although the author defines base paper as not being resin treated downstream of the forming process, this does not mean to say that the paper does not contain a resin. Most base sheet filter papers contain a resin added by “beater addition”, i.e. the resin is mixed with the fiber slurry prior to the forming process. Other additives and fillers are added this way to provide special properties, such as biological resistance and adsorption properties. Beater addition resins are intended to provide dry and/or wet strength to the media. The wet strength is important for the many applications designed for filtration of aqueous fluids.

3.5.2 Resin treated filter media

Resin treated filter media are mostly designed for use in pleated filter cartridges and panels. The fiber composition is chosen to provide for filtration properties such as bulk, permeability, and pore size, whereas the resins are chosen to provide processability, strength, endurance, and stability. It is important that the paper be stiff and yet flexible enough to go through the pleating process and not degrade in the thermal aspects of this process. In the end use application, the medium has to have the strength and rigidity to maintain their structural integrity against the pressure of the fluid flowing through them. Pleat collapse is to be avoided. They also have to be resistant to the thermo-chemical environment to which they are exposed. In short the best filter medium are worthless if they cannot be made into a lasting filter.

Resin treated filter media are categorized by the type of resin: water- or solvent-based resins (solvent defined as a nonaqueous fluid such as methanol). The media are also categorized by whether the resin is a thermoplastic resin or a thermosetting resin. A thermoplastic resin softens when a medium is heated for the pleating operation. After the media is pleated, the resin is cooled, and the pleats are set. A medium treated with a thermosetting resin is usually B-staged (uncured) when presented to the pleating operation. It is flexible and pliable for pleating. After the pleat folds are formed the medium is subject to an oven type of heat treatment to cure the resin, stiffen the medium, and fix the pleats.

Water-based resins offer a wider choice of polymers than do solvent-based resins. The most common type of polymers are polyvinyl acetate, polyacrylates, styrene acrylates, ethylene vinyl chloride, and water-based phenolics. Most often, they come in the form of a latex emulsion something like latex paint. Most latex resins used by the nonwovens industry are designed to be soft and provide hand to the fabric. In contrast resins used for filter media are intended to provide stiffness and high modulus. Tg (glass transition temperature) of latex resins used for filter paper are usually in the range of 30–50°C.

Some polymers are available or prepared as solution polymers. This includes starch, polyvinyl alcohol, and some forms of phenolics. Water-based resins can range from thermoplastic to thermosetting depending how they are formulated. Catalysts,
cross-linking agents, and curing agents are often employed to provide some degree of
cure or thermoset. Other ingredients can be added to provide for properties such as
flame retardancy, water repellency, dimensional stability, formaldehyde control, etc.

Almost all solvent-based resins are thermosetting and are based on phenol
formaldehyde polymer (phenolic). There are some applications where epoxies are used.
At one time solvent-based polyvinyl acetate was used for automotive air intake filter
media. The largest use of phenolic filter media are for automotive engine oil and fuel fil-
tration. For over 50 years filter media made from solvent-based phenol formaldehyde
have unique properties that, to date, have not been duplicated by any water-based
system. Unlike water, alcohol solvent does not cause fiber swelling and related pinch-
ing of pore structure. Better filtration results are obtainable with phenolic media
than comparable water-based media. Uncured phenolic media can be B-staged to be
pliable for the pleating process and cured to a very rigid structure. The cured media
have good moisture resistance, excellent heat and temperature resistance up to over
150°C, and good resistance to many chemical environments. The biggest concern
related to phenolic filter media are the environmental emissions of volatile organic
compounds (VOC), which include the solvent, formaldehyde, and phenol. People
who produce and process these media have to comply with severe government
restrictions on emissions.

An important feature of resin treated filter media is that they are often corrugated.
The corrugations in filter media are different than the corrugations in corrugated
board for containers. The board corrugations are in the cross-direction of the sheet
whereas the corrugations in filter media are machine direction oriented. The corru-
gations are actually embossed into the media as they pass through a set of rollers that
are grooved to have a set of meshing sine wave configurations on their surfaces. The
corrugation process is discussed in more detail in Chapter 5, Section 5.2.4.1. Figure
3.4 depicts resin treated filter paper that is corrugated. The corrugation depth of a
corrugated filter media are in the range of 0.2–0.5 mm (8–20 mil). Figure 3.5 is a pic-
ture of a corrugated medium from a panel filter pack used for engine air intake filtra-
tion. Note that the pleats are tightly packed. The corrugations serve as pleat spacers
and provide flow channels to the inside of the pleat folds. The flow channels allow the full
area of the medium to be utilized in the filtration application. Accordingly, corruga-
tion adds several features to the media:

1. It increases the surface area for filtration.
2. The corrugations act as pleat separators for the pleat folds.
3. In filters where the pleat folds are close together, the corrugations come
together to provide flow channels to the interior of the pleat pack.
4. The corrugations provide additional stiffness to the medium in the machine
direction, the direction in which the pleat pack is most vulnerable to pressure
deformation.

Some pleating lines like to purchase flat (noncorrugated) media and emboss them
with carefully designed dimples such as shown in Figure 3.6. The embossments
serve as pleat spacers in the pleat pack.
Figure 3.4. Corrugated media.

Figure 3.5. Corrugated medium from an auto air intake panel pleat pack. The corrugations serve as pleat separators and provide flow channels to the interior of the pleat folds.
3.5.3 Glass microfiber filter media

Almost all HEPA (high efficient particulate air) and ULPA (ultra low penetration air) filter media containing glass microfibers and many ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) grades are produced by the wet lay process. In North America two major producers of glass filtration grades are Lydall Filtration/Separation Group (Lydall) in Rochester, New Hampshire and Hollingsworth & Vose Co., Inc. (H&V) in East Walpole, Massachusetts.

The following tables (Tables 3.8 and 3.9) list the glass microfiber filter products of Lydall designated by their Lydair® trade name. Table 3.8 lists grades used in ASHRAE applications discussed in Chapter 8. Table 3.9 lists glass microfiber grades used for high efficiency HEPA applications. Note that properties identified for micro-glass filter media include water repellency which, in this case, is the height of water that the media will support before penetration occurs and LOI (loss on ignition) which is an indicator of organic binder content (that which is burned off).
Dioctylphthalate (DOP) percent is the filter medium penetration by DOP smoke. Resistance is the pressure drop across the media in mm H₂O at the specified flow rate (1.1 cfm or 32 l/min in accordance with ASME AG-1\(^{(148)}\)).

### Table 3.8  Typical values of Lydair® ASHRAE grades

<table>
<thead>
<tr>
<th>Grade</th>
<th>BW (#/3,000 ft²)</th>
<th>Caliper (g/in.)</th>
<th>Tensile (g/in.)</th>
<th>Stiffness MD (mg)</th>
<th>LOI (%)</th>
<th>DOP (%)</th>
<th>Resistance (mm)</th>
<th>Water rep. (inches H₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1909</td>
<td>40</td>
<td>13</td>
<td>5,000</td>
<td>2,000</td>
<td>1,000</td>
<td>11.5</td>
<td>85</td>
<td>1</td>
</tr>
<tr>
<td>1894</td>
<td>42</td>
<td>13</td>
<td>6,000</td>
<td>1,700</td>
<td>1,000</td>
<td>11.5</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>1229B</td>
<td>50</td>
<td>16</td>
<td>4,000</td>
<td>1,400</td>
<td>925</td>
<td>6</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>1923</td>
<td>42</td>
<td>12.5</td>
<td>6,000</td>
<td>1,800</td>
<td>1,000</td>
<td>11.5</td>
<td>38</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grade</th>
<th>BW (#/3,000 ft²)</th>
<th>Caliper (g/in.)</th>
<th>Tensile (g/in.)</th>
<th>Stiffness MD (mg)</th>
<th>LOI (%)</th>
<th>DOP (%)</th>
<th>Resistance (mm)</th>
<th>Water rep. (inches H₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>247</td>
<td>48</td>
<td>16</td>
<td>6,000</td>
<td>2,500</td>
<td>1,700</td>
<td>10</td>
<td>85</td>
<td>0.8</td>
</tr>
<tr>
<td>1296</td>
<td>48</td>
<td>16</td>
<td>7,000</td>
<td>2,000</td>
<td>1,700</td>
<td>10</td>
<td>50</td>
<td>3.5</td>
</tr>
<tr>
<td>1306</td>
<td>48</td>
<td>15</td>
<td>6,000</td>
<td>2,000</td>
<td>1,250</td>
<td>9.3</td>
<td>30</td>
<td>5.9</td>
</tr>
<tr>
<td>1297</td>
<td>48</td>
<td>15</td>
<td>6,000</td>
<td>2,000</td>
<td>1,300</td>
<td>9.3</td>
<td>26</td>
<td>6</td>
</tr>
</tbody>
</table>

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### Table 3.9  Typical values of Lydair® HEPA grades

<table>
<thead>
<tr>
<th>Grade</th>
<th>BW (#/3,000 ft²)</th>
<th>Caliper (g/in.)</th>
<th>Tensile (g/in.)</th>
<th>Stiffness MD (mg)</th>
<th>LOI (%)</th>
<th>DOP (%)</th>
<th>Resistance (mm)</th>
<th>Water rep. (inches H₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3428</td>
<td>46</td>
<td>14</td>
<td>4,300</td>
<td>1,700</td>
<td>1,000</td>
<td>6</td>
<td>0.015</td>
<td>34</td>
</tr>
<tr>
<td>3255</td>
<td>55</td>
<td>17</td>
<td>3,800</td>
<td>2,000</td>
<td>1,000</td>
<td>6</td>
<td>0.012</td>
<td>36</td>
</tr>
<tr>
<td>4350</td>
<td>48</td>
<td>16</td>
<td>3,000</td>
<td>1,400</td>
<td>900</td>
<td>6</td>
<td>0.03</td>
<td>27</td>
</tr>
<tr>
<td>4450</td>
<td>48</td>
<td>16</td>
<td>2,900</td>
<td>1,400</td>
<td>1,000</td>
<td>6</td>
<td>0.02</td>
<td>29</td>
</tr>
<tr>
<td>4450-HS</td>
<td>48</td>
<td>15</td>
<td>3,800</td>
<td>1,500</td>
<td>1,300</td>
<td>6</td>
<td>0.02</td>
<td>29</td>
</tr>
<tr>
<td>4470</td>
<td>48</td>
<td>16</td>
<td>3,000</td>
<td>1,400</td>
<td>950</td>
<td>6</td>
<td>0.01</td>
<td>31</td>
</tr>
<tr>
<td>4470-HS</td>
<td>48</td>
<td>15.5</td>
<td>3,900</td>
<td>1,500</td>
<td>1,200</td>
<td>6</td>
<td>0.008</td>
<td>33</td>
</tr>
</tbody>
</table>

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\(^1\)The DOP test and other related tests to measure medium filtration efficiency is discussed in Chapter 6, Section 6.13.1.13.
3.6 Electret Filter Media

Electrets are dielectric materials that exhibit an external electric field in the absence of an applied field. When used in air filtration applications, they can greatly increase initial filtration efficiency and reduce pressure drop, because of its electrostatic attraction for air particles. Films, fibers, and nonwoven web structures are among the materials that can be formed into electrets. There are two distinct categories of electrets: space charge electrets and dipolar electrets. Space charge electrets are formed by the deposit or injection of an electric charge directly into the dielectric material. Dipolar electrets are formed or polarized by the application of an electric field. For polarization to occur polymers must be heated sufficiently to a point where dipoles are mobile and then cooled to fix the new orientation of the dipoles. Myers and Arnold\(^7^7\) report that dipoles can also be formed by charge injection to cause dipole reorientation.

Lifshutz\(^7^8\) identifies four basic families of electret filter media: electrostatically spun fibers, fibrillated electret film, corona treated melt-blown fibers, and carded blends of triboelectric fibers.

3.6.1 Electrostatically spun fibers

The “Electrospun” process for producing electret media is described in Chapter 5, Section 5.1.5. The product from this process is composed of very fine fibers (nanofibers — see Figure 3.7) that are electrostatically charged. The electrospun media achieve high efficiency filtration performance by combining fine fibered structure with electrostatic properties. The medium attributes allow for high surface area, small fiber diameter, layer thinness, and low basis weight. The small fiber diameters are significance because they are 5–10 times smaller than the smallest melt-blown fibers available. Fiber diameters as low as 0.25 μm (250 nm) have been used in commercial and military filtration operations for more than 20 years\(^1^0^2\). The web itself is very thin. A thickness of four 250 nm nanofiber diameters approaches only one micron.

The thin electrospun webs have limited mechanical properties, therefore, they are used in combination with other substrates. Ultra-Web\(^R\), a nanofiber media combined with a wet laid substrate, is produced by Donaldson Company Inc. It has become available for a broad range of filtration applications (Graham et al.\(^1^6\)).

Graham et al.\(^1^6\) relates the performance of fine fibers to the Knudsen number, previously defined in Chapter 2, Section 2.2.4.4:

\[
Kn = \frac{\lambda}{r_f}
\]

(3.1)

\(Kn\) is the Knudsen number.
\(\lambda\) is the gas mean free path.
\(r_f\) is the radius of the fiber.

Graham et al. argue that at high \(Kn > 0.1\) slip flow will prevail at the fiber surfaces which allows for more air traveling near the fiber surfaces. This translates into more particles...
traveling near the surface thus increasing their probability for capture. Figure 3.8 shows how sub-micron salt crystals preferentially attach to the nanofibers of a spunbond–electrospun composite. Note how few crystals have attached to the spunbond fiber in the upper right hand corner.

Graham, Schreuder-Gibson, and Gogins describe a number of composite structures that combine various substrates with electrospun webs. This includes combination with woven webs, spunbonded nylon, and spunbonded polyester webs. Laminates increase the number of possible combinations. For example, an electrospun–spunbonded was laminated to itself so that the two electrospun layers were on the inside and the spunbonded layers were on the outside. Another combination was to laminate the electrospun–spunbonded to another spunbonded web so that the electrospun layer was sandwiched between the two spunbonded layers. The advantage of having the electrospun layer between the spunbonded layers is that the outer layers protect the nanofiber layer from abrasion and other mechanical damage. It is interesting to note that the electrospun–spunbond combinations were explored for protective apparel that would allow for the high air permeability and yet prevent the penetration of hazardous and toxic aerosols. In such cases, the apparel is a filter and the fabric is a filter medium.

3.6.2 **Fibrillated electret film**

Fibrillated electret film is a unique medium because the fiber source is made differently than the fibers for the other types of filter media discussed in this book. The
The patent by van Turnhout (US Patent 3,998,916) provides a fundamental description of the process. It describes "A method for the manufacture of an electrically charged fibrous media from a highly molecular nonpolar fiber material wherein a web of the fiber material is continuously fed and stretched. At least one side of the stretched web is homopolarly charged by a plurality of corona charging elements. The charged web material is then fibrillated, collected, and processed into a filter".

The process starts with a film that is stretched, in two successive stages, under heat, in the machine direction. While hot, the film is charged by corona discharge. The film is then fibrillated by passing it over a needle roller moving at a different speed than the film. The fibrillation is in the longitudinal direction resulting in a nicely spread layer of ribbon-like fibers which is wound up on a collecting roller. The fiber on this collecting roll is then formed into the desired filter. Myers and Arnold suggest that the collected fibers or fibrils are carded into a filter web. The patent claims that if the charge applied to the top of the film is a negative charge, positive charges are then induced at the bottom side of the media. This two-sided charging provides a filtration advantage because it will electrostatically collect both positively charged and negatively charged particles in its filtration application. The patent also provides a way to charge both sides of the film.

Fibrillated film filter media are used in home furnace and ventilation filters. 3M Company of St. Paul, Minnesota markets these filters under the trade name of Filtrete.
3.6.3 Corona treated melt-blown fibers

Arnold\(^{(81)}\) states "An exemplary conventional method of this type is described in detail in US Patent Number 5,401,446 to Tsai et al. entitled ‘Method and Apparatus for the Electrostatic Charging of a Web or Film’\(^{(82)}\). The patent by Tsai and Wadsworth is not limited to melt-blown fiber, but can be used for any sheet material that lends itself to be a web or film material. In contrast to the van Turnhout patent discussed above, this patent allows for the sheet to be “cold charged”, i.e. the web is charged without heat and stretching. The patent has two embodiments. The first embodiment has the moving web s-wraping around two charged rollers. While in contact with each roller the web passes a charging bar on the side of the web away from the roll. According to the invention, the charged drums have a negative charge, whereas, the charging bars are assumed to be positively charged. The patent also states that the charging means generates electric fields of 1–12 kVDC/cm. The web as it travels around the first drum becomes positively charged on the side against the drum and negatively charged on the side facing the charging bar. The charging reverses itself as the web travels in its s-wrap path around the second drum and past the second charging bar. The web side against the first charging drum now faces the charging bar of the second drum and the web side facing the first charging bar wraps itself against the second charging drum. The web side that was positively charged at the first drum now takes on a negative charge at the second drum and vice versa for the other side of the web.

The second embodiment has the web s-wraping around two sets of four charge positioning rolls as shown in Figure 3.9. Instead of charging drums there are charging shells that cover the web as it transverses the charge positioning rolls. Charging wires are located on the other side of the web, more or less in the middle of the charge positioning rolls. According to the patent, the charging shells are assumed to be positively charged and the charging wires are assumed to be negatively charged. Just as in the first embodiment of the invention, each side of the web is successively exposed to a negative charge followed by a positive charge or vice versa.

The patent indicates that the alternate switching of polarity of the charges to each side of the web results in an improvement in charge density of the web and an improvement in the lifetime of the charge on the web. The patent notes that the polymer in the web should be nonconductive. Polypropylene, polyethylene, polyester, low density polyethylene, polybutylene terephthalate, polycarbonate, polychlorotrifluoroethylene, and polycyclohexyldimethylene terephthalate all fit in this category. The patent also notes that the method is also suitable for charging composite web structures including those that contain both conductive and nonconductive fibers. Polyolefin mixtures to which a small amount of acrylic acid has been grafted retain their charges for longer than would be expected.

The patent provides data demonstrating the effectiveness of the corona discharge technique on filtration performance and on charge aging stability. Table 3.10 is an example of filtration results on several materials charged in accordance with the charging shell embodiment. The testing was done with a TSI Model 8110 tester (see Chapter 6, Section 6.13.1.14) using NaCl aerosol. Filtration efficiency is defined as:

\[
\text{Filtration efficiency} = (100 - P)
\] 

(3.2)
where \( P \) is the penetration of particles through the media percent or fraction. The term \( q_F \) in the last column of Table 3.10 is a measure of filtration quality. It relates the filtration penetration and the pressure drop\(^2\).

\[
q_F = \frac{\ln (1/P)}{\Delta p}
\]  
(3.3)

where \( \Delta p \) is the pressure drop across the media.

\(^2\)The designation \( q_F \) is commonly known as the gamma number and is often designated by \( \gamma \).
Table 3.10  Filtration results from apparatus of Figure 3.9

<table>
<thead>
<tr>
<th>No.</th>
<th>Filt. eff. a</th>
<th>Charging voltage c</th>
<th>Filt. eff. d</th>
<th>Δp</th>
<th>qP</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>71.65</td>
<td>+23, -19 (2X)</td>
<td>99.956</td>
<td>6.9</td>
<td>1.120</td>
</tr>
<tr>
<td>16</td>
<td>71.65</td>
<td>+21, -19 (1X)</td>
<td>99.950</td>
<td>6.55</td>
<td>1.160</td>
</tr>
<tr>
<td>17</td>
<td>41.55</td>
<td>+25, -19 (2X)</td>
<td>96.278</td>
<td>2.3</td>
<td>1.431</td>
</tr>
<tr>
<td>18</td>
<td>41.55</td>
<td>+25, -19 (1X)</td>
<td>95.525</td>
<td>2.55</td>
<td>1.218</td>
</tr>
<tr>
<td>19</td>
<td>24.55</td>
<td>+25, -19 (2X)</td>
<td>80.35</td>
<td>0.9</td>
<td>1.808</td>
</tr>
<tr>
<td>20</td>
<td>24.55</td>
<td>+25, -15 (1X)</td>
<td>81.90</td>
<td>1.0</td>
<td>1.709</td>
</tr>
</tbody>
</table>

a 15 and 16 are 3 oz/yd², 17 and 18 are 1 oz/yd², 19 and 20 are 1 oz/yd² recycled PET.
b Before charging.
c kV for wire, shell (number of chargings).
d After charging.

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Table 3.11  Accelerated aging

<table>
<thead>
<tr>
<th>No.</th>
<th>Filt. Eff. a</th>
<th>Filt. Eff. b</th>
<th>Δp a</th>
<th>Δp b</th>
<th>qP a</th>
<th>qP b</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>98.708</td>
<td>92.390</td>
<td>2.2</td>
<td>2.1</td>
<td>1.977</td>
<td>1.227</td>
</tr>
<tr>
<td>6</td>
<td>98.460</td>
<td>97.370</td>
<td>2.45</td>
<td>2.2</td>
<td>1.703</td>
<td>1.653</td>
</tr>
<tr>
<td>7</td>
<td>99.937</td>
<td>99.866</td>
<td>6.8</td>
<td>6.1</td>
<td>1.084</td>
<td>1.084</td>
</tr>
<tr>
<td>8</td>
<td>99.317</td>
<td>99.279</td>
<td>6.83</td>
<td>6.1</td>
<td>0.730</td>
<td>0.809</td>
</tr>
<tr>
<td>9</td>
<td>98.610</td>
<td>98.588</td>
<td>6.8</td>
<td>6.2</td>
<td>0.629</td>
<td>0.687</td>
</tr>
<tr>
<td>10</td>
<td>98.308</td>
<td>97.583</td>
<td>2.4</td>
<td>2.2</td>
<td>1.700</td>
<td>1.692</td>
</tr>
<tr>
<td>11</td>
<td>98.718</td>
<td>97.178</td>
<td>2.5</td>
<td>2.2</td>
<td>1.743</td>
<td>1.622</td>
</tr>
<tr>
<td>12</td>
<td>98.063</td>
<td>96.143</td>
<td>9.7</td>
<td>9.8</td>
<td>0.407</td>
<td>0.332</td>
</tr>
<tr>
<td>15</td>
<td>99.956</td>
<td>99.925</td>
<td>6.9</td>
<td>6.3</td>
<td>1.120</td>
<td>1.142</td>
</tr>
<tr>
<td>16</td>
<td>99.950</td>
<td>99.886</td>
<td>6.55</td>
<td>6.0</td>
<td>1.160</td>
<td>1.129</td>
</tr>
<tr>
<td>17</td>
<td>96.278</td>
<td>95.858</td>
<td>2.3</td>
<td>2.2</td>
<td>1.431</td>
<td>1.447</td>
</tr>
<tr>
<td>18</td>
<td>95.525</td>
<td>94.913</td>
<td>2.55</td>
<td>2.2</td>
<td>1.218</td>
<td>1.354</td>
</tr>
</tbody>
</table>

a Before accelerated aging.
b After accelerated aging.

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The higher the value of qP, the better is the quality of the medium. It is apparent from the comparison of filtration efficiencies before and after charging that the charging caused a very significant improvement.

Table 3.11 demonstrates how aging effects the electrostatic filtration performance of several media. The aging was accelerated by exposing the webs to 1,370°C for 10 min. There appears to be very little loss in filtration efficiency and qPb because of the accelerated aging.

3.6.4 Carded blends of triboelectric fibers

Triboelectric charging involves the rubbing or intimate contact of two dissimilar dielectric materials. The kinetic energy dissipated from the rubbing action induces a charge transfer. It is believed that contact electrification is affected by the relative affinities of the two contacting materials. Table 3.12 is the triboelectric series of several types of materials. The series is arranged so that materials that donate electrons are at
Table 3.12 Triboelectric series of fiber materials

<table>
<thead>
<tr>
<th>Most positively charged</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiberglass</td>
</tr>
<tr>
<td>Wool</td>
</tr>
<tr>
<td>Nylon</td>
</tr>
<tr>
<td>Viscose</td>
</tr>
<tr>
<td>Cotton</td>
</tr>
<tr>
<td>Wood pulp</td>
</tr>
<tr>
<td>Polyester</td>
</tr>
<tr>
<td>Acetate</td>
</tr>
<tr>
<td>Acrylic</td>
</tr>
<tr>
<td>Polyethylene</td>
</tr>
<tr>
<td>Polypropylene</td>
</tr>
<tr>
<td>Teflon</td>
</tr>
<tr>
<td>Most negatively charged</td>
</tr>
</tbody>
</table>

The triboelectric series is ordered from the top and progressing downward to materials that accept electrons. There are several sources for this series (Brown\cite{1},\cite{2} (p. 125, p. 222), Sutherland and Purchas\cite{3} (p. 176) and Lifshutz\cite{4}). They are not necessarily consistent with each other.

There are variations in the order of materials listed and the types of materials listed. The series presented in Table 3.12 is a simplified redaction with modifications based on the author’s judgment.

It is evident that for a medium to develop a triboelectric charge it must be composed of at least two dissimilar dielectric materials. Lifshutz\cite{4} theorized that the filtration performance of a wet laid medium could be related to the triboelectric difference of the materials. He developed a rating system by assigning numbers to each material, which he defined as triboelectric units (TU). He assigned a TU value to six different fiber materials (glass, polyester, Nylon, acrylic, polypropylene, and polytetrafluoroethylene (PTFE)) in accordance with their position in the triboelectric series. The higher the value, the more positive was the triboelectric charge. Lifshutz produced wet lay handsheets from 50:50 volume mixtures of various selected pairs of the six fibers. He hypothesized that the Gamma number or filtration performance from Equation (3.3) would be related to the absolute difference (∆TU) in the TU values of the two fibers.

\[ \gamma = q_v = C + \text{abs}(\Delta TU) \] (3.4)

Lifshutz tested the 50:50 handsheets in an ATI Q127 DOP penetrometer (see Chapter 6, Section 6.1.3.1.14). The results are presented in Figure 3.10. Based on the \( R^2 \) value of 0.986, the relationship looks pretty good. Note that the constant, \( C \), in Equation (3.4) has the value of 5.485. Presumably this would be the gamma rating of a filter medium that had no electrostatic charge.

Lifshutz mentions that the charge on the wet lay sheets is considerably lower than what is seen on needle punched dry laid media. Gamma values, as high as 200, are encountered in these types of media. Indeed, manufacturers of dry laid media take advantage of triboelectric effects by composing these webs from fiber blends chosen from appropriate ends of the triboelectric series. Hollingsworth & Vose Air Filtration Ltd. offers a line of needle punched felt media under the label of Technostat®.
The brochure states that “Technostat is an electrostatically charged needle-felt comprising two electrically dissimilar synthetic polymers which are especially prepared and processed at the manufacturing stage, creating a charge transfer between the two different types of fiber”. Table 3.13 is a tabulation of the general data for the Technostat line of products. The media is used as filter medium in respirators, industrial air filtration, bacterial filtration for medical filters, residential air filtration, vacuum cleaner filtration, and vehicle cabin filtration.

Table 3.13 Technostat® general data

<table>
<thead>
<tr>
<th>Technostat</th>
<th>Basis weight</th>
<th>Thickness</th>
<th>Roll length</th>
<th>Resistance</th>
<th>Penetration*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>38 g</td>
<td>0.7 mm</td>
<td>250 m</td>
<td>&lt;8 Pa</td>
<td>&lt;53%</td>
</tr>
<tr>
<td>B</td>
<td>45 g</td>
<td>0.8 mm</td>
<td>250 m</td>
<td>&lt;10 Pa</td>
<td>&lt;40%</td>
</tr>
<tr>
<td>C</td>
<td>65 g</td>
<td>1.2 mm</td>
<td>250 m</td>
<td>&lt;20 Pa</td>
<td>&lt;22.7%</td>
</tr>
<tr>
<td>D</td>
<td>85 g</td>
<td>1.5 mm</td>
<td>200 m</td>
<td>&lt;24 Pa</td>
<td>&lt;15.6%</td>
</tr>
<tr>
<td>E</td>
<td>105 g</td>
<td>1.8 mm</td>
<td>200 m</td>
<td>&lt;28 Pa</td>
<td>&lt;9.45%</td>
</tr>
<tr>
<td>F</td>
<td>115 g</td>
<td>2.0 mm</td>
<td>200 m</td>
<td>&lt;30 Pa</td>
<td>&lt;7.35%</td>
</tr>
<tr>
<td>G</td>
<td>165 g</td>
<td>2.5 mm</td>
<td>150 m</td>
<td>&lt;30 Pa</td>
<td>&lt;3.6%</td>
</tr>
<tr>
<td>H</td>
<td>215 g</td>
<td>2.9 mm</td>
<td>125 m</td>
<td>&lt;35 Pa</td>
<td>&lt;2.1%</td>
</tr>
<tr>
<td>I</td>
<td>265 g</td>
<td>3.2 mm</td>
<td>100 m</td>
<td>&lt;40 Pa</td>
<td>&lt;1.26%</td>
</tr>
<tr>
<td>J</td>
<td>315 g</td>
<td>3.8 mm</td>
<td>100 m</td>
<td>&lt;45 Pa</td>
<td>&lt;0.83%</td>
</tr>
<tr>
<td>K</td>
<td>415 g</td>
<td>4.2 mm</td>
<td>100 m</td>
<td>&lt;60 Pa</td>
<td>&lt;0.37%</td>
</tr>
<tr>
<td>L</td>
<td>515 g</td>
<td>4.8 mm</td>
<td>70 m</td>
<td>&lt;70 Pa</td>
<td>&lt;0.192%</td>
</tr>
<tr>
<td>M</td>
<td>265 g</td>
<td>2.8 mm</td>
<td>200 m</td>
<td>&lt;280 Pa</td>
<td>&lt;15.6%</td>
</tr>
<tr>
<td>N</td>
<td>305 g</td>
<td>2.8 mm</td>
<td>120 m</td>
<td>&lt;130 Pa</td>
<td>&lt;7.35%</td>
</tr>
</tbody>
</table>

* Day of manufacture results.

Resistance and penetration data was measured in accordance with BS4400 using 0.65 micron NaCl particles and an air flow rate of 95 l/min.

Basis weights are reported as g/m².

Reproduced with permission of Hollingsworth & Vose Company Inc., East Walpole, Massachusetts, USA.
3.7 Coalescing Media

Coalescing filters separate liquid particles from a fluid stream. The fluid can either be gas or liquid. Gas phase separations are used to separate moisture and/or oil mists from contaminated air streams.

Examples of gas phase separations are:

1. Separation of moisture from moisture laden air streams (demisters).
2. Separation of oil mists from air streams.
   (a) Compressed air operations.
   (b) Crank case ventilation.
   (c) Lubricated machining.
   (d) Cutting processes.

Examples of liquid phase separations are:

1. Separation of liquid moisture particles from organic streams.
   (a) Moisture removal from fuel pipeline streams.
   (b) Diesel fuel filtration in engine operated vehicles.
2. Separation of liquid organic particles from water streams.
   (a) Environmental cleanup of oily water waste streams.
   (b) Purification of water for drinking water and high purity applications in industry.
   (c) Removal of unwanted oil in water-based coolants used for metal working operations.

In water–oil separation, the coalescing filter medium consists of a pleated upstream element and wrapped glass fiber blankets downstream. The pleated elements contain glass fiber filter papers that are in some cases impregnated with phenolic resin to withstand high pressure and vibration.

Generally coalescing theory follows filtration theory.\(^1\) Interception of liquid particles may be either by direct interception, by inertial impaction or by Brownian movement (diffusion). Once collected on the fibers, the droplets have to grow into large drops of sufficient size to be removed from the fiber surface, either by the friction and viscous forces of the fluid flowing through the medium, or by gravity forces, or both. The drops so removed from the fibers either separate by settling to the bottom of the medium or separate in a separating chamber downstream of the media.

There is some concern whether the fibers should be wettable and of low surface energy (hydrophilic in the case of water mists) or nonwettable and of high surface energy (hydrophobic for water mists). If the wettability of the fibers is high, liquid droplets will form film-wise collections on the fibers as shown in Figure 3.11 (a). If too wettable the medium will become “water logged”: resulting in high pressure drop, medium plugging, re-entrainment, and low separation efficiency. On the other hand, if the fibers are not wettable (hydrophilic) the collection will be dropwise as shown in Figure 3.11 (b). If the surface energy is too low to hold the droplets to the fiber surface, they will release and reentrain into the fluid stream.

\(^1\) Ziebold\(^187\) provides a detailed listing of the equations for fiber bed gas–liquid mist coalescence.
Fuel filter/separators for marine and aviation fuel are usually two-stage operations. The first stage is a filter element whose function is to remove particulate matter and to capture and coalesce minute water droplets. The larger coalesced water droplets are eventually forced through the medium and settle to the bottom of the settling chamber provided in the filter housing. The second stage is on the exit side of the filter housing and consists of a filter containing a medium coated with a hydrophobic fluorocarbon coating. The hydrophobic media allows hydrocarbon fuel to pass through but repels any entrained water droplets.

Gas–liquid separation is used to remove oil and particles from compressed air streams. The coalescing filter element uses glass media with fine fiber diameter distribution. This reduces the amount of oil penetrating the filter material. Air velocity through the medium also must be low enough to ensure proper filtration.

A large scale use of coalescing media is for industrial mist eliminators (demisters). The medium is often a bed or thick mat of glass fiber. Demisters are discussed in Chapter 8, Section 8.7. Refer to Figure 8.21 in Chapter 8 for examples of circular mist eliminators.

3.8 Composite Structures

Composite structures are multilayer filter media, each layer serving a different purpose in the filtration/separation phenomena. The structures may serve any of the following purposes:

1. One or more layers provide mechanical support for the other layer or layers doing the filtering. Scrim reinforced needle felts are an example.
2. Provide two or more layers of different filtration efficiency to develop a gradient density medium, i.e. the upstream layers remove the large particle rocks and stones from the fluid whereas the downstream layers remove the fine particles.

3. Combine different separation technologies into one filter medium. For example, an activated carbon layer is combined with one or more nonwoven layers, whereby the nonwoven layers do particulate filtration and the activated carbon layer separates molecular contaminants by adsorption (see Section 3.9).

4. The outer layers serve as a containment to inhibit medium migration, dusting, and particle fallout from the inner layers.

There are many forms of composite structures. Prominent are the SMS (spunbond/melt-blown/spunbond) composites first patented by Robert J. Brock and Gary H. Meitner of Kimberly-Clark in 1977. This structure sandwiches a melt-blown web between two spunbond webs that are thermally bonded by passing them through a set of heated rolls. The structure provides a filter fabric with microfiber filtration capability and exceptional strength properties. Variations include SM (spunbond/melt-blown) and SMMS (spunbond/melt-blown/melt-blown/spunbond). PGI markets SMS filter media under the trade name of TINOVA®.

There are a number of ways of forming composite structures in addition to the SMS process. Among them are:

1. **Laminating:** Two or more different layers of media are sandwiched to achieve the desired composite structure. The different layers may be attached to each other by a glue, latex adhesive or hot melt adhesive. Sometimes electrostatic or Van der Waals forces are sufficient to hold the layers together for the desired filter making process.

2. **Entanglement:** Hydroentanglement, needle punching, and stitch bonding are ways of combining the individual layers.

3. **Multiple forming:** Some forming processes are capable of forming multilayered media. Carding lines with successive in-line carding machines may be capable doing this. Some wet lay machines are capable of forming dual-ply and triple-ply media. Ahlstrom uses a three-ply machine to produce a three layered filter medium composite identified as their Trinitex® technology.

4. **Collector:** One nonwoven layer serves as the collector for forming another type of nonwoven layer. Nanofiber webs from the electrospun process are usually formed this way.

### 3.9 Adsorptive Media

Nonwoven filter media containing adsorbents are used for both of adsorption of contaminants from both air and water. In both situations, it compete with granular or pellet adsorbents used in bed form.
Adsorption of a contaminant on an adsorbent surface can either be by a physical attraction, or a chemical attraction, or a combination of both. In the physical attraction, the particle is bound to the surface by Van der Waals forces. Chemical attraction causes some form of chemical change in the contaminant. Middlebrooks lists the following mechanisms of adsorption:

(a) **Physical adsorption**: A molecular species is attracted to a surface and held in place by weak forces; similar in the concept of condensation of gases. It is a reversible process.

(b) **Chemical adsorption (chem-sorption)**: A molecular species is attracted to a surface and reacts with that surface or something on that surface to form a chemical bond which holds it in place. Typically considered irreversible at constant conditions. Often the surface is impregnated with a chemical that promotes a desired reaction to remove specific contaminants.

(c) **Catalysis**: A molecular species is attracted to the surface which encourages a chemical reaction. The reaction product(s) move away leaving the surface unchanged. Typically, the reaction is considered irreversible.

Adsorbent media are used in a number of applications including filters for odor and irritant vapor control in automobile cabins, residences, commercial HVAC (heat, ventilation, air conditioning) systems, and workplace environments. They are used for control of VOC emissions in industrial locations that otherwise would source these contaminants to the environment. They are very important in the protective clothing, face masks, and respirators used to protect military personnel and civilians that may be exposed to the toxic and poisonous gases used in warfare and terror incidents.

The factors for choosing an adsorbent medium are as follows:

- Types of contaminant(s).
- Amount of adsorbent.
- Type of adsorbent.
- Desired removal efficiency of the contaminants.
- In air filtration, volatility of the contaminants.
- Particle size of the adsorbent.
- Impregnation.
- Concentration of contaminants.
- Humidity.
- Filter format.

Activated carbon filter paper is a form of wet lay medium used greatly in home water filters to remove undesirable taste and odor contaminants. The medium is produced by impregnating a wet lay fiber slurry with particles of activated carbon and producing a single layer wet lay medium with the carbon content. Activated carbon contents of 50–60% are achievable. A resin binder also added to the fiber–carbon slurry is effective in bonding the carbon particles to the fiber matrix. Lydall Filtration/Separation Group in Rochester, New Hampshire produces Actipure® which they promote for...
Table 3.14  Target values of Actipure® activated carbon grades

<table>
<thead>
<tr>
<th>Grade</th>
<th>BW (#/1,000 sq. ft.)</th>
<th>Carbon content</th>
<th>Caliper (8 psi)</th>
<th>Frazier (cfm)</th>
<th>Suggested application</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-688</td>
<td>130</td>
<td>50</td>
<td>0.016</td>
<td>40</td>
<td>Water filtration, air filtration</td>
</tr>
<tr>
<td>C-892</td>
<td>130</td>
<td>50</td>
<td>0.016</td>
<td>28</td>
<td>Water filtration, air filtration</td>
</tr>
<tr>
<td>C-703</td>
<td>100</td>
<td>50</td>
<td>0.032</td>
<td>75</td>
<td>Air filtration</td>
</tr>
</tbody>
</table>

TRACE ORGANICS AMENABLE TO ADSORPTION BY ACTIVATED CARBON

- Aromatic solvents (i.e. benzene, toluene, xylene).
- Polynuclear aromatics (i.e. naphthalene, biphenyl/st).
- Chlorinated aromatics (i.e. chlorobenzene, PCBs, aldrin, endrin, toxaphene, DDT).
- Phenolics (i.e. phenol, cresol, resorcinol).
- High molecular weight aliphatic amines and aromatic amines (i.e. aniline, toluene diamine).
- High molecular weight ketones, esters, ethers, and alcohols (i.e. dextran, polyethylene glycol).
- Surfactants (i.e. alkyl benzene sulfonates).
- Soluble organic dyes (i.e. methylene blue, textile dyes).
- Fuels (i.e. gasoline, kerosene, oil).
- Chlorinated solvents (i.e. carbon tetrachloride, perchlorethylene).
- Aliphatic and aromatic acids (i.e. tar acids, benzoic acid).

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both water and air filtration. Table 3.14 is a summary of their Actipure® activated carbon grades.

Several medium manufacturers produce composite structures that contain a carbon layer sandwiched between two nonwoven layers. Figure 3.12 is a photograph showing the layers of PLEKX® adsorption medium by KX Industries, L.P. In this structure the outer layers are polyester nonwovens. Figure 3.13 is a photomicrograph of the structure. The inner layer is activated carbon particles held together with a thermal bonding resin.

Fiberweb™, Charlotte, North Carolina has introduced their AQF® technology which utilizes a patented fiber structure to suspend functional particles, such as activated carbon, for “molecular filtration applications”. The technology utilizes bicomponent sheath-core fiber with a low melting sheath to bond the structure into a three dimensional network as illustrated in Figure 3.14.

Flanders Corporation in St. Petersburg, Florida markets “Arm and Hammer” pleated filters for residential air-conditioning and furnace systems (Figure 3.15). These filters combine fine particle removal with the odor removal properties of baking soda (sodium bicarbonate – NaHCO₃). Each fiber in the web is coated with a fuzzy covering of baking soda. The “fuzziness” increases odor removal and provides increased surface area for particulate removal. Flanders markets three filter products with the “Arm and Hammer® *" identification: the "Arm and Hammer® Standard Pleated Air

*Arm and Hammer® is a trade name of Church and Dwight Co., Inc.
Figure 3.12. PLEKX adsorption medium by KX Industries, L.P. – an activated carbon layer sandwiched between two nonwoven layers.
Reproduced with permission of KX Industries, L.P., Orange, Connecticut, USA.

Figure 3.13. Microstructure of PLEKX adsorption medium.
Reproduced with permission of KX Industries, L.P., Orange, Connecticut, USA.
Figure 3.14. AQE® by Fiberweb® – patented fiber structure.
Reproduced with permission of Fiberweb®. Simpsonville, North Carolina, USA.

Figure 3.15. Flanders standard filter with Arm and Hammer baking soda for odor removal purposes.
Reproduced with permission of Flanders-Precisionair, St. Petersburg, Florida, USA.
Filter” for filtering particles as small as 5 μm, the “Arm and Hammer® Microparticle Pleated Air Filter” for filtering particles as small as 1 μm and the “Arm and Hammer® Elite Pleated Air Filter” for filtering particles as small as 0.3 μm. The fibers in the “Microparticle” and “Elite” filters are electrostatically charged to further enhance particulate filtration efficiency.

### 3.10 Antimicrobial Media

Antimicrobial activity in a filter medium serves two basic purposes:

1. It protects the filter and filter medium from biological decay and resulting failure.
2. It prevents the passage of biological organisms to the downstream environment of the filter.

Price et al. have shown\(^{(89)}\) that even in filters, such as HEPA filters designed to filter out microorganisms, arrested microorganisms can grow and in some cases “grow through” the filter medium. Some organic media such as cellulose media provide nutrition for microbiological growth. A function of activated carbon media is to adsorb organic material and this makes the medium vulnerable to being a nutritional haven for microorganisms. In aqueous and high moisture air environments, biological activity can cause serious degradation of the filter medium and be a source of contamination downstream of the medium.

Price et al.\(^{(89)}\) demonstrated that an antimicrobial preservative can significantly inhibit fungal colonialization. In their studies, the preservative investigated was Intersept\(^{{5}}\), a phosphated amine antimicrobial complex.

A number of filter medium and filter manufacturers are now incorporating antimicrobial agents into their filter media.

In aqueous filtration, swimming pool and spa filters are logical candidates for antimicrobial filter media. Fiberweb™ in Old Hickory, Tennessee offers two spunbond polyester lines (Reemay Advantage® and Reemay Freedom®) treated with Microban® antimicrobial agent. Hollingsworth & Vose is marketing their AquaSure® AG spa and pool medium incorporating the Fossgard® antimicrobial technology.

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\(^{5}\) Intersept® is a trade name of Interface Research Corporation, Kennesaw, Georgia, USA.

\(^{6}\) Microban® is a trade name of Microban International, Ltd.
CHAPTER 4

Raw Materials for Nonwoven Filter Media

4.1 Introduction

The raw materials for nonwoven filter media are divided into the following categories:

1. Polymers.
2. Fibers.
4. Additives.

The choice of materials for the design of nonwoven filter media depends on performance, processability, and economics. The web must have the right combination of physical properties such as thickness, strength, flexibility, and tear resistance to be processed into its final filter form. It must have a raw material structure that optimizes its performance as a filter medium. Finally, the medium must be composed of materials that give it durability, chemical resistance, and environmental stability in its intended application.

4.2 Polymers

Polymers are used for the fibers in nonwoven webs and for the resins and additives used to bond, coat, and provide other properties to the fiber formed web.

In meltblown, spunbonded, and electrospinning processes the polymer is the fundamental raw material supplied to the process and the forming of filament fibers is an intermediate stage in the forming of the web. Web properties for these processes are determined by the appropriate choice of polymer based on its properties and selection of the process conditions for forming that polymer into a fibrous form.

On the other hand, formation of webs by the air laid, dry laid and wet laid processes begins with a raw material that is already in fiber form. These are shorter nonfilament
types of fibers provided by some form of outside supplier. The choice of fiber properties is the guiding criterion in the design of the web.

Organic fibers and resin binders are composed of polymers. Their properties and processability are very much dependent on the chemistry and properties of the polymers from which they were made. A listing of the structures of many of the polymers used for nonwoven materials is tabulated in Table 4.1.

Natural fibers such as wood pulp, cotton and other vegetable fibers are composed of cellulose, a natural polymer structure. Animal fibers such as wool and hog’s hair are composed of keratin, also a natural polymer.

Important properties of polymers are melting point, glass transition temperature ($T_g$), and the degree of polymerization. According to Stille (90.1) (p. 31), the glass transition temperature is the temperature at which a polymer loses its hardness or brittleness, becomes more flexible, and takes on rubbery or leathery properties. Notable changes in specific volume, thermal conductivity, refractive index, stiffness, heat content, and dielectric loss are apparent. The degree of polymerization, $d_p$, describes the molecular size of the polymer. It is the number of repeat units in the polymer chain (Stille (90.1) (p. 4)).

Vinyl polymers are linear polymers containing ethylene as the repeat structure in its backbone. Important to the properties of vinyl polymers and the materials made from it is stereoregularity. This term refers to the regularity of the substituent groups on the main carbon chain. This regularity can greatly affect the properties of the polymer. Figure 4.1 illustrates this. A and B are hypothetical substituent groups on the carbon chain of the polymer. If all the substituent groups are in the same position on each repeating unit of the polymer chain, then the polymer is referred to as “isotactic”. If they alternate on the polymer chain, then the polymer is “syndiotactic”. If they are random along the chain, then they are “atactic”.

![Polymer stereochemical structures](image-url)

*Figure 4.1. Polymer stereochemical structures*

Reproduced with permission of TAPPI Press, Atlanta, Georgia, USA (90.2 p. 31).
### Table 4.1  Structures of polymers used in nonwovens

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Type(s) &amp; trade name(s)</th>
<th>Chemical name</th>
<th>Application</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>Woodpulp, Vegetable Fibers, Abaca (Manila hemp), Hemp, Esparto Grass, Sisal, Jute, Kenaf, Flax, Cotton</td>
<td>Repeat unit: anhydro-beta-cellulose</td>
<td>Fiber</td>
<td><img src="image" alt="Cellulose Structure" /></td>
</tr>
<tr>
<td>Cellulose</td>
<td>Regenerated Cellulose – Rayon</td>
<td></td>
<td>Fiber</td>
<td><img src="image" alt="Cellulose Structure" /></td>
</tr>
<tr>
<td>Phenol formaldehyde</td>
<td>Resole</td>
<td>Phenol formaldehyde</td>
<td>Resin – solvent based</td>
<td><img src="image" alt="Resole Structure" /></td>
</tr>
</tbody>
</table>

(Continued)
Table 4.1 (Continued)

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Type(s) &amp; trade name(s)</th>
<th>Chemical name</th>
<th>Application</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenol formaldehyde</td>
<td>Novolak</td>
<td>Phenol formaldehyde</td>
<td>Resin – solvent based</td>
<td><img src="image" alt="Novolak Structure" /></td>
</tr>
<tr>
<td>Polyamide</td>
<td>Nylon 6,6</td>
<td>Polycapro lactam</td>
<td>Fiber</td>
<td>$H_2N \left[ (CH_2)_6 - NH - C\left(CH_2\right)_4 - C\left(NH\right) \right]_n - (CH_2)_6 - NH_2$</td>
</tr>
<tr>
<td>Polyamide</td>
<td>Nylon 6</td>
<td>Poly(hexamethylene adipamide)</td>
<td>Fiber</td>
<td>$\left[ C\left(CH_5\right) - N \right]_n$</td>
</tr>
<tr>
<td>Polyaramid</td>
<td>Kevlar® Twaron®</td>
<td>Polyparaphenylene terephthalamide</td>
<td>Fiber</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>-----------------</td>
<td>-----------------------------------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>Polyaramid</td>
<td>Nomex®</td>
<td>Polymetaphenylene isophthalamide</td>
<td>Fiber</td>
<td></td>
</tr>
<tr>
<td>Polyester (PET)</td>
<td>Dacron</td>
<td>Polyethylene terephthalate</td>
<td>Fiber</td>
<td></td>
</tr>
<tr>
<td>Polyester (PBT)</td>
<td>Poly(butylene terephthalate)</td>
<td>Fiber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyimide</td>
<td>P84®</td>
<td>Polyimide</td>
<td>Fiber</td>
<td></td>
</tr>
</tbody>
</table>

(Continued)
<table>
<thead>
<tr>
<th>Polymer and properties</th>
<th>Type(s) &amp; trade name(s)</th>
<th>Chemical name</th>
<th>Application</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyphenylene sulphide</td>
<td>Ryton&lt;sup&gt;®&lt;/sup&gt;</td>
<td>Poly(phenylene sulphide)</td>
<td>Fiber</td>
<td><img src="image" alt="Structure" /></td>
</tr>
<tr>
<td>Polyurethane</td>
<td>Spandex</td>
<td>Polyurethane</td>
<td>Electrospun nanofibers Resin</td>
<td><img src="image" alt="Structure" /></td>
</tr>
<tr>
<td>Polytetrafluoroethylene (PTFE)</td>
<td>Teflon</td>
<td>Poly(difluoromethylene)</td>
<td>Fiber Finish Membrane material</td>
<td><img src="image" alt="Structure" /></td>
</tr>
<tr>
<td>Silicone</td>
<td>Polysiloxane</td>
<td>Finish for water repellency and cake release</td>
<td><img src="image" alt="Structure" /></td>
<td></td>
</tr>
<tr>
<td>Raw Materials</td>
<td>or Nonwoven Filter Media</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>--------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Styrene butadiene (SBR)</td>
<td>Latex binder coating for air filter fibers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Styrene-acrylic</td>
<td>Latex resin</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Polyvinyl compounds**

<table>
<thead>
<tr>
<th>Polyvinyl compounds</th>
<th>General Fibers and resins</th>
</tr>
</thead>
</table>

Polyethylene
- HDPE
- LDPE
- UHMWPE

Poly(propylene)
- Typar®
- Tekton®

<table>
<thead>
<tr>
<th>Polyethylene</th>
<th>Poly(propylene)</th>
</tr>
</thead>
</table>

If $Y = H$ and $X = H$

If $Y = CH_3$ and $X = H$

---

(Continued)
<table>
<thead>
<tr>
<th>Polymer</th>
<th>Type(s) &amp; trade name(s)</th>
<th>Chemical name</th>
<th>Application</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poly styrene</td>
<td>Poly(1-phenylethylene)</td>
<td></td>
<td>Resin Electrospun fiber</td>
<td><img src="#" alt="Structure" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyacrylonitrile</td>
<td>Modacrylic PAN</td>
<td></td>
<td>Fiber Latex component Source for carbon fiber</td>
<td><img src="#" alt="Structure" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polye(vinylacetate) (PVAc)</td>
<td>Homopolymer forms Copolymer forms</td>
<td>Poly(1-acetoxyethylene)</td>
<td>Latex resin (sometimes solvent based)</td>
<td><img src="#" alt="Structure" /></td>
</tr>
</tbody>
</table>

Table 4.1 (Continued)

[Image of chemical structures]
<table>
<thead>
<tr>
<th>Raw Materials</th>
<th>Nonwoven Filter Media</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poly(vinyl alcohol) (PVOH)</td>
<td>Fully hydrolyzed</td>
</tr>
<tr>
<td></td>
<td>Intermediate</td>
</tr>
<tr>
<td></td>
<td>hydrolyzed</td>
</tr>
<tr>
<td></td>
<td>Partially</td>
</tr>
<tr>
<td></td>
<td>hydrolyzed Specialty</td>
</tr>
<tr>
<td></td>
<td>grades</td>
</tr>
<tr>
<td></td>
<td>Kuralon*</td>
</tr>
<tr>
<td>Poly(vinyl chloride) (PVC)</td>
<td>Flame retardant</td>
</tr>
<tr>
<td></td>
<td>Latex resin</td>
</tr>
<tr>
<td>Poly(vinylidene chloride) PVdCl</td>
<td>Poly (1,1-dichloroethylene)</td>
</tr>
<tr>
<td></td>
<td>Flame retardant resin systems</td>
</tr>
</tbody>
</table>

If $Y = \text{OH}$ and $X = \text{H}$

$$\begin{align*}
\text{If } Y &= \text{OH} \text{ and } X = \text{H} \\
\begin{array}{c}
\text{If } Y = \text{Cl} \text{ and } X = \text{H} \\
\begin{array}{c}
\text{If } Y = \text{Cl} \text{ and } X = \text{Cl} \\
\end{array}
\end{align*}
$$
4.3 Fibers

4.3.1 Classification

Fibers are classified by their source as follows:

1. Natural fibers
   (a) wood pulp,
   (b) vegetable fibers,
   (c) cotton,
   (d) animal fibers (wool).
2. Synthetic polymer fibers
   (a) polyester,
   (b) rayon (regenerated cellulose),
   (c) nylon (polyamide),
   (d) polyaramid (e.g. Kevlar®),
   (e) polyphenylene sulfide,
   (f) nomex,
   (g) polypropylene,
   (h) polyethylene,
   (i) polyacrylic,
   (j) polyimide.
3. Inorganic and mineral fibers
   (a) glass,
   (b) ceramic,
   (c) carbon,
   (d) asbestos,
   (e) basalt.
4. Binder fibers
   (a) bi-component high melt/low melt polymer,
   (b) polyester copolymer,
   (c) polyvinyl chloride,
   (d) polyvinyl acetate/polyvinyl chloride copolymer,
   (e) polyamide copolymer,
   (f) polyvinyl alcohol.
5. Bi-component fibers
6. Nanofibers
   (a) electrospun,
   (b) carbon (graphite),
   (c) microglass.

4.3.2 Physical characteristics

The following physical characteristics of fiber that are important for their use in filter media.

1. Diameter
2. Length
3. Aspect (length to diameter) ratio
4. Density
5. Linear density
6. Cross-section shape
7. Length characteristics
   (a) crimp.
   (b) curl.
   (c) kinkiness.
8. Internal structure (cellular or solid)
9. Strength properties
   (a) tensile strength and breaking length.
   (b) stretch or elongation.
   (c) Young's modulus.
   (d) stiffness.
   (e) bending modulus.

4.3.3 Physical chemical characteristics

The following are chemical and physical chemical properties of fibers to be considered in their choice for use in filter media:

1. Glass transition temperature.
2. Melting point.
3. Additives, components, contaminants, and impurities.
4. Bonding properties.
5. Chemical composition.
6. Chemical resistance.
7. Corrosion resistance.
8. Electrostatic charge.
10. Moisture absorption.
11. Moisture content.
12. Dimensional stability.
13. Polymer structure.
14. Temperature and heat resistance.
15. Surface properties.
16. Surface size.
17. Surface tension and energy.
18. Volatile components.

4.3.4 Fiber properties for filtration media

The choice of fibers for nonwoven filter media depends on the properties of the filter medium to be produced, the process by which it is produced, and the application.
<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Specific gravity</th>
<th>Melt point (°F)</th>
<th>Moisture regain (%)</th>
<th>Breaking tenacity (gpd)</th>
<th>Chemical reactivity note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetate</td>
<td>1.32</td>
<td>500°F (Tg: 6.3-6.5°F)</td>
<td>6.3-6.5</td>
<td>1.2-1.6</td>
<td>Poor resistance to strong acids. Strong bases cause loss of strength. Dissolved by acetone</td>
</tr>
<tr>
<td>Acrylic</td>
<td>1.14-1.19</td>
<td>No definite melt</td>
<td>1.0-2.5</td>
<td>2.2-5.4</td>
<td>Good resistance to acids, except nitric acid. Moderate resistance to weak bases</td>
</tr>
<tr>
<td>Cellulose</td>
<td>1.5</td>
<td>Does not melt</td>
<td>10.7-16.1</td>
<td></td>
<td>Poor resistance to acids and bases</td>
</tr>
<tr>
<td>Kevlar (Technora)</td>
<td>1.44</td>
<td>Does not melt</td>
<td>3.5-5.1</td>
<td>18-30</td>
<td>Good resistance to dilute acids and bases. Degraded by strong mineral acids</td>
</tr>
<tr>
<td>Nomex</td>
<td>1.37-1.38</td>
<td>Does not melt</td>
<td>3.5-5.1</td>
<td>2.3-5.1</td>
<td>Good resistance to acids and bases</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>3.5-5.0</td>
<td>500°F (Tg: 400°F)</td>
<td>3.5-5.0</td>
<td>3.5-6.0</td>
<td>Degraded by hot, concentrated acids and bases</td>
</tr>
<tr>
<td>Nylon 6.6</td>
<td>3.5-5.0</td>
<td>500°F (Tg: 400°F)</td>
<td>3.5-5.1</td>
<td>3.5-6.0</td>
<td>Degraded by hot, concentrated acids and bases</td>
</tr>
<tr>
<td>Polyester – High Tenacity</td>
<td>1.38</td>
<td>482-550</td>
<td>0.4-0.9</td>
<td>4.0-8.6</td>
<td>Good resistance to acids. Poor resistance to strong bases. Good resistance to organic solvents</td>
</tr>
<tr>
<td>Polyester – Regular Tenacity</td>
<td>1.38</td>
<td>482-550</td>
<td>0.4-0.9</td>
<td>2.0-4.0</td>
<td>Good resistance to acids. Poor resistance to strong bases. Good resistance to organic solvents</td>
</tr>
<tr>
<td>Polyester – Undrawn</td>
<td>1.38</td>
<td>482-550</td>
<td>0.4-0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyethylene</td>
<td>0.92-0.96</td>
<td>220-255</td>
<td>&lt;1.0</td>
<td>3.0-4.2</td>
<td>Excellent resistance to acids and bases</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>0.91</td>
<td>325-335</td>
<td>&lt;1.0</td>
<td>3.0-4.2</td>
<td>Excellent resistance to acids and bases</td>
</tr>
<tr>
<td>Rayon</td>
<td>1.54</td>
<td>Does not melt</td>
<td>10.7-16.0</td>
<td>1.9-3.4</td>
<td>Poor resistance to strong acids and bases</td>
</tr>
</tbody>
</table>

Reproduced with permission of MiniFIBERS, Inc., Johnson City, Tennessee, USA.

Table 4.2 provided by MiniFIBERS, Inc., compares the properties of several fibers used in filter media.

The principal fiber properties for filtration performance are those designed to optimize bulk, air permeability and pore size of the medium. Bulk and air permeability
relates to the porosity (or solidity) of a web and would affect the dirt holding capacity. Air permeability is important to filter design. It would determine the type and capacity and size of the pump, blower, or fan that would be used to force fluid through the media. Pore size relates to the size of the particle that is capable of penetrating the medium, in effect its filtration efficiency. These properties do not go hand in hand. Generally, the goal is to maximize bulk and permeability of the filter medium and to minimize pore size. Unfortunately, the fiber properties one would choose to maximize bulk and permeability are not the properties that would reduce pore size. Fine fibers of low diameter will give filter media of high density, small pore size, and high filtration efficiency. On the other hand, coarse fibers will give bulky media and high permeability, but at the expense of filtration efficiency. Obviously, filter medium design requires compromise and imagination in the choice of fibers and their properties.

Other fiber properties have to be considered in the design of the medium. These include properties that affect medium strength, stiffness, chemical resistance, temperature resistance, and other properties that would relate to its processability and filtration. The following is a discussion of fiber properties and how they relate to filter media produced from these fibers.

4.3.4.1 Diameter

In Chapter 2, a review of various filtration theories (e.g. Langmuir, Davies, Happel, Kuwabara, etc.) reveals that the fiber diameter is a dominant factor affecting the filtration properties of fibrous filter media. In the models of Langmuir, Happel, and Kuwabara, porosity is assumed from the diameter of the fiber and the surrounding void space. Peart and Ludwig reported that the number of fibers and number of pores in a medium can be related to fiber diameter as follows:

\[
N_f = \frac{4M_s}{\pi \rho_f D_f^2 l_f} \quad (4.1)
\]

\[
N_p = \frac{16M_s^2 l_f}{\pi^3 \rho_f D_f^4} \quad (4.2)
\]

\(N_f\) is the number of fibers per unit area (m\(^2\)) of medium.
\(N_p\) is the number of pores per unit area (m\(^2\)) of medium.
\(D_f\) is the fiber diameter (m).
\(M_s\) is the grammage of the medium (gm cm\(^{-2}\)).
\(l_f\) is the fiber length (m).
\(\rho_f\) is the density of the fiber (gm cm\(^{-3}\)).

Depending on porosity, fiber diameter is inversely related to the flow resistance of the web: that is, the smaller the diameter, the greater is the resistance. The density of nonwoven webs tends to increase with decreasing fiber diameter.

On the other hand, reducing fiber diameter is the dominant way of increasing filtration efficiency of a nonwoven filter medium. High efficiency air filtration of nanoparticles
is achieved by using fibers such as glass microfibers and electrospun nanofibers that have ultra fine diameters in the range of 0.2–6 µm.

McCulloch\(^{(92)}\) identifies the following meltblown possibilities for achieving ultra fine fiber dimensions:

1. modified meltblown process,
2. splittable fiber process,
3. electrospinning process.

The meltblown and electrospinning processes are discussed in detail in Chapter 5. Splittable fibers are a form of bi-component multi-component fibers and are further discussed in Section 4.3.5.4.2. McCulloch mentions “segmented pies” and “islands in a sea” as sources of ultra fine fibers. Dugan and Homonoff\(^{(93)}\) discuss the possibilities of splittable fibers as an alternative to glass microfibers for high efficiency filtration. They note that splittable fibers can be split into nanofiber diameter dimensions (250 nm) and have an advantage over glass fibers in that they can be electrostatically charged.

As important as fiber diameter is to the filtration properties of the medium it is also difficult to measure, particularly if the cross-section is not circular. Broughton and Brady\(^{(94)}\) mention “the difficulty in measuring a fiber’s physical dimensions (particularly diameter)”. To illustrate, most wood pulp fibers are ribbon shaped. Often the measurement is made by micrograph or image analysis techniques. In such cases the fiber diameter may be pseudo-determined from measuring the width of the ribbon. The measurement is further complicated with natural fibers because the diameter varies along the length of the fiber and from fiber to fiber. At best, some form of statistical average is necessary to express natural fiber diameters. To deal with this, weight-based systems such as linear density (see Section 4.3.4.5 below) have been devised for relating to a fiber’s diameter.

4.3.4.2 Length

The spun fiber types of webs (spunbond, meltblown, and electrospun) are produced from filament fibers; therefore, fiber length is not a variable for these types of webs. Air laid, dry laid, and wet laid processes use short fibers or staple fibers of finite lengths, ranging from 25 µm for glass microfiber up to 12 cm for staple fibers used in the dry laid process. Following are length categories of fibers that are commonly used for nonwoven media.

**Pulp fibers**: Lengths vary based on plant source of the pulp. Hardwood pulps are generally 1–2 mm whereas softwoods are in the 3.5–5.0 mm range. Pulped vegetable fibers such as abaca (Manila hemp) are as long as 6 mm. Natural fibers have a great deal of length variation, and at best the length of any pulp fiber species can only be a statistical average of what has been observed.

**Staple fibers**: Staple fibers are used in carding operations. They have to be long enough to satisfactorily entangle for web consolidation during the carding process and yet, short enough to be easily individualized by the carding action. Longer staple fibers will have more tendencies for machine direction (MD) orientation of the web. The fibers have to be long enough for subsequent entanglement bonding such as needlepunching or hydroentanglement. Lengths can range from 25 to 200 mm.
The American cotton industry further breaks down staple fibers into the following length categories:

- short staple: up to 1 in. (25.4 mm)
- medium staple: 1-1/32 in. to 1-3/32 in. (26.2–27.8 mm)
- long staple: over 1-1/8 in. (over 28.6 mm)

**Short-cut fibers**: Filament fibers that are cut to short lengths for wet laid or dry laid purposes are also referred to as chopped fibers. Short-cut lengths can vary from 3 mm to as long as 40 mm. Short-cut fibers are not only differentiated from staple fibers by length, but also by the way they are cut. Generally, staple fibers will be cut from filament fibers as they are spun or produced in-line. Short-cut fibers are produced by off-line converting operations. The filament fiber is shipped to the converter in bale or spool form and precisely cut by the converter to the desired length. Minifibers, Inc. is one such converter. Table 4.3 lists the type and minimum length of short-cut fibers available from this supplier.

<table>
<thead>
<tr>
<th>Generic type</th>
<th>Deniers available (dpf)</th>
<th>Types available</th>
<th>Minimum cut length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic</td>
<td>1.5, 3.0, and 15.0</td>
<td>Bright, dull, semi-dull luster</td>
<td>1</td>
</tr>
<tr>
<td>Nylon</td>
<td>1.8, 3.0, 6.0, and 15.0</td>
<td>Regular tenacity, high tenacity, regular shrinkage, high shrinkage, undrawn fiber binder</td>
<td>3</td>
</tr>
<tr>
<td>Polyester</td>
<td>0.5, 3.0, 6.0, 12.0, and 25.0</td>
<td>Regular tenacity, high tenacity, regular shrinkage, high shrinkage, undrawn fiber binder</td>
<td>3</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>3.0, 6.0, and 15.0</td>
<td>Flocking tow</td>
<td>3</td>
</tr>
<tr>
<td>Rayon</td>
<td>0.5–25.0</td>
<td></td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

The estimated fiber length limitations by process are as follows:

- Air laid: 12 mm.
- Dry laid: 12 cm.
  - Spunbond: Continuous filament.
  - Meltblown: Continuous filament.
  - Electrospun: Continuous filament.
- Wet laid: 40 mm.

The length of fiber that can be used in these processes is not only process dependent, but also related to other characteristics of the fiber such as diameter and modulus. For example, the 40-mm limitation on the wet laid process is based on technology for dispersing rigid glass rovings. On the other hand, the same technology will have a difficult time dispersing much shorter 2-mm cotton linters, because of the extreme tendency of cotton to entangle in water.

The tendency to entangle, flocculate, and disrupt formation is a primary reason for process limitations of fiber length. Longer fibers tend to lay down in the machine direction (MD) of the forming process. This results in highly oriented webs, low in cross-direction (CD) strength properties.
The advantage of using longer fibers is that the entanglement effect enhances better tensile and tear strength of the web. Webs made of longer fibers are more flexible and exhibit better resistance to flexing and tearing. Longer fibers also result in better elongation.

### 4.3.4.3 Aspect ratio
Aspect ratio is the ratio of fiber length to fiber diameter. It has been discussed previously in Chapter 1 as being a condition for determining if a substrate should be called nonwoven or paper. It is also an important property that affects the quality and performance of the nonwoven web. Aspect ratio, even more than length, is the variable that affects web formation and MD:CD orientation of the fibers. Table 4.4 reports the aspect ratios of several types of fibers used for wet lay media.

#### Table 4.4 Aspect ratio and modulus properties of fibers used for wet lay purposes

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Description</th>
<th>Length (mm)</th>
<th>Equivalent fiber diameter (μm)</th>
<th>Aspect ratio (mm/mm)</th>
<th>Modulus (g/de)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Esparto</td>
<td>Grass</td>
<td>1.3</td>
<td>9</td>
<td>144</td>
<td></td>
</tr>
<tr>
<td>Sisal</td>
<td></td>
<td>3.0</td>
<td>20</td>
<td>150</td>
<td>1,300–2,600</td>
</tr>
<tr>
<td>Abaca</td>
<td>Manila hemp</td>
<td>6.0</td>
<td>24</td>
<td>250</td>
<td>1,750</td>
</tr>
<tr>
<td>Eucalyptus</td>
<td>Short fibered hdwd. kraft</td>
<td>1.0</td>
<td>13</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>Birch</td>
<td>Hardwood kraft</td>
<td>1.9</td>
<td>28</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>Aspen</td>
<td>Hardwood kraft</td>
<td>1.1</td>
<td>18</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>Beech</td>
<td>Hardwood kraft</td>
<td>1.2</td>
<td>18</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>Redwood</td>
<td>Northern softwood kraft</td>
<td>6.1</td>
<td>58</td>
<td>105</td>
<td>870</td>
</tr>
<tr>
<td>Douglas fir</td>
<td>Northern softwood kraft</td>
<td>3.8</td>
<td>40</td>
<td>95</td>
<td>599</td>
</tr>
<tr>
<td>West. red cedar</td>
<td>Northern softwood kraft</td>
<td>3.5</td>
<td>35</td>
<td>100</td>
<td>900</td>
</tr>
<tr>
<td>Slash pine</td>
<td>Southern softwood kraft</td>
<td>4.6</td>
<td>40</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td>Lobolly Pine</td>
<td>Southern softwood kraft</td>
<td>3.5</td>
<td>40</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>Cotton linters</td>
<td>Cotton</td>
<td>2.0</td>
<td>18</td>
<td>111</td>
<td>360–450</td>
</tr>
<tr>
<td>1 06 glass microfiber</td>
<td>Glass</td>
<td>1.0</td>
<td>0.6</td>
<td>1.667</td>
<td>1,200–3,000</td>
</tr>
<tr>
<td>DE rovings</td>
<td>Glass</td>
<td>6.4</td>
<td>6.5</td>
<td>985</td>
<td>1,200–3,000</td>
</tr>
<tr>
<td>Rayon</td>
<td>3d, ¾ in.</td>
<td>6.4</td>
<td>16</td>
<td>400</td>
<td>400–600</td>
</tr>
<tr>
<td>Rayon</td>
<td>3d, ⅞ in.</td>
<td>12.7</td>
<td>16</td>
<td>794</td>
<td>400–600</td>
</tr>
<tr>
<td>Rayon</td>
<td>1.5d, ¾ in.</td>
<td>12.7</td>
<td>11.8</td>
<td>1,076</td>
<td>400–600</td>
</tr>
<tr>
<td>Rayon</td>
<td>20d, ¾ in.</td>
<td>19.1</td>
<td>43</td>
<td>444</td>
<td>400–600</td>
</tr>
<tr>
<td>PET (Polyester)</td>
<td>3d, ¼ in.</td>
<td>6.4</td>
<td>18</td>
<td>356</td>
<td>300–600</td>
</tr>
<tr>
<td>PET (Polyester)</td>
<td>3d, ⅞ in.</td>
<td>12.7</td>
<td>18</td>
<td>706</td>
<td>300–600</td>
</tr>
<tr>
<td>PET (Polyester)</td>
<td>1.5d, ¾ in.</td>
<td>6.4</td>
<td>12.4</td>
<td>516</td>
<td>300–600</td>
</tr>
<tr>
<td>PET (Polyester)</td>
<td>1.5d, ⅞ in.</td>
<td>12.7</td>
<td>12.4</td>
<td>1,024</td>
<td>300–600</td>
</tr>
<tr>
<td>Nylon</td>
<td>3d, ¾ in.</td>
<td>6.4</td>
<td>19.3</td>
<td>332</td>
<td>210–340</td>
</tr>
<tr>
<td>Nylon</td>
<td>3d, ⅞ in.</td>
<td>12.7</td>
<td>19.3</td>
<td>658</td>
<td>210–340</td>
</tr>
</tbody>
</table>

### 4.3.4.4 Density
The density of a fiber is of course the mass weight of the fiber divided by its volume (gm/cm³). Densities (specific gravities) of various fibers are included in Tables 4.2 and 4.5. Note in Table 4.2 the term specific gravity is used. Specific gravity is the relative density of a substance compared to the density of water at 20°C which is 1.0 g/cm³.
As long as density is expressed as g/cm\(^3\), the numbers will be the same and there will be no confusion. However, if different units are used for density (e.g., lb/gal), one must be careful not to use specific gravity when density was intended or vice versa.

Density of a fiber is used for the calculation of its linear density to be discussed in Section 4.3.4.5 below. It is also used for calculation of the porosity of the web produced from that fiber. It will be noted that certain types of fibers such as cellulose fibers have densities different than the polymers from which they were composed. Cellulose fibers are cellular structures with lumen (openings) through the length of the fiber. Because of lumen and other parts of the cell structure, the cellular inter-fiber structure includes a considerable amount of air so that its apparent density may be considerable less than the 1.55 g/cm\(^3\) of pure cellulose polymer. Note in Section 4.3.4.5 below that this is considered in the definition of fiber coarseness for cellulose pulp fibers. The coarseness is expressed in terms of “wall material per specified length of fiber” (Smook\(^{195}\))

4.3.4.5 Linear density

The linear density of a fiber is an expression of its weight per unit length. In papermaking, the equivalent term is fiber coarseness. There are several terms for linear density and/or fiber coarseness:

1. Denier (de) – the weight in grams of 9,000 m of fiber. It is often expressed as denier per filament (dpf).
2. Tex – the weight in grams of 1,000 m of fiber.
3. Decitex – the weight in grams of 10,000 m of fiber.
4. Micronaire – Term used by the American Cotton Industry\(^1\) (Boyer\(^{103}\)); the weight in micrograms of one inch of fiber. Note: 1 micronaire = 2.82 de.
5. Fiber coarseness (pulp fiber) – The “weight of fiber wall material in a specified fiber length”\(^2\) Smook\(^{195}\), usually expressed as mg/100 m.
6. Decigrex (dg) – Papermaker’s units for fiber coarseness\(^3\); the weight in milligrams of 100 m of fiber or the weight in decigrams of 10 km of fiber.

4.3.4.6 Cross-section shape

It has been mentioned in Section 4.3.4.1 above that fibers are not necessarily round in their cross-section. Cellulose wood pulp fibers tend to be ribbon shaped. Synthetic fibers can be produced in ribbon shapes, cross-shapes, trilobal shapes, and multi-lobal shapes. Figure 4.2 shows the cross-sections of \(\text{P84TM}\) polyimide fiber used in heat resistant needlefelt filter bags. The advantage of trilobal fiber in filtration applications is that it increases the filter surface area for filtration.

Trilobal fiber can be made from a number of polymers including polyester, nylon, carbon, etc. Dugan\(^{196}\) discusses segmented bi-component fibers (see Section 4.3.5.4.2 below) that can be split into smaller fibers. He mentions that these fibers when used in cross or trilobal shape provide for improved processability in carding operations.

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\(^{1}\) “Cotton in Nonwovens” TAPPI 1205–121995\(^{100}\).


\(^{3}\) TAPPI “Coarseness of Pulp Fibers” F2 34 cm-84.
4.3.4.7 Moisture content and moisture absorption

The moisture content of a fiber is related to its surface properties and physical properties. Hydrogen bonding, which is the mechanism by which cellulose fibers attach to each other, is a major determinant of how much moisture a fiber can absorb. Hydrogen bonding sites include hydroxyls (-OH) and/or amides (-NH₂). The greater the number of hydrogen bonding sites, the greater is the amount of moisture that the polymer might absorb.

Crystallinity also has an effect on moisture absorption. Usually moisture absorption will occur only in the amorphous regions of a fiber and will not invade the crystalline regions of a fiber. For highly amorphous fibers water absorption can also cause swelling of the fibers. Broughton and Brady(94) suggest that an amorphous fiber having at least one hydrogen-bonding site for every two carbons in the polymer backbone can absorb up to about 12% of its weight in moisture. This may have undesirable effects in a fiber medium. For example, fiber swelling may cause pore closure resulting in greater flow resistance and loss of filtration efficiency.

In a cellular fiber structure after wetting, moisture retained within the cellular void space of the fiber is difficult to remove by mechanical means such as pressing or vacuum. This part of the moisture content can only be removed by evaporation or drying.

The equilibrium moisture content of a fiber is that which is in equilibrium with its environment. This depends on the temperature and relative humidity of the environment. The equilibrium relative humidity is the relative humidity at a given temperature at which exposure of the fiber will not result in either moisture absorption or desorption. This will only happen if the fiber is already at the equilibrium moisture content for that humidity. In measuring the equilibrium moisture content of a fiber or for that matter any substance, one must be careful about hysteresis effects. This means that the equilibrium moisture content will be different depending on whether the substance is

---

4 P-84™ is the trademark of Inspec Fibres GmbH, Lenzing, Austria.
approaching equilibrium from a dryer state or a wetter state. For example, fibers conditioned at 50% relative humidity will have greater moisture content when this environment is approached from a higher relative humidity than from a lower relative humidity. For this reason TAPPI T402 om-93 recommends that pulp products be preconditioned at a lower humidity prior to conditioning at conditions for equilibrium moisture content.

Table 4.5 lists the equilibrium moisture contents of several types of natural and man-made fibers.

### Table 4.5 Specific gravity and moisture content of common natural and manmade fibers

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Specific gravity (g/cc)</th>
<th>Equilibrium moisture content (%) at 21°C and 65% relative humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic b</td>
<td>1.15</td>
<td>1–2</td>
</tr>
<tr>
<td>Cellulose acetate</td>
<td>1.32</td>
<td>6</td>
</tr>
<tr>
<td>Cellulose triacetate b</td>
<td>1.25</td>
<td>2.5–4.5</td>
</tr>
<tr>
<td>Cotton</td>
<td>1.54</td>
<td>7 (Commercial = 8.5)</td>
</tr>
<tr>
<td>Glass b</td>
<td>2.54</td>
<td>0</td>
</tr>
<tr>
<td>Polyamide (nylon 6 and nylon 6.6)</td>
<td>1.14</td>
<td>4.1–4.5</td>
</tr>
<tr>
<td>Polyester b</td>
<td>1.38</td>
<td>0.4–0.5</td>
</tr>
<tr>
<td>Polyethylene b</td>
<td>0.92</td>
<td>0</td>
</tr>
<tr>
<td>Polypropylene b</td>
<td>0.90</td>
<td>0</td>
</tr>
<tr>
<td>Polyurethane b</td>
<td>1.21</td>
<td>1.0–1.5</td>
</tr>
<tr>
<td>Polyvinyl chloride b</td>
<td>1.38</td>
<td>0–1</td>
</tr>
<tr>
<td>Polyvinylidene chloride b</td>
<td>1.70</td>
<td>0</td>
</tr>
<tr>
<td>Protein b</td>
<td>1.25</td>
<td>10–18</td>
</tr>
<tr>
<td>Silk</td>
<td>1.37</td>
<td>9</td>
</tr>
<tr>
<td>Viscose rayon</td>
<td>1.51</td>
<td>13</td>
</tr>
<tr>
<td>Wool</td>
<td>1.32</td>
<td>13–15</td>
</tr>
</tbody>
</table>

*Man-Made Fiber and Textile Dictionary*.

Average of major commercial brands.

Reproduced with permission of Invista, Wichita, Kansas, USA.

4.3.4.8 Thermal properties

4.3.4.8.1 Melting point

The melting point of polymer fibers has many ramifications to filter media. It is the temperature at which the crystallized segments of the polymer are transformed into noncrystalline forms. In other words, the point at which they soften and melt. Fibers from high melting polymers will implicitly have better heat resistance and be used accordingly; e.g., high temperature baghouse operations. On the other hand there is a need for low melting polymers in thermobonding operations. Thermobonding fibers or the thermobonding components of bi-component fibers have to be melted and liquefied enough to be able to flow into and conform to fiber intersections.

Some fibers such as cellulose have melting points, however, will undergo thermal and chemical decomposition at temperatures well below their melting point.

4.3.4.8.2 Glass transition temperature ($T_g$)

Glass transition temperature, $T_g$, is a fiber property that can dramatically affect the performance of the fabric, because it relates to amorphous regions of the fiber. Bresee [97]
points out that all polymeric objects contain at least some amorphous regions of non-
crystalline material. These regions are stiff and brittle and become rubbery above their
\( T_g \). The cause is polymer segmental mobility. Some defects caused by physical handling
and aging can be simply erased by heating the polymer above its \( T_g \). An example of this
is the ironing or textile fabrics to remove wrinkles. In Section 4.3.4.7 above it was
noted that amorphous regions have more tendency to absorb water. Water acts as a
plasticizer and lowers the \( T_g \) of the polymer. This is particularly true for natural fibers,
such as cotton, that have high levels of moisture absorbency. For example, the ironing
process, mentioned above, requires the use of steam and moisture.

Polymers do not crystallize below the \( T_g \), but may crystallize above the \( T_g \). Some
rayon fibers of low crystallinity will undergo distinct changes in properties, such as
hardness and stiffness, when crystallized.

\( T_g \) is almost always lower than the melting point. Bresee \(^{97} \) reports the relation-
ship to be:

\[
T_g = \frac{2}{3} T_m
\]  

\( T_g \) is the glass transition temperature, K,
\( T_m \) is the melting point, K.

**4.3.4.9 Strength properties of fibers**

Two important properties of fibers are tenacity and modulus. Tenacity is the breaking
strength of the fiber usually expressed as gm/de (denier). Modulus relates to the rigid-
ity or flexibility of the fiber and is also expressed in units of gm/de. High modulus fibers
result in bulkier webs; however, they will be weaker because the bonding area at fiber
intersections is reduced. High tenacity fibers do not necessarily produce stronger webs.
This often depends on how well the fibers are bonded. If the fibers are well bonded, then
the strength will be enhanced by the tenacity of the fibers. Table 4.2 above contains
tenacity data on the fibers listed used in the wet lay process. Table 4.4 above lists mod-
ulus data for various fibers used in the wet laid process.

**4.3.5 Fiber types**

**4.3.5.1 Natural fibers**

**4.3.5.1.1 Wood pulp**

Wood pulp fibers used for making paper are a dominant fiber material in paper filter
media and in wet laid nonwoven filter media. All wood pulps consist of cellulose,
although in varying degrees of purity and contamination. Contaminants such as
lignins are important to the properties of the fiber, either because they are there or
because they are not there. Filter medium manufacturers are concerned with the
purity of a pulp as measured by its \( \alpha \)-cellulose content. High purity pulps do not bond
very well and form weak, bulky structures. Yet, bulk is important to a filter medium
and to achieve it, wet laid filter medium manufacturers will find ways to compensate
for the lower strength properties. Caustic treated, mercerized pulps are of very high
purity (99% + \( \alpha \)-cellulose) and are known as high bulk pulps. They are important to
wet laid filter media because they provide for bulk and permeability that cannot be achieved with less pure wood pulps. Several factors influence the properties of wood pulp fibers. These include:

1. Type of tree.
2. Tree source.
3. Growing season.
4. Growing location.
5. Pulping process.

Two basic types of trees from which wood pulp is made are hardwoods and softwoods. Hardwoods are broad leaf (deciduous or evergreen) trees. Hardwoods used for papermaking include oaks, gum trees, birch, beech, and aspen. Eucalyptus is also a form of hardwood whose fiber is becoming increasingly popular in filter paper.

Softwoods or conifers are normally known as pine trees, although there is a wide variety of pine trees and each type offers specific properties to the wood pulp fiber. Softwoods used for papermaking include spruce, fir, cedar, hemlock, redwood, loblolly pine, and slash pine.

Fibers produced from softwood trees are typically longer and of coarser diameter than fiber produced from hardwood trees. This is important because both types are incorporated into the design of filter media: softwood to provide bulk, strength, and permeability, whereas the finer fibered hardwoods provide for filtration efficiency. The following comparison illustrates the typical properties of the two types of fibers:

<table>
<thead>
<tr>
<th>Type</th>
<th>Length (mm)</th>
<th>Diameter (μm)</th>
<th>Aspect ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Softwood</td>
<td>4.0</td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>Hardwood</td>
<td>2.0</td>
<td>22</td>
<td>90</td>
</tr>
</tbody>
</table>

Northern softwoods (NSWs) have distinctly different properties than Southern softwoods. This is largely due to the difference in growing seasons. There are two stages to a growing season: spring when springwood or earlywood is grown and summer when summerwood or latewood is grown. The properties of summerwood are quite different from springwood and explain the visible ring structure in the trunks of trees. Tracheids are long tapering cells of wood that become fibers. A tracheid consists of a wall structure and a long open canal called the lumen. Springwood tracheids are of lower density than summerwood tracheids and are characterized by thin wall structures and large lumen. On the other hand, summerwood may have two or three times the density of springwood and is characterized by thick wall structure and small lumen. Figure 4.3 is an electron micrograph of a wood specimen from a Southern yellow pine revealing the transition from earlywood to latewood. It reveals how the tracheid structure is changed in the transition. The transition from earlywood to latewood is the change at the bottom of the picture. Note how abrupt it is.

Southern softwoods have a longer summer growing season than do Northern Softwoods; therefore, they have a higher percentage of thicker walled latewood fiber.
For this reason Southern softwoods provide for bulkier structures. This is illustrated in Figure 4.4. The thick walled fiber structure being less conformable than the thin wall structure would form a less compressible and thereby bulkier paper medium. To further illustrate this effect, Figures 4.5 and 4.6 are microphotographs of handsheets made from earlywood and latewood fibers of Southern pine, respectively. The flat ribbon-like shapes of the earlywood fibers are in contrast to the more three-dimensional shape of the latewood fibers.

It has been mentioned above that tracheids are the fundamental building blocks of a wood that is converted to a fiber form. Figure 4.7 illustrates the structure of a softwood tracheid. Note that the tracheid consists of a number of layers. The layers are as follows:

- **Middle lamella (ML):** bond between fibers, mostly lignin.
- **Primary wall (P):** a thin, relatively impermeable covering about 0.05 μm thick.
- **Secondary wall:** makes up bulk of cell wall; forms three distinct layers characterized by different fibril alignments:
  - $S_1$ is the outer layer of secondary wall (0.1–0.2 μm thick).
  - $S_2$ forms the main body of the fiber and is 2–10 μm thick.
  - $S_3$ is the inner layer of the secondary wall (about 0.1 μm thick).

- **Tertiary wall (T):** same as $S_3$.
- **Lumen (L):** the central canal of the fiber.
Figure 4.4. Idealized fiber structures. The thick-wall fibers are less conformable than the thin-walled fibers. Reproduced with permission of Angus Wilde Publications Inc., Vancouver, British Columbia, Canada, p. 18.

Figure 4.5. Southern pine earlywood.

Figure 4.6. Southern pine latewood.

Reproduced with permission of the Institute of Paper Science and Technology Atlanta, Georgia, USA.
The pulping process breaks down tracheids into individualized wood pulp fibers by destroying the lignin bonding that holds the fibers together in the ML layer. There are several types of pulping processes that include mechanical pulping, chemical pulping, and semi-chemical pulping. Chemical pulping includes the alkaline kraft process and the acidic sulfite process. The kraft process uses sodium hydroxide (NaOH) and sodium sulfide Na₂S to break down the molecules lignin into smaller segments. The sulfite process uses sulfurous acid (H₂SO₃) and bisulfite (HSO₃⁻) ion to attack and solubilize the lignin.

The kraft process is by far the favored process for producing filter pulps. The word “kraft” is German for “strong”. Accordingly, kraft pulps are characterized by being stronger. The wood raw material, depending on its source, is broken down into chips. The chips are then fed to a digester, which can either be a batch process or continuous
process. In the batch process, the wood chips are fed to a large digester vessel. The cooking liquor, containing the NaOH and Na₂S, is then added to completely cover the chips. The contents are then heated, usually by forced circulation of the cooking liquor through a heat exchanger. Maximum temperature is typically reached in 1 h. The cook is then maintained at its cooking temperature for the predetermined cooking time. Typical cooking conditions for a kraft cook are:

- temperature: 170–180°C.
- pH: 13+.
- cooking time: 2–4 h.

When the cooking cycle is completed, the contents are discharged into a blow tank where the softened chips are disintegrated into fibers. The cooking liquor, now known as black liquor, is extracted from the pulp and sent to a chemical recovery system. The pulp is separated from the residual liquor in a process known as brown washing. The pulp is then screened and cleaned.

The pulping process may be followed by a bleaching process depending on whether bleached or unbleached pulp is desired. The washed pulp from the cooking process will have an inherently yellow or brownish color. The bleaching process makes it into the white color usually associated with high-grade paper. Most pulps used for filter media are bleached. Some filter media use unbleached pulp in applications where there are no quality demands for whiteness.

The secondary ($S_2$) wall layers of Figure 4.7 are composed of micro-fibrils. Micro-fibrils are bundles of cellulose molecules. Their orientation relative to the axis of the fiber influences the characteristics of the fiber. This orientation is often referred to as the “fibril angle”.

Fibrillation is the shearing of wet wood pulp fibers to loosen the micro-fibrils from the fiber surface and fiber wall. In effect, the micro-fibrils are unraveled, and the fiber is “frayed” similar to the fraying of a cotton thread. Shearing the stock slurry of fibers between two steel surfaces causes fibrillation: one surface is part of a moving rotor, the other is static. Refining or beating is the process by which fibrillation occurs. These process steps are discussed in Chapter 5. Figure 4.8 is a micrograph of fibrillated fiber showing the unraveling of the micro-fibrils. The unraveled micro-fibrils are seen to spider web across fibers and increase their bonding area. Fibrillation by refining increases the strength of a wood pulp substrate. It also reduces the air permeability. Wet lay filter machines producing cellulose filter media will use refining as a fine tune control for controlling air permeability.

### 4.3.5.1.2 Handsheet testing of woodpulp fibers
Numerous tests can be conducted on wood pulp fibers. Among these are fiber length, diameter, coarseness, modulus and strength, freeness, and chemical purity. For the filter medium manufacturer, laboratory handsheet testing is the most informative. Based on handsheet testing, the manufacturer can categorize and evaluate various pulps for their suitability in filter medium products. It is the basic experimental tool for furnish design and evaluation. Handsheets are tested for air permeability, pore size, strength properties, bulk, and other related properties. The handsheet procedure also provides a
way of noting the dispersion qualities of the pulp. Handsheets are often used as base sheets for resin impregnation and subsequent resin studies. Handsheets, resin treated and not resin treated, can be subject to several types of flat sheet filter tests to estimate and compare furnish performance.

The TAPPI specified handsheet procedure is little used by filter medium laboratories because of the dense structure that results from this procedure. Filter medium companies all have their provincial procedures, and there does not appear to be much standardization between companies. It is even unlikely that different mills in the same company will have the same procedure. What is important is that the parallels be the same. Different mills may get different handsheet numbers for the same pulp, but the results have to correlate. Each mill designs its handsheet procedure based on the wet lay machine(s) at the mill and the types of products they produce.

The procedure involves the following steps:

1. Dispersion of the fiber — usually done in a disintegrator of laboratory beater.
2. Forming the handsheet in a sheet mold.
3. Couching of the handsheet from the forming fabric.
4. Drying of the handsheet on a heated surface.
Disintegrators or beaters are used to disperse fibers into an aqueous slurry. Disintegrators are vessels with an agitator at the bottom and operate much like a Waring blender. Beaters are oval-shaped vessels that circulate the slurry past a beater roll that has protruding bars to rub the fibers against a flat steel breastplate. A laboratory beater, commonly called a Valley beater, is depicted in Figure 4.9.

![Disintegrator Image](image)

**Figure 4.9. Valley beater showing the beater roll and its protruding bars.**
Reproduced with permission of Hollingsworth & Vose Company Inc, East Walpole, Massachusetts, USA.

A sheet mold is a vessel that has a wire or forming fabric at the bottom. It is either cylindrically shaped or square shaped. The vessel is filled with water and a measured amount of stock from the disintegrator is added. The pulp is usually agitated by a perforated plate plunger that fits closely to the dimensions of the sheet mold. The plunger is manually pumped up and down the inside of the sheet mold to adequately mix and disperse the fibers. After the fibers are adequately dispersed, a valve at the bottom of the mold is opened. The water drains through the forming fabric. The fibers are retained on the fabric to form the wet handsheet. Two square 30.5 × 30.5 cm (12 × 12 in.) sheet molds are depicted in Figure 4.10. The perforated plunger is shown resting on top of the open sheet mold to the right.

The wet formed handsheet is removed from the wire by couching (pronounced kooching). The couching procedure involves mechanically removing enough water from the handsheet so that it can be peeled off the forming wire. The water is removed by sandwiching the wire and sheet between blotters and applying some
form of pressure to help blot of the water. In some places, it is done by vacuum suction from the wire side.

The couched sheet is dried on a surface heated dryer. Electric photo dryers work very well for this purpose. Once dried the handsheet is tested for basis weight, air permeability, and a host of other properties. It is important that the handsheet be made to a specific basis weight target so that all handsheets are compared on the same basis.

Table 4.6 is a tabulation of handsheet data on a broad range of filter pulps. The tabulation was presented in a brochure by Buckeye Cellulose Corporation of Memphis, Tennessee. Note that the handsheet properties measured included air permeability (Frazier), tensile strength, density, bulk, and mean flow pore size. The table also lists fiber properties as determined by image analyzing techniques of the fiber slurries. Curl is a measure of the nonstraightness of the fibers. Weighted length is an average length of all the fibers tested in the sample. Coarseness was determined from the total weight of sample and the total measured length of all the fibers in the specimen.

It should be noted that handsheet testing of pulp fibers is not limited to just wood pulps. It can also be used for vegetable fibers, synthetic fibers, and inorganic fibers that can be formed into a fiber slurry. In the discussion of vegetable fibers to follow, some handsheet data are presented. Some fibers such as polyester may be difficult handsheets because their wet web strength is too weak for couching.

4.3.5.1.3 Vegetable fibers
A number of natural fibers used in nonwoven filter media come from plants other than trees. Typical length, diameter, and aspect ratios are listed in Table 4.7. Chemical compositions of some common vegetable fibers are listed in Table 4.8. It is important to note from which part of the plant the fiber came. This is indicated in Table 4.8.
Table 4.6  Wood Pulps Commonly Used in Filter Paper

The fibers of different wood species vary considerably in such morphological features as fiber length, diameter, and wall thickness. These differences affect paper properties such as porosity, tensile, bulk, and pore size. Special treatment in the pulping process can also affect papermaking properties. Shown below are the properties of fibers with a range of morphological and processing differences.

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Mean Pore Size (microns)</th>
<th>Curie (%)</th>
<th>Weighted Length (mm)</th>
<th>Coarseness (tag/100m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPZ (MERCERIZED)</td>
<td>455</td>
<td>5.2</td>
<td>0.144</td>
<td>7.09</td>
</tr>
<tr>
<td>SLASH (PINE)</td>
<td>308</td>
<td>5.0</td>
<td>0.157</td>
<td>6.17</td>
</tr>
<tr>
<td>BUCKEYE COTTON LINTERS, Grade 512</td>
<td>194</td>
<td>2.67</td>
<td>0.106</td>
<td>5.99</td>
</tr>
<tr>
<td>PEC</td>
<td>112</td>
<td>1.45</td>
<td>0.198</td>
<td>5.05</td>
</tr>
<tr>
<td>HPZ (PREDOMINANTLY SAWN) SLASH</td>
<td>64</td>
<td>1.17</td>
<td>0.272</td>
<td>4.31</td>
</tr>
<tr>
<td>FLASH-DRIED SOUTHERN HARDWOOD KRAFT</td>
<td>70</td>
<td>2.02</td>
<td>0.198</td>
<td>5.05</td>
</tr>
<tr>
<td>PREDOMINANTLY SAWN PINE KRAFT</td>
<td>64</td>
<td>1.61</td>
<td>0.243</td>
<td>4.42</td>
</tr>
<tr>
<td>SLASH/DLOROLLY PINE KRAFT</td>
<td>50</td>
<td>1.95</td>
<td>0.259</td>
<td>5.91</td>
</tr>
<tr>
<td>ISPARTO</td>
<td>17</td>
<td>1.57</td>
<td>0.225</td>
<td>1.44</td>
</tr>
<tr>
<td>TEAKOLYTIS</td>
<td>12</td>
<td>1.51</td>
<td>0.296</td>
<td>3.18</td>
</tr>
<tr>
<td>NORTHERN SOFTWOOD KRAFT</td>
<td>10</td>
<td>2.85</td>
<td>0.329</td>
<td>3.04</td>
</tr>
</tbody>
</table>

Reproduced with permission of Buckley Cellulose Corporation, Memphis, Tennessee, USA.

Table 4.7  Average length, average diameter, and length/diameter ratio of various vegetable fibers

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Length (mm)</th>
<th>Diameter ((\mu m))</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woods</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coniferous (softwood)</td>
<td>4.0</td>
<td>40</td>
<td>100.0</td>
</tr>
<tr>
<td>Deciduous (hardwood)</td>
<td>2.0</td>
<td>22</td>
<td>90.0</td>
</tr>
<tr>
<td>Straws and grasses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>0.5</td>
<td>9</td>
<td>60.0</td>
</tr>
<tr>
<td>Ispar(\text{t})</td>
<td>1.1</td>
<td>10</td>
<td>110.0</td>
</tr>
<tr>
<td>Misc. (wheat, rice, wheat)</td>
<td>1.5</td>
<td>13</td>
<td>120.0</td>
</tr>
<tr>
<td>Canes and reeds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bagasse (sugar cane)</td>
<td>1.7</td>
<td>20</td>
<td>80.0</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>1.2</td>
<td>12</td>
<td>100.0</td>
</tr>
<tr>
<td>Bamboos</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Several varieties</td>
<td>2.8</td>
<td>15</td>
<td>180.0</td>
</tr>
<tr>
<td>Woody stalks with bast fibers (jute, flax, kenaf, cannabis)</td>
<td>0.25</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>Bast fibers(\text{a})</td>
<td>20</td>
<td>20</td>
<td>1,000</td>
</tr>
<tr>
<td>Bast fibers(\text{a})</td>
<td>20</td>
<td>20</td>
<td>1,000</td>
</tr>
<tr>
<td>Cotton</td>
<td>30</td>
<td>20</td>
<td>1,500</td>
</tr>
<tr>
<td>Seed fibers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cotton</td>
<td>30</td>
<td>20</td>
<td>1,500</td>
</tr>
<tr>
<td>Cotton linters</td>
<td>20</td>
<td>20</td>
<td>1,000</td>
</tr>
</tbody>
</table>

\(\text{a}\) Fibers obtained from inner bark.

Reproduced with permission of Angus Wilde Publications Inc., Vancouver, British Columbia, Canada\(\text{b}\).

\(\text{b}\)Reference Smook\(\text{a}\) page 4.
example, cotton is a seed hull fiber. Fibers like flax, jute, hemp, ramie, and flax are bast fibers; fibers obtained from the inner bark or phloem of a woody plant. Abaca and sisal are leaf fibers. Kenaf is listed as a core fiber; however, the bast fibers from this plant are of more interest to filter media. Esparto is a grass fiber that has important applications in filter media. Other vegetable fibers such as those from cane (bamboo and sugar) and stalks (rice, wheat, barley, oat, and rye) have utility as papermaking pulps; however, they have not gained acceptance as fibers for filter media.

4.3.5.1.3.1 Cotton
Cotton is the product of a woody shrub that is grown from an annual field crop. When it is harvested, the fiber and seed are removed from the plant as seed cotton. Ginning is the process by which the fibers are separated from the seed. The ginned cotton is compressed into bales and referred to as raw cotton.
The separated seeds are used for making cotton oil. They still contain short fibers known as linters. At the oil mill, linters are removed from the seed by delinting machines. The fibers removed are known as mill run linters. Usually, the seeds are run through the delinting machines twice to produce first-cut and second-cut linters. Cotton staple and first-cut linters are a source of fiber for many nonwoven products including needlefelt filter media. First- and second-cut linters are used in wet lay filter products. They are an alternative to high alpha wood pulp for providing bulk and permeability to wet lay filter media. Actually, it is the other way around. The high alpha wood pulps were developed as a lower cost replacement for cotton to provide high air permeability to wet laid filter media.

Another by-product of the gin is motes. Motes are small, immature seeds with attached fiber that are removed at a different stage of the gin stand than the mature seeds. The fiber can be removed from the motes using a delinting machine. This fiber is called gin mote fiber and is used in nonwoven products.

According to Cotton Incorporated, classification or classing of cotton is based on three primary parameters: micronaire, length, strength. These and other properties are measured by a test instrument known as a High Volume Instrument (HVI). It is manufactured by Uster Technologies, Switzerland.

1. Micronaire: Micronaire, already defined in Section 4.3.4.5, is determined by compacting a 2.34 gm specimen to a specific volume in a porous chamber. Air is forced through the chamber and the resistance to airflow is proportional to the linear density of the fibers (expressed in μgm/in.). TAPPI 1205-42 (Boyer) states “the micronaire of cotton is governed by the variety of cotton planted, and varies within each variety due to fiber diameter and actual amount of cellulose present. In general, shorter staple length cottons tend to be coarser, and longer staple length cottons tend to be finer.”

2. Length: Cotton fiber length varies genetically. It follows a fiber length array or fiber length distribution as demonstrated in the graph of Figure 4.11. American upland cottons are classified as short staple, medium staple, or long staple
Handbook of Nonwoven Filter Media

(see Section 4.3.4.2). The length of most waste cotton, which includes linters, comber noils, strips, and motes, will be shorter than raw, unprocessed fiber. Comber noils are the short fibers removed by a combing operation. The machine doing this is called a comber. The waste fibers, usually 0.5 in. (12.7 mm) or less, in length are often used in nonwoven materials and filter media.

3. Strength: Fiber strength is one of the properties measured by the HVI tester. It is the force to break a bundle of fibers of 1 tex unit (1 g per 1,000 m) in size. It is expressed in gm/tex.

4. Nep count: Nep count is another property important to cotton. Nepes are small tangled knots of fiber caused by mechanical processing. It is measured by an AFIS-M tester also manufactured by Uster Technologies, AG.

Raw cotton, when harvested and ginned, contains considerable contaminants and impurities, as well as oils and waxes that make it hydrophobic. Raw cotton has some utility in industrial nonwovens where absorbency and esthetics are unimportant; however for applications where absorbency, whiteness, and purity are desired the cotton has to be scoured and bleached. Figure 4.12 is a block diagram of the bleaching process. Table 4.9 lists the properties of bleached cotton as published by Cotton Incorporated(99).

Figure 4.12. Cotton scouring and bleaching.
Reproduced with permission of Cotton Incorporated, Cary, North Carolina, USA.

Cotton is 99% pure cellulose. Cellulose is a polymer containing anhydro-beta-cellobiose as the repeat unit. The number of repeat units in a cellulose molecule is its degree of polymerization. The simplified chemical structure of cellulose is among those listed in Table 4.1. Wood pulp fibers and rayon are also polymers of cellulose. The difference is in their degrees of polymerization or polymer length and in their degree of crystallinity. Crystallinity indicates that the fiber molecules are closely packed and parallel to one another. Table 4.10 compares the degree of polymerization of cotton to rayon and wood pulp.

The shape of a cotton fiber is that of a convoluted ribbon. This twisted shape is well demonstrated in the micrograph of Figure 4.13. Because of the twists and convolutions, cotton is a very flexible fiber that can readily bend in any direction. The fiber has a high degree of curl and this contributes to bulking behavior in filter media.
Table 4.9  Properties of bleached cotton

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (in.)</td>
<td>0.75–1.25</td>
</tr>
<tr>
<td>A. Commodity staple</td>
<td></td>
</tr>
<tr>
<td>B. Gin motes</td>
<td>0.5–0.75</td>
</tr>
<tr>
<td>C. Comber</td>
<td>Less than 0.5</td>
</tr>
<tr>
<td>D. First-cut linters</td>
<td>0.25–0.5</td>
</tr>
<tr>
<td>Fiber diameter</td>
<td></td>
</tr>
<tr>
<td>A. Micronaire (μg/in.)</td>
<td>2.0–6.5</td>
</tr>
<tr>
<td>B. Denier (g/9,000 m)</td>
<td>0.7–2.3</td>
</tr>
<tr>
<td>Elastic recovery</td>
<td></td>
</tr>
<tr>
<td>A. At 2% extension</td>
<td>74%</td>
</tr>
<tr>
<td>B. At 5% extension</td>
<td>45%</td>
</tr>
<tr>
<td>Breaking elongation (dry)</td>
<td>3%–9.5%</td>
</tr>
<tr>
<td>Tensile strength</td>
<td></td>
</tr>
<tr>
<td>A. Dry</td>
<td>27–44 g/tex; 3.0–4.9 g/de</td>
</tr>
<tr>
<td>B. Wet</td>
<td>28–57 g/tex; 3.3–6.4 g/de</td>
</tr>
<tr>
<td>Water absorbing capacity (USP method)</td>
<td>Greater than 2.4 g water/g fiber</td>
</tr>
<tr>
<td>Specific gravity</td>
<td></td>
</tr>
<tr>
<td>A. Cellulose polymer</td>
<td>1.54 gm/cm³</td>
</tr>
<tr>
<td>B. Cotton fiber</td>
<td>1.27 gm/cm³</td>
</tr>
<tr>
<td>Degree of polymerization</td>
<td>9,000–15,000</td>
</tr>
<tr>
<td>Crystallinity by X-ray diffraction (average)</td>
<td>73%</td>
</tr>
<tr>
<td>Color (Hunter colorimeter)</td>
<td></td>
</tr>
<tr>
<td>A. Whiteness index</td>
<td>90–100</td>
</tr>
<tr>
<td>B. Blue reflectance</td>
<td>75–85</td>
</tr>
<tr>
<td>Thermal resistance</td>
<td></td>
</tr>
<tr>
<td>A. Long exposure to dry heat above 300°F will cause gradual decomposition</td>
<td></td>
</tr>
<tr>
<td>B. Temperatures greater than 475°F causes rapid deterioration</td>
<td></td>
</tr>
<tr>
<td>Acid resistance</td>
<td></td>
</tr>
<tr>
<td>A. Disintegrated by hot dilute acids or cold concentrated adds</td>
<td></td>
</tr>
<tr>
<td>B. Unaffected by cold weak adds</td>
<td></td>
</tr>
<tr>
<td>Alkali resistance</td>
<td></td>
</tr>
<tr>
<td>Swelling in NaOH above 18% but no damage</td>
<td></td>
</tr>
<tr>
<td>Organic solvent resistance</td>
<td></td>
</tr>
<tr>
<td>Resistant to most common industrial and household solvents</td>
<td></td>
</tr>
<tr>
<td>Web formation</td>
<td></td>
</tr>
<tr>
<td>A. Dry lay (carding, garneting)</td>
<td></td>
</tr>
<tr>
<td>B. Air lay</td>
<td></td>
</tr>
<tr>
<td>Bonding mechanisms</td>
<td></td>
</tr>
<tr>
<td>A. Needlepunching</td>
<td></td>
</tr>
<tr>
<td>B. Hydroentanglement</td>
<td></td>
</tr>
<tr>
<td>C. Stitchbonding</td>
<td></td>
</tr>
<tr>
<td>D. Chemical bonding</td>
<td></td>
</tr>
<tr>
<td>E. Thermal bonding</td>
<td></td>
</tr>
</tbody>
</table>

Reproduced with permission of TAPPI. Atlanta, Georgia, USA.
Table 4.10  Comparison of cellulose polymer fibers

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Degree of polymerization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>9,000–15,000</td>
</tr>
<tr>
<td>Viscose rayon</td>
<td></td>
</tr>
<tr>
<td>Regular</td>
<td>250–450</td>
</tr>
<tr>
<td>High tenacity</td>
<td>500–650</td>
</tr>
<tr>
<td>High wet modulus</td>
<td>400–550</td>
</tr>
<tr>
<td>Wood pulp</td>
<td>600–1,500</td>
</tr>
</tbody>
</table>

Reproduced with permission of TAPPI, Atlanta, Georgia, USA(100), p. 9, Table 1.

Figure 4.13. Convoluted cotton fiber.
Reproduced with permission of the Institute of Paper Science and Technology, Atlanta, Georgia, USA(98).

4.3.5.1.3.2 Abaca (Manila hemp)
Abaca is more commonly known as Manila hemp, the type used for making Manila rope. Abaca is not a true hemp, but comes from a plant related to the banana tree. Abaca’s use in filter media is mostly for wet lay filter applications. It is used in filter products such as teabag, coffee filter, industrial filter, and vacuum bag. It is also used in medical gas masks and as a reinforcement in microglass air filters. Eighty-five percent of the world’s output of abaca is grown in the Philippine Islands. Much of the remainder is grown in Ecuador.
The abaca fiber is derived from the leaf sheaths of *Musa textilis*. The plant consists of a cluster of sheath-like leaf stalks. The stalks often grow to heights of 6 m or more. The fiber comes from the outer layer of the sheath-like leaves. At harvest time, the stalks are separated from the stem of the plant and grouped as follows: outside sheaths, adjacent to the outside sheaths, middle sheaths, and inner sheaths. The location and width of each sheath affects the yield and quality of fiber. The fiber layer is separated from the leaf sheath by a process known as stripping. In its simplest form, the fiber is peeled away from the rest of the plant with a serrated stripping knife. A more productive technique is to strip the fiber on a motor driven tapered spindle called a “hagotan”. In some places a “decorticator” is used which increases productivity, but produces a lower quality fiber.

Table 4.11 lists the various grades of Philippine hand stripped abaca. Note much of the grading depends on the type of stripping knife. If the fiber is spindle stripped the grade rating is similar; however, the designation is preceded by an “S”.

| Table 4.11 Main hand stripped abaca grades of the Philippines and its principal end uses |
|---------------------------------------------|-------------|-------------|------------------|
| Cleaning                                   | Grade       | Layer of leaf sheath | Uses                           |
| Excellent cleaning (nonserrated stripping knife) | AD | Middle area | Handicraft industry |
|                                           | EF | Middle area | Handicraft industry |
|                                           | S2 | Next to outside | Cordage, teabags, filters, stencil, casing paper, handicraft |
|                                           | S1 | Outside | Cordage |
| Good cleaning (20 tooth/in. stripping knife) | I  | Innermost and middle | Cordage, teabags, filters, stencil, casing paper |
|                                           | H  | Outside | – |
|                                           | G  | Next to outside | Cordage, teabags, filters, stencil, cigarette, handicraft industry |
| Fair cleaning (17 tooth/in. stripping knife) | JK | All except outside | Cordage, cigarette, currency paper |
|                                           | M1 | Outside | Cordage, cigarette |
| Coarse cleaning (14 tooth/in. stripping knife) | L  | Innermost and middle | – |
| Damaged during cleaning | Y1 - Y2 | All | Cordage, cigarette, currency paper |

Nomenclature:
- **AD**: Superior current: white-to-light yellow aspect; 5–8 mm fiber length.
- **EF**: Mid-current: light ochre brown or red with small quantities of ivory yellow; about 5 mm fiber length.
- **S2**: Streaky two.
- **S1**: Streaky three.
- **I**: Fair current: light brown, but darker than EF; about 5 mm fiber length.
- **G**: Soft seconds: light brown or red mixed with yellow ochre in variable proportions; 3–5 mm fiber length.
- **H**: Soft brown: brown or dark red mixed with light purple or light burnt sienna; 3–5 mm fiber length.
- **JK**: Superior-medium seconds: light brown, dingy white; 3–5 mm fiber length.
- **M1**: Medium brown: same as grade H but ranging to dark brown and black; 3–5 mm fiber length.
- **L**: Coarse: same as grade H but ranging to darker brown; about 5 mm fiber length.
- **Y1**: Damaged fine from grades AD, EF, S2, I, S1 and G.
- **Y2**: Damaged medium coarse from grades H, JK, M1 and L.

Note: Spindle stripped abaca grades follow a similar designation, but are preceded by an “S”.

Reproduced with permission of TAPPI, Atlanta, Georgia USA. p. 136, Table 11.
Most abaca fiber used for filtration is processed into wet lay filter media. The fiber has to be pulped in a pulping process much like wood fiber. Table 4.12 lists hand sheet properties of some abaca grades including an Ecuadorian grade (AB-EC). Note for permeability, the Ecuadorian grade is considerably more open and porous than the Philippine grades.

Abaca fibers are up to 6 mm in length and 20–24 μm in diameter. The 6-mm length makes abaca just about the longest pulp fiber used in the wet lay process. The fiber has tapered ends. It also has large lumen and thin cell walls. Because of its length and good hydrogen bonding qualities, abaca provides enhanced strength to wet laid pulp products.

<table>
<thead>
<tr>
<th>Fibergrade</th>
<th>$S_2$</th>
<th>JK</th>
<th>$Y_2$</th>
<th>AB-EC(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beating time, min</td>
<td>13</td>
<td>11</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Breaking length, km</td>
<td>5.3</td>
<td>5.1</td>
<td>5.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Permeability, cm(^3)/min</td>
<td>72,000</td>
<td>76,800</td>
<td>74,400</td>
<td>108,000</td>
</tr>
<tr>
<td>Tear index, mNm(^2)/g</td>
<td>43.4</td>
<td>42.3</td>
<td>40.8</td>
<td>45.9</td>
</tr>
</tbody>
</table>

\(^a\)Ecuadorian grade.
All results tested at 27°SR (Shopper Riegler)

Reproduced with permission of TAPPI, Atlanta, Georgia, USA\(^{103}\), p. 137.

4.3.5.1.3.3 Sisal

Sisal (Agave sisalana) is a nonwood leaf plant of the Amaryllidaceae family. It is a native of Mexico; however, the plant has thrived in semi-arid regions of Africa and South America. Other forms of sisal that are commercially available are *A. cantala* and *A. fourcroydes* (also known as henequen). The plant is characterized by rosettes of fleshy leaves, usually long and narrow, which grow out from a central bud. The fibers lie embedded longitudinally in the leaves, being most abundant near the leaf surfaces. Sisal grows all year and the first harvest can be made 2½ years after planting. The productive period of sisal is 4–6 years.

The leaves contain about 90% moisture-forming firm, fleshy pulp. Fiber removal is accomplished by scraping the pulpy material. This is done by a decorticating process. The process consists of pairs of metal drums on which scraping blades are mounted. The leaves are passed between the drums in such a way that the pulp is scraped away by the scraping blades. Water is sprayed on to the leaves to assist in the process. The wet decorticated fiber is washed and dried. The dried fibers are then brushed to remove clinging dust and bring out the luster.

Each leaf contains three main fiber zones: peripheral, median, and ground tissue (Martinez et al.\(^{103}\), p. 128). They contain either ribbon fibers (median zone) or mechanical fibers (peripheral zone) or both (ground tissue zone). Ribbon fibers run the full length of the leaf and are coarser than mechanical fibers. They have a
crescent-shaped cross-section. They are easily split in the longitudinal direction to cross-mechanical ribbon fibers. Mechanical fibers are nearly round in cross-section. They do not split; therefore, they determine the maximum diameter of the fiber.

A single sisal filament or fiber is constructed of numerous elongated cells with tapering ends. These are known as ultimates and are closely packed and bonded together so that there are no intercellular spaces. Ultimates range in length from 1.5 to 4.0 mm long and average approximately 3.0 mm. The cell diameters range from 20 to 30 μm.

Sisal fiber is graded according to the country and the district of growth and further subgraded according to color, cleanness, and length. Table 4.13 lists the classification of some grades from Brazil and East Africa. Sisal is known for its use in the cordage industry. Sisal strand is used in air laid and needlepunch nonwovens. In pulp form it has interesting properties for wet laid filter media. The fiber shape is very much like a shorter form of abaca discussed above. It offers 40%–70% higher tear strength than softwood pulp. Because it is a stiff (high modulus) fiber and has a relatively narrow fiber diameter, it forms wet laid webs that are bulky, permeable, small in pore size, and strong. Some pulp handsheet properties for various grades of sisal are listed in Table 4.14.

<table>
<thead>
<tr>
<th>Length Quality</th>
<th>EL Extra-long</th>
<th>L-Long</th>
<th>M-Medium</th>
<th>C-Short</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type Superior</td>
<td>Grades A and 2</td>
<td>Grade 3L</td>
<td>Grade 3</td>
<td>Grades UG and SCWF</td>
</tr>
<tr>
<td>Residues from processing</td>
<td>Bucha 1</td>
<td>Bucha 2</td>
<td>Bucha 3</td>
<td>Aperas</td>
</tr>
<tr>
<td>Residues from spinning</td>
<td>Combing</td>
<td>Calander</td>
<td>Spinning</td>
<td>Brushing</td>
</tr>
</tbody>
</table>

- Grades UG, rejects from processing operations are normally used for papermaking.
- Superior grades are destined for cordage or handicraft works.

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<table>
<thead>
<tr>
<th>Grade</th>
<th>Brazilian type</th>
<th>Brazilian bucha</th>
<th>African grade 3L</th>
<th>African grade UG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 long</td>
<td>5</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Beating Time, min</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Breaking length, km</td>
<td>3.5</td>
<td>3.0</td>
<td>3.9</td>
<td>3.7</td>
</tr>
<tr>
<td>Permeability, ml/min</td>
<td>72,000</td>
<td>88,800</td>
<td>96,000</td>
<td>100,800</td>
</tr>
<tr>
<td>Tear index, mN·m/g</td>
<td>26.5</td>
<td>23.5</td>
<td>22.9</td>
<td>22.4</td>
</tr>
</tbody>
</table>

All results tested at 25°SR (Shopper Riegler)

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4.3.5.1.3.4 Kenaf

Kenaf (Hibiscus cannabinus) is interesting because of its potential as a papermaking fiber, and its applicability for wet lay filter media. Kenaf is an annual plant that requires regular amounts of water. It grows best in Southern climates. The plant reaches a height of approximately 5 m and a diameter of approximately 10–25 cm. The plant provides two sources of fibers: the inner core which provides a short fiber much like hardwood, and the bast fiber which is considerably longer. These are depicted in Figure 4.14. Table 4.15 compares the two forms of the fiber along with flax (see Section 4.3.5.1.3.5 below) to NSW and southern hardwood (SHW). The advantage of the Kenaf fiber becomes apparent. It is as long as softwood fiber and has a narrower diameter. It is also a relatively high modulus fiber; therefore, it has the potential of providing bulk, air permeability, and strength to wet lay filter media. There is considerable development of Kenaf as an alternate fiber source to wood pulp in the USA; however, commercialization is still in the future. In Japan and Europe, there has been some success in the development of Kenaf and flax as nonwoven reinforcements for automotive plastic components. Presently, there are no known filter applications.

Figure 4.14. Kenaf fiber: bast fiber on left, core fiber on right.

Table 4.15 Kenaf and flax fiber comparison

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Length, mm</th>
<th>Diameter, μm</th>
<th>L/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flax – Bast</td>
<td>30</td>
<td>20</td>
<td>1,350:1</td>
</tr>
<tr>
<td>Kenaf – bast</td>
<td>2.6</td>
<td>20</td>
<td>135:1</td>
</tr>
<tr>
<td>Kenaf – core</td>
<td>0.6</td>
<td>30</td>
<td>20:1</td>
</tr>
<tr>
<td>NSW</td>
<td>2.7–4.6</td>
<td>32–43</td>
<td>100:1</td>
</tr>
<tr>
<td>SHW</td>
<td>0.7–1.6</td>
<td>20–40</td>
<td>40:1</td>
</tr>
</tbody>
</table>

Reproduced with permission of TAPPI, Atlanta, Georgia, USA\(^{100}\), p. 100.
4.3.5.1.3.5 Flax
Flax is a group of the bast annual and perennial plants from the Linaceae family that form the genus *Linum*. Long known for its use in producing the fabric known as linen, it is one of the oldest cultivated plants. The primary fibers are from the bast layer. Ultimates are 10–65 mm in length and 14–30 μm in diameter. The fibers are separated by a process known as retting. This is a natural, enzymatic process lasting approximately 2 weeks. In the process, the woody cores holding the fiber bundles together are broken down and the fibers are then easily separated. The longer high quality fibers are used for fabric applications including dry laid nonwovens. The shorter fibers, most of which come from process residues, are directed toward products of papermaking. Cigarette wrap is one of the larger markets for flax paper. There appears to be little application for flax fibers in filter medium markets. Table 4.16 lists some handsheet properties of flax pulp with various levels of shive content.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Textile flax</th>
<th>15%–20% shive</th>
<th>30%–35% shive</th>
<th>Seed flax 40%–45% shive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beating time, min</td>
<td>11</td>
<td>26</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>Breaking length, km</td>
<td>6.8</td>
<td>6.7</td>
<td>6.6</td>
<td>7.3</td>
</tr>
<tr>
<td>Permeability, ml/min</td>
<td>12.0</td>
<td>10.0</td>
<td>10.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Tear index mNm⁻²/g</td>
<td>26.5</td>
<td>23.5</td>
<td>22.9</td>
<td>22.4</td>
</tr>
</tbody>
</table>

All results tested at 90° SR (Shopper Riegler).
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4.3.5.1.3.6 Hemp
Although hemp may be the oldest cultivated fiber plant, its commercial usage for fiber products has declined in recent times (although its commercial use for illegal products may have increased). True hemp (*Cannabis sativa*) is a completely different plant than the abaca plant, which is not a hemp plant even though it is known as Manila hemp. The hemp fiber is produced by retting process similar to the flax operation. Hemp fibers are flat ribbons 1–5 m long and 0.5–5 mm wide. The ultimate cells are 5–55 mm long and 16–50 μm in diameter. The longer fibers are used for production of yarns and twine. Shorter fibers, which may contain an impurity called hurds, are used for specialty papers. There is no known specific use of hemp in nonwoven filter media. Table 4.17 lists handsheet properties of hemp pulp containing various degrees of hurd content.

4.3.5.1.3.7 Esparto grass
Esparto is a coarse grass native to Southern Spain and Northern Africa. It is also known as “halfah grass” and “needle grass”. There are two species, *Lygeum spartum* and *Stipa tenacissima*. The fiber length is less than 3 mm and averages 1.5 mm. The fiber diameter ranges from 5 to 15 μm. The average is approximately 12 μm. The fiber has a fiber density of 15 million fibers per gram making it the highest of any paper pulp.
Table 4.17 Evaluation of some bleached pulps from hemp with a different quantity of shive in the original raw material

<table>
<thead>
<tr>
<th>Grade</th>
<th>25% hurd\textsuperscript{a}</th>
<th>35% hurd\textsuperscript{a}</th>
<th>75% hurd\textsuperscript{b}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beating time, min</td>
<td>37</td>
<td>33</td>
<td>27</td>
</tr>
<tr>
<td>Breaking length, km</td>
<td>6.5</td>
<td>6.7</td>
<td>7.3</td>
</tr>
<tr>
<td>Permeability, ml/min</td>
<td>10</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Tear index mN m\textsuperscript{2}/g</td>
<td>8.5</td>
<td>8.1</td>
<td>5.8</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Results tested at 90° SR (Shopper Riegler).
\textsuperscript{b}Results tested at 45° SR.

Reproduced with permission of TAPPI, Atlanta, Georgia, USA\textsuperscript{[101]}, p. 127.

The fiber cross-section is round and the cell wall is thick. The cross-section is pictured in Figure 4.15. The fiber is not straight, but has some curvature to it. This contributes to bulking qualities in a filter medium.

Esparto pulp, considerably more expensive than wood pulp fibers and yet, is broadly used as a fiber for wet laid filter media, particularly in those grades where high filtration efficiency is desired. Its fine fiber diameter combined with fiber curvature provides for

![Figure 4.15. Cross-section through an esparto grass stalk.](image)

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high efficiency along with relatively high bulk for the efficiency. The thick cell wall structure contributes to the bulk and permeability properties and adds to the dimensional stability to the sheet structure. The filtration properties of esparto are better appreciated by the comparison of Figure 4.16. The figure shows side-by-side micrographs from handsheets of esparto and bagasse pulp (a sugar cane fiber). Note that the slender esparto fiber structure allows for ample pore openings in the medium, whereas the broad flat ribbon structure of bagasse fiber covers the openings and blinds the medium. Bagasse pulp has found some important niches in board and paper products; however, filter medium is not one of them.

![Esparto and Sugarcane Bagasse](image)

**Figure 4.16.** Esparto-bagasse comparison.
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4.3.5.1.3.8 Coconut fiber
Coconut fiber, commonly known as coir, is obtained from the fibrous husk of the coconut. This is the thick fibrous middle layer (2) of the coconut sketched in Figure 4.17. To separate the fibers the coconut shells are cut in half and then retted. In the retting process, the coconut shells are buried in wet soil to allow microbial degradation of the softer tissues. The shells are then beaten and washed to readily separate the coir fibers. Incidentally, the hard inner layer, called the stone (3) in Figure 4.17, is the source of coconut shell activated carbon, so very popular in adsorbent filter media.

Coir fiber has a high lignin content which makes it resilient, strong, and highly durable. It is graded into “bristle” fiber (combed, approximately 20–40 cm long) and “mattress” fiber (random fibers approximately 2–10 cm long). The fiber finds application in residential furnace and ventilation filter pads. It is often combined with hog’s hair in natural filters.
Figure 4.17. The components of a coconut. The thick fibrous middle layer 2 is the source layer for coir (coconut fiber). The hard inner layer 3 is a source of coconut shell activated carbon.

4.3.5.9 Others

There is a long list of nonwood natural fibers that find application in nonwoven and paper structures; however, like bagasse they are not readily found in filter media. Included in this list are jute, various straw fibers, reed fibers, bamboo, grass fibers other than esparto, various variations of hemp fibers, ramie, etc. Some of these fibers might be good filter medium fibers; however, their use is limited because of availability and other economic considerations.

4.3.5.1.4 Animal fibers

4.3.5.1.4.1 Wool

Although sheep are generally perceived as the source of wool, the wool of other animals are also cultivated for their properties. This includes goat’s wool (mohair) and alpaca wool from a camel-related animal of South America. Although the usage of wool in many of its commercial applications is being displaced by synthetic fibers, it has unique characteristics for filter medium applications. It is most often used in needlefelt form for bag filters. It is used in air filter applications, such as baghouse filtration, residential filters, vacuum cleaner bags, and industrial respirators. It is also has application in the filtration of oils. National Nonwovens of Easthampton, Massachusetts, produces a wool felt medium under the Phoenix Felt® trade name. They advertise it for hydraulic filtration, home/cabin filtration, and oil filtration.

Wool has some unique properties for filtration. Wool fibers are naturally cramped, offering bulk and loft. They can easily be electrostatically charged. They have good
strength and dimensional stability. They are durable. To illustrate, a wool fiber can be flexed back and forth on itself more than 20,000 times without breaking as compared to 3,000 times for cotton, 2,000 times for silk, and 75 times for rayon. Wool is flame resistant. It will char in the presence of a flame; however, it will self-extinguish once the flame is pulled away. Wool will absorb up to 30% by weight of moisture. It absorbs over 40 times its weight in oil, more than polypropylene. Mats made from wool are very useful for the clean-up of oil and chemical spills. It is biodegradable and may help alleviate the problems of hazardous waste disposal.

4.3.5.1.4.2 Silk
For centuries and centuries silk has been the high-end fiber for luxurious fabrics and clothes. It is produced by the silkworm in preparing its cocoon. There has been very little use of silk in filter media.

4.3.5.1.4.3 Hog’s hair
Hog’s hair has been traditionally used as the bristles in hairbrushes and is often referred to as bristle. When carded into filter medium and coated with a rubber coating they form a bulky, high loft structure used as filter pads in residential and ventilation furnace filter systems. Sometimes the fiber composition includes coir or coconut fiber. Several companies manufacture hog hair filters for residential furnace and air conditioning systems. Among these are Purolator of Henderson, North Carolina, American Air Filters International (AAF), Air Guard of Louisville, Kentucky, and Air Filters, Inc. They are often advertised as “natural” fiber filters.

4.3.5.2 Synthetic fibers: organic
Almost all organic synthetic fibers are produced by a spinning process. One exception is fibrillated film such as that used in some of the Filtrete® filters produced by 3M Company.

4.3.5.2.1 Rayon
In the 1880s, a Frenchman named Hilaire de Chardonnet first spun fibers of “artificial silk” from a solution of cellulose. Two Englishmen, Charles Cross and Ernest Bevan, invented the “viscose” process in 1891. Courtaulds, a British company, started producing the viscose fiber in 1905. The first American producer of artificial silk was American Viscose Corporation (now Avtex Fibers) in 1910. In 1920, DuPont secured from the French, the American rights to produce artificial silk. In 1921, The DuPont Fibersilk Company produced the first yarn of what later became known as rayon. In the evolution, The DuPont Fibersilk Company became the DuPont Rayon Company, which was the predecessor for DuPont’s Textile Fibers Department. As this book was being written, the Textile Fibers Department was sold and reorganized into a company now known as Invista.

Four primary forms or modifications of rayon are:

(a) viscose rayon,
(b) high wet modulus (HWM) rayon,
(c) high tenacity rayon,
(d) cuprammonium rayon.
HWM and high tenacity rayon are variations of the viscose process for producing rayon. HWM seeks to correct the wet strength deficiencies of regular viscose rayon. It is also known as “polynosic” rayon and as modal rayon. Modal rayon is used in high end apparel products. High tenacity rayon is a modification of regular viscose rayon to provide exceptional strength. It has twice the strength of HWM rayon. High tenacity rayon has been widely used in tire cord. Cuprammonium rayon is produced from a different chemistry.

The process for producing rayon involves preparing a viscous solution of cellulose and spinning it into fiber form. The cellulose source is either cotton linters or a highly purified form of wood pulp. In the viscose process, the cellulose is treated with caustic and carbon disulfide. The resulting material referred to as “yellow crumb” is a copolymer of cellulose and cellulose xanthate. The yellow crumb is dissolved in an aqueous caustic solution. The high viscosity of this solution lends itself to the term “viscose”. The solution is aged, filtered, and further treated before being subject to a wet spinning process. The fiber precipitates as cellulose as it is spun into a solution consisting of sulfuric acid, sodium sulfate, and zinc (Zn\(^{2+}\)) ions. The fiber filaments are drawn out of the solution, washed, and cut into staple form – if staple is the desired form.

Cuprammonium rayon fiber is produced from a solution of cellulose in cuprammonium hydroxide at low temperatures and in a nitrogen atmosphere. The solution is wet spun into a precipitating solution of sulfuric acid. Although no longer produced in the USA, rayon is still being produced in Europe. Accordis (formerly Courtalds) in England, Lenzing in Austria, and Mitsubishi Rayon in Japan are all major producers of rayon fiber.

Other forms of rayon are saponified rayon and lyocell. Saponified rayon is an acetate derivative of cellulose made by steeping cellulose in acetic acid, then treating it with acetic anhydride. Acetate rayon fiber has a higher degree of orientation than rayon fiber and is more durable. It is a popular fiber for cigarette filters because it is believed to have an affinity for certain contaminants in cigarette smoke.

Lyocell is a fiber made from wood pulp or cotton cellulose. The cellulose is directly dissolved in an amine oxide solvent. It was first manufactured in 1992 by Acordis Cellulosic Fibers, Inc. The only current manufacturer in the USA is Tencel Ltd., which markets it under the trademarked brand name Tencel®. The product is also manufactured by Austrian-based Lenzing A.G. under the trademark Lenzing Lyocell®. In 2004, Lenzing bought out Tencel Ltd. and became the world’s largest producer of lyocell. Note that lyocell by itself is a not a trade name. It is a fiber designation as is nylon and rayon. Lyocell has interesting properties for clothing and apparel; however, the author is unaware of any significant use of this fiber for filter media.

Viscose rayon is the dominant form of rayon in the world. Rayon is a soft, highly absorbent fiber that drapes well and is easy to dye. It is heat resistant up to 149°C. It will char and decompose at temperatures in the range of 175–200°C. Unless modified the fiber has low wet strength. It has moderate chemical resistance. It does not build up static electricity. It is biodegradable which gives it an advantage in disposable filter products. It has poor dimensional stability when exposed to moisture. It will gradually degrade from sunlight and moisture in outdoor environments. The typical properties of viscose rayon are presented in Table 4.18.

Filter media are rarely composed of 100% rayon, but rather the rayon is blended with other fibers such as polyester in carded webs and wood pulp in wet lay substrates.
Table 4.18  Properties of viscose rayon fiber

<table>
<thead>
<tr>
<th>Property</th>
<th>Value or level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point</td>
<td>&gt;400</td>
</tr>
<tr>
<td>Glass transition</td>
<td>Indeterminate</td>
</tr>
<tr>
<td>Moisture regain</td>
<td>6%-8%</td>
</tr>
<tr>
<td>Static electricity</td>
<td>Does not accumulate except in very dry atmosphere</td>
</tr>
<tr>
<td>Dyeability</td>
<td>Excellent dyeability with a variety of different dye classes</td>
</tr>
<tr>
<td>Density</td>
<td>1.5 g/cm³</td>
</tr>
<tr>
<td>Tenacity</td>
<td>~1-5 g/den</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>8%, 25%</td>
</tr>
<tr>
<td>Modulus</td>
<td>Moderate</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>Good</td>
</tr>
<tr>
<td>Flammability</td>
<td>Burns quickly, O.I. = 18</td>
</tr>
<tr>
<td>Acid/base stability</td>
<td>Attacked by mineral acids, reasonably stable in bases</td>
</tr>
<tr>
<td>Oxidative/light</td>
<td>Degraded by strong oxidants and UV light</td>
</tr>
<tr>
<td>Solvents</td>
<td>Strongly polar compounds, amine complexes with Cu and Cd</td>
</tr>
</tbody>
</table>

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It helps provide bulk to a filter medium. When used with polyester, it provides some moisture absorbency to alleviate the dryness and static electricity of 100% polyester. Carded webs containing rayon are most often needlepunched and used in air filter applications. This is not to say that rayon is not used in liquid filtration applications. National Nonwovens advertises a coolant filter medium, FIIDO 3, which is chemically bonded and composed of 10% rayon and 90% polyester. There is still some use of rayon staple in wet laid filter media; however, most of this has been replaced by polyester.

4.3.5.2.2 Polyethylene

Polyethylene is produced through the polymerization of ethylene molecules. The reactions can be either free radical, coordination, or cationic. The free-radical reaction produces a low-density form of polyethylene (LDPE). It is low density because the reaction mechanism allows for the formation of branch chains on the polymer's backbone. The branch chains mechanically reduce the polymer's density. The cationic reaction produces a linear, denser structure known as high-density polyethylene (HDPE). Catalyzed coordination polymerization is capable of producing an ultra high molecular weight polyethylene (UHMWPE). UHMWPE is an extremely long linear polymer capable of inordinately high orientation and strength.

Polyethylene is composed of only carbon and hydrogen. It is the simplest of all polymer structures. It has a low polarity over a long chain length. The polymer is highly flexible. The repeating units are symmetrical with very few reactive functional groups. The HDPE and UHMWPE repeating units are highly regular. LDPE is less so. The degrees of polymerization may range from 500 to 10,000 for LDPE and HDPE, and may exceed 35,000 for UHMWPE.
LDPE has a low melting point. This makes it suitable for meltblown webs. It is also suitable for the sheath in thermobonding sheath–core fiber. HDPE has a higher melting point than does LDPE. The glass transition temperature of polyethylene is extremely low (in the neighborhood of −115°C). Polyethylene has an absence of hydrogen bonding sites; therefore, it is hydrophobic. Its equilibrium moisture content is very low. On the other hand, the polymer is oleophilic. It finds widespread use in operations to separate hydrocarbon liquids in a fluid stream. This would include coalescing separations. It is also used in oil spill clean-up situations ranging from oil spills at sea to the clean up of oil spills in machine shops and metal working operations.

Because the fiber does not absorb water, it is very susceptible to static electricity charging. There are no chemically reactive functional groups on the polymer structure; therefore, polyethylene has relatively good resistance to chemicals. Although the polyethylene will burn, it resists flammability by melting away from a flame. Some of the key properties of polyethylene fiber are listed in Table 4.19.

### Table 4.19 Properties of polyethylene fiber (LDPE and HDPE)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value or level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point</td>
<td>110°C LDPE, 135°C HDPE</td>
</tr>
<tr>
<td>Glass transition</td>
<td>ca. −115°C</td>
</tr>
<tr>
<td>Moisture regain</td>
<td>&lt;0.1% at standard conditions</td>
</tr>
<tr>
<td>Static electricity</td>
<td>Accumulates</td>
</tr>
<tr>
<td>Dyeability</td>
<td>No dyeable product commercially available</td>
</tr>
<tr>
<td>Density</td>
<td>0.90 g/cm³ LDPE, 0.95 g/cm³, HDPE</td>
</tr>
<tr>
<td>Tenacity</td>
<td>Low up to 6 g/den, depending on processing</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>High to low depending on previous treatment (600%-50%)</td>
</tr>
<tr>
<td>Modulus</td>
<td>Low to high depending on orientation, tendency to creep at high stress</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>Excellent</td>
</tr>
<tr>
<td>Flammability</td>
<td>Melts and burns, oxygen index: ca. 15</td>
</tr>
<tr>
<td>Acid/base stability</td>
<td>Excellent/good</td>
</tr>
<tr>
<td>Oxidative/light</td>
<td>Can be etched by strong oxidants, relatively poor light stability</td>
</tr>
<tr>
<td>Solvents</td>
<td>Hydrocarbons at high temperature (&gt;80°C)</td>
</tr>
</tbody>
</table>

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### 4.3.5.2.3 Polypropylene

\[
\text{H} \quad \text{CH}_3
\]

\[
\text{H} \quad \text{C} \quad \text{C} \quad \text{H} \quad \text{H}
\]

The polymerization of polypropylene from propylene is a coordination reaction. Depending on the parameters of the coordination process, the polymer can be produced in isotactic, syndiotactic, or atactic forms. The isotactic form is the one used in fibers. In the isotactic form polymer, repeating units do not vary in their symmetry. Average molecular weights are similar to polyethylene. Degrees of polymerization range from 500 to 10,000. Polypropylene is the fiber form most often used in meltblown products. It is also used in spunbonded products such as Typar® and Tekton® produced by Fiberweb™.
Polypropylene differs from polyethylene in that it has a methyl group attached to its backbone. The steric hindrance of the methyl groups makes the polypropylene polymer less flexible than polyethylene. It also has a higher melting point and $T_g$. Nevertheless, these properties are still low enough so that the fiber will avoid burning by melting away from a flame. In air filtration, the maximum operating temperature for polypropylene is 90–100°C. Properties of polypropylene fiber are listed in Table 4.20.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value or level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point</td>
<td>165°C</td>
</tr>
<tr>
<td>Glass transition</td>
<td>$-15^\circ$C</td>
</tr>
<tr>
<td>Moisture regain</td>
<td>$&gt;0.1%$ moisture regain at standard conditions</td>
</tr>
<tr>
<td>Static electricity</td>
<td>Accumulates</td>
</tr>
<tr>
<td>Dyebility</td>
<td>No dyeable polypropylene is commercially available</td>
</tr>
<tr>
<td>Density</td>
<td>0.90 g/cm$^3$</td>
</tr>
<tr>
<td>Tenacity</td>
<td>up to 7 g/den depending on processing</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>drawn: $&lt;50%$, un-drawn: $50%$+</td>
</tr>
<tr>
<td>Modulus</td>
<td>Low to moderate depending on orientation, typically 20–50 g/den</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>Excellent</td>
</tr>
<tr>
<td>Flammability</td>
<td>Melts and burns</td>
</tr>
<tr>
<td>Acid/base stability</td>
<td>Excellent/good</td>
</tr>
<tr>
<td>Oxidative/light</td>
<td>Can be etched by strong oxidants, relatively poor light stability, unless stabilized</td>
</tr>
<tr>
<td>Solvents</td>
<td>Soluble in hot hydrocarbons, chlorinated hydrocarbons</td>
</tr>
</tbody>
</table>

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4.3.5.2.4 Acrylic fiber

\[
\begin{align*}
&\text{\text{C}} \\
&\text{\text{H}} \\
\end{align*}
\]

According to TAPPI TIP 1205-11(12), the Federal Trade Commission defines acrylic fibers as containing in excess of 85% by weight of acrylonitrile monomers. At the higher acrylonitrile content, the polymer is referred to as polyacrylonitrile (PAN). If the acrylonitrile content is 15%–85%, the fiber is defined as modacrylic. Like polyethylene and polypropylene, the repeat unit is an ethyl group with one of its hydrogens substituted by a pendant nitrile (cyano) group. The cyano pendant is carbon triple bonded to nitrogen. Unlike polyethylene and polypropylene, co-monomers (up to the allowable 15%) are deliberately added to provide sites for the attachment of dye molecules. Co-monomers can be methyl methacrylate, methyl acrylate, and vinyl acetate.

PAN can be produced by free-radical, anionic, or coordination polymerization process chemistry. The free-radical mechanism is the one most commonly used for commercial production. This results in a mostly atactic structure. The melting point of PAN is usually higher than the temperature at which it begins to thermally decompose. To be spun into a fiber it has to be solution spun, or sometimes spun from a plasticized melt. The polymer is mixed with the solvent to form a very viscous solution called a “dope”. 
There are a number of solvents that can be used including sodium thiocyanate, dimethylacetamide, dimethylfomamide, nitric acid, zinc chloride, dimethylsulfoxide, and ethylene carbonate.

Acrylic fibers can be “wet spun” or “dry spun”. In the wet-spinning process, the dope is spun through a spinnerette immersed in a spin bath containing a mixture of solvents and nonsolvents. The dope is coagulated (precipitated) into a fiber form. The fiber form is withdrawn from the solution and further processed to establish and reinforce fiber properties.

In the dry-spinning process, the viscous solution is spun with a stream of hot air into a vertical chamber. Filament formation occurs due to evaporation of the solvent. Dry-spun fibers normally have a dog bone cross-section because of inherent factors of the process. Approximately 75% of world’s capacity of PAN is from the wet-spinning process and 25% from the dry-spinning process.

Acrylic fibers tend to be more brittle and less flexible than polyethylene and polypropylene fiber. On the other hand, they have better temperature resistance, good chemical resistance, and particularly good resistance to outdoor exposure – sunlight and microorganisms. For this reason they have a niche in outdoor applications such as tenting and awning fabrics. Acrylic fibers also have good wicking properties making them suitable for wipes and absorbent products.

The staple fiber form of the polymer is used in filter media in both dry laid and wet laid applications. The fiber has good bulking properties for filter media. Its temperature and chemical resistance make it suitable in media for corrosive baghouse operations.

Special forms of the polymer exist. It can be fibrillated into a synthetic pulp for papermaking purposes. In this manner, it serves as a binder fiber. Filter medium is one application of fibrillated acrylics. Bi-component fibers can be produced by spinning two acrylic polymers with dissimilar copolymer levels. Unlike polyester, nylon, or polypropylene sheath–core fibers, the acrylic bi-components tend to be side by side. Such a structure shrinks unevenly when exposed to high temperatures above 100°C.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value or level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point</td>
<td>Not very crystalline, decomposes before melting</td>
</tr>
<tr>
<td>Glass transition</td>
<td>105°C</td>
</tr>
<tr>
<td>Moisture regain</td>
<td>1%–2%</td>
</tr>
<tr>
<td>Static electricity</td>
<td>Accumulates</td>
</tr>
<tr>
<td>Dyeability</td>
<td>Dyeable with disperse and cationic dyes</td>
</tr>
<tr>
<td>Density</td>
<td>1.14–1.17 g/cm³</td>
</tr>
<tr>
<td>Tenacity</td>
<td>Low up to 5 g/den, depending on processing</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>10%–50%</td>
</tr>
<tr>
<td>Modulus</td>
<td>Low to moderate, typically 5–10 g/den</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>Poor to fair</td>
</tr>
<tr>
<td>Flammability</td>
<td>Burns slowly, can evolve cyanide gas if no oxygen present</td>
</tr>
<tr>
<td>Acid/base stability</td>
<td>Excellent for most acids, moderate for bases</td>
</tr>
<tr>
<td>Oxidative/light</td>
<td>Excellent</td>
</tr>
<tr>
<td>Solvents</td>
<td>Polar solvents such as DMF and DMSO and even water at elevated temperatures, are solvents for PAN</td>
</tr>
</tbody>
</table>

and form into a spiral or coil shape; very handy where high loft is desired. PAN fibers can be carbonized and is the basis for carbon fiber manufacture.

Table 4.21 above is a summary of the properties of acrylic fibers.

4.3.5.2.5 Polyester

The development of polyester fiber began in the late 1930s, originally by W.H. Carothers of DuPont and later by a group of British scientists J.R. Whinfield, J.T. Dickson, W.K. Birtwhistle, and C.G. Ritchie. In 1941, the British produced the first polyester fiber called Terylene. In 1946, DuPont purchased all legal rights to the technology. In 1953, they initiated the commercial production or the polyester fiber known as Dacron. In 1958, Eastman Chemicals Products, Inc. introduced another polyester fiber called Kodet. Since then, the demand for polyester fiber has grown incessantly. In 2002, McGowan reported that the global demand for polyester fiber exceeded that of cotton.

Polyester is a condensation polymer composed of esters, 85% or more are attached to two aromatic rings. There are several different chemistries for producing polyester; however, the one most commonly used is the reaction product of terephthalic acid and ethylene glycol. The polymer is polyethylene terephthalate (PET). PET is a relatively stiff polymer and has moderate polarity. It has a relatively high melting point of 260°C, and therefore, it can be used in environments where heat resistance is desired. There are very few hydrogen bonding sites and these are at the end of the molecule—none in the repeating unit. The polymer has good resistance to moisture and very little moisture absorption. The low moisture allows the polymer to accumulate a static electricity charge.

The properties of PET fiber along with the continuous progress in its economics have made it a very popular fiber for nonwovens filter media. PET staple fiber is carded, either by itself or with other fibers (e.g., cotton) to form needle-punched webs for air filtration applications. PET is the principal fiber in thermally bonded high loft webs for HVAC applications. Short-cut PET fiber is widely used for wet laid filter applications. The 6- and 12-mm PET fibers are often mixed with cellulose slurries to offer improved wet laid, resin treated filter media. The improvements being a web with a more open structure, higher tensile and tear strength, and greater flex resistance.

Spunbonded structures such as Reemay, produced from PET, have found many applications in both air and liquid filtration.
A sister fiber to PET is polybutylene terephthalate (PBT). PBT has a lower melting point and a lower $T_m$ than does PET. It can be used in both spunbond and meltblown processes. A meltblown medium for blood filtration is produced from PBT. Ticona, the technical polymers business for Celanese AG, produces a PBT polymer trade named Celanex®. The polymer is also produced by DuPont and GE Plastics.

The properties of polyester fiber are summarized in Table 4.22 (for PET) and Table 4.23 (for PBT).

### Table 4.22 Properties of PET polyester fiber

<table>
<thead>
<tr>
<th>Property</th>
<th>Value or level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point</td>
<td>260°C</td>
</tr>
<tr>
<td>Glass transition</td>
<td>85°C</td>
</tr>
<tr>
<td>Moisture regain</td>
<td>&lt;1% standard regain</td>
</tr>
<tr>
<td>Static electricity</td>
<td>Accumulates</td>
</tr>
<tr>
<td>Dyeability</td>
<td>Moderate, requires disperse dyes, and assistants or pressure</td>
</tr>
<tr>
<td>Density</td>
<td>1.43</td>
</tr>
<tr>
<td>Tenacity</td>
<td>Low – up to 9 g/den</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>500%–15%</td>
</tr>
<tr>
<td>Modulus</td>
<td>Average modulus of 15 g/den typical, can be 100 g/den for industrial fibers</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>Excellent, not quite as good as olefin or nylon in flex abrasion</td>
</tr>
<tr>
<td>Flammability</td>
<td>Burns slowly with smoke, O.I. = 20</td>
</tr>
<tr>
<td>Acid/base stability</td>
<td>Attacked readily by hot dilute bases, less affected by acids</td>
</tr>
<tr>
<td>Oxidative/light</td>
<td>Reasonably good light stability</td>
</tr>
<tr>
<td>Solvents</td>
<td>Trifluoroacetic acid, phenol/tetrachloroethylene mixed, and concentrated H$_2$SO$_4$</td>
</tr>
</tbody>
</table>

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### Table 4.23 Properties of PBT polyester fiber

<table>
<thead>
<tr>
<th>Property</th>
<th>Value or level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point</td>
<td>227°C</td>
</tr>
<tr>
<td>Glass transition</td>
<td>66°C</td>
</tr>
<tr>
<td>Moisture regain</td>
<td>0%–0.5%</td>
</tr>
<tr>
<td>Static electricity</td>
<td>Good anti-static properties</td>
</tr>
<tr>
<td>Density</td>
<td>1.3 g/cm$^3$</td>
</tr>
<tr>
<td>Tenacity</td>
<td>2.8 cN/dtex convert to 1 g/den</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>5%–300%</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>Good</td>
</tr>
<tr>
<td>Flammability</td>
<td>O.I. = 22</td>
</tr>
<tr>
<td>Acid/base stability</td>
<td>Excellent acid resistance, fair base resistance</td>
</tr>
<tr>
<td>Oxidative/light</td>
<td>Exceptional resistance to thermal oxidative degradation</td>
</tr>
</tbody>
</table>

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4.3.5.2.6 Nylon

Nylon is the generic name for polyamide fiber. According to Fibersource⁶, the US Federal Trade Commission defines nylon as "A manufactured fiber in which the fiber-forming substance is a long-chain synthetic polyamide in which less than 85% of the amide-linkages are attached directly (-CO-NH-) to two aliphatic groups."

There are two major commercial forms of nylon: nylon 6,6 and nylon 6. Nylon 6,6 was the first form invented by W.H. Carothers of DuPont in the 1930s and first commercialized by DuPont in 1939. By 1938, Paul Schlack of I.G. Farben in Germany had polymerized caprolactam and created nylon 6.

Nylon 6,6 is the condensation product of hexamethylene diamine and adipoyl chloride. Nylon 6,6 is produced by the polymerization of caprolactam, a ring opening reaction. Nylon fibers are flexible and exceptionally strong. Hydrogen bonding sites every six atoms along the backbone allow for some moisture absorption. The presence of moisture affects the glass transition temperature, which is relatively low compared to polyester or acrylic fibers. The presence of moisture also makes the fiber less vulnerable to static accumulation, particularly in environments of high humidity. The low glass transition temperature combined with the flexibility in the chain structure allows for the easy orientation in the fiber. Orientation enhances the strength of the fiber; however, the elongation will be low. On the other hand, un-oriented nylon can be stretched to several times its original length. Nylon 6,6 has a higher melting point than nylon 6. Otherwise their properties are fairly similar.

Polyamides are not particularly stable to oxidants and ultraviolet light. They are resistant to damage from oil and many chemicals. They are attacked by alkali solutions but are reasonably resistant to weak acids. Nylon will dissolve in strong acids.

Nylon fiber is widely used in filter media. It is used in needlefelt filter media for baghouse filtration applications. It is used in other carded web structures such as high loft and gradient density media for air and liquid filter applications. It is the fiber in spunbonded Cerex™ webs, many of which have filter medium applications. Donaldson Company, Inc. uses nylon as the fiber material in their electrospun nanofiber filters.

⁶Fibersource is an educational website maintained by the American Fiber Manufacturers Association, Inc.
Table 4.24 summarizes the typical properties of nylon fiber.

### Table 4.24 Properties of nylon fiber

<table>
<thead>
<tr>
<th>Property</th>
<th>Value or level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point</td>
<td>Nylon 6.6: 260°C, nylon 6: 220°C</td>
</tr>
<tr>
<td>Glass transition</td>
<td>50°C for both</td>
</tr>
<tr>
<td>Moisture regain</td>
<td>4% standard regain</td>
</tr>
<tr>
<td>Static electricity</td>
<td>Accumulates in dry atmosphere. Usually not a problem in moist environs</td>
</tr>
<tr>
<td>Dyeability</td>
<td>Dyeable with direct, acid, disperse, and vat dyes</td>
</tr>
<tr>
<td>Density</td>
<td>1.12–1.15 g/cm³</td>
</tr>
<tr>
<td>Tenacity</td>
<td>Low – 10 g/den</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>20%–500%</td>
</tr>
<tr>
<td>Modulus</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>Excellent</td>
</tr>
<tr>
<td>Flammability</td>
<td>Burns after melting</td>
</tr>
<tr>
<td>Acid/base stability</td>
<td>Degraded by bases, dissolves in strong acids</td>
</tr>
<tr>
<td>Oxidative/light</td>
<td>Degrades in UV light and in oxidant solutions</td>
</tr>
<tr>
<td>Solvents</td>
<td>Strong mineral and organic acids, DME, and other polar organics</td>
</tr>
</tbody>
</table>

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#### 4.3.5.2.7 Polyaramid

There are two well-known forms of polyaramid fibers: para-aramid (polyparaphenylene terephthalamide) and meta-aramid (polymetaphenylene isophthalamide). The para-aramids are better known by the trade names of Kevlar\(^{®}\) (trademark of DuPont) and Twaron\(^{®}\) (trademark of Teijin Limited, Osaka, Japan). Likewise, the meta-aramids are commonly referred to by their trade names: Nomex\(^{®}\) (DuPont) and Teijinconex\(^{®}\) (Teijin Limited – often referred to as Conex\(^{®}\)). Both polymers are related to nylon in that they are forms of polyamide; the difference is that nylon has a carbon chain linkage with the amide structure whereas the polyaramids have a phenyl linkage. Referring to the structures above, the para-aramid connects at the para-position of the phenyl link whereas the meta-aramid connects at the meta-position of the phenyl linkage.

The fibers from both forms of the polymer are very heat resistant. They find application in heat resistant air filters. TDC Filter Manufacturing, Inc. of Cicero, Illinois,
USA, advertises a KV medium containing a blend of Kevlar®, Nomex®, and glass microfibers. They recommend this medium for temperatures up to 177°C (350°F).

The para-aramid fiber is tremendously strong. The tenacity can go up to 25 g/den when annealed under tension. It is a very rigid fiber of very high modulus. Its most notable application is in bullet-proof vests for police and military protection. When used in filter medium it absorbs just enough moisture to prevent static charge build-up. Properties of para-aramid fiber are listed in Table 4.25.

Table 4.26 reveals that the meta-aramid form of the polyaramid polymer is not as strong, but it is more flexible. Nomex® is widely used in needlefelt filter media for high temperature bag house operations. It resists attacks by mild acids, mild alkalies, and most hydrocarbons. It has flex resistance comparable to polyester fiber and much higher temperature resistance. It has exceptional dimensional stability.

**Table 4.25 Properties of para-aramid fiber**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value or level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point</td>
<td>&gt;500°C</td>
</tr>
<tr>
<td>Glass transition</td>
<td>175°C</td>
</tr>
<tr>
<td>Moisture regain</td>
<td>1%–4%</td>
</tr>
<tr>
<td>Static accumulation</td>
<td>Low static build-up</td>
</tr>
<tr>
<td>Dyeability</td>
<td>Poor due to high T. and high crystallinity</td>
</tr>
<tr>
<td>Density</td>
<td>1.44 g/cm³</td>
</tr>
<tr>
<td>Tenacity</td>
<td>15 g/den as spun, 25 g/den when annealed under tension</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>1%–4%</td>
</tr>
<tr>
<td>Modulus</td>
<td>Very high</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>Poor compared to melt-spun fibers, better than inorganics</td>
</tr>
<tr>
<td>Flammability</td>
<td>Does not burn under standard conditions, O.L. = 30</td>
</tr>
<tr>
<td>Acid/base stability</td>
<td>Excellent</td>
</tr>
<tr>
<td>Oxidative/light</td>
<td>Oxidized by bleaches. Degraded by prolonged exposure to UV</td>
</tr>
<tr>
<td>Solvents</td>
<td>Soluble in concentrated H₂SO₄</td>
</tr>
</tbody>
</table>

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**Table 4.26 Properties of meta-aramid fiber**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value or level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point</td>
<td>390°C</td>
</tr>
<tr>
<td>Glass transition</td>
<td>280–290°C</td>
</tr>
<tr>
<td>Moisture regain</td>
<td>4%</td>
</tr>
<tr>
<td>Static accumulation</td>
<td>Static build-up possible in dry conditions</td>
</tr>
<tr>
<td>Density</td>
<td>1.38 g/cm³</td>
</tr>
<tr>
<td>Tenacity</td>
<td>2.6–2.9 g/den</td>
</tr>
<tr>
<td>Modulus</td>
<td>8–14 N/tex</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>19%–22%</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>Excellent</td>
</tr>
<tr>
<td>Flammability</td>
<td>Does not burn in air, melt, or drip</td>
</tr>
<tr>
<td>Acid/base stability</td>
<td>Fair in strong acids, good in alkalies and weak acids</td>
</tr>
<tr>
<td>Oxidative/light</td>
<td>Yellows on prolonged light exposure</td>
</tr>
<tr>
<td>Solvents</td>
<td>Sodium hydroxide solution</td>
</tr>
</tbody>
</table>
Polyphenylene sulfide (PPS) is a rigid, thermoplastic fiber that is used in felt filter media for high temperature air filter applications. The polymer is available in branched and linear forms. The fiber is produced from the linear form. It is a semi-crystalline material (60%–65% crystallinity). No solvent is known that will dissolve the fiber at temperatures less than 200°C.

The fiber is ideal for filter media exposed to continuous operating temperatures up to 190°C (375°F). It has exceptional chemical resistance to most acids, alkalies, organic solvents and oxidizers. It also has excellent resistance to gamma and neutron radiation. It is nonburning, thus increasing its desirability for high temperature applications.

The polymer is marketed under the trade names of Ryton® (Chevron Phillips Chemical Co. LP) and Fortron® (Ticona Technical Polymers). Toray, headquartered in Japan, is the world’s leading producer of PPS fiber. Other fiber producers are Inspec Fibres, Amoco Fiber, and Fiber Innovation Technology, Inc. of Johnson City, Tennessee, USA. National Nonwovens Inc. of Easthampton, Massachusetts, markets a needlepunch felt media, TFIL17®, composed of 100% PPS fiber and reinforced with a PPS woven scrim.

The heat resistance, chemical resistance, and resistance to hydrolysis of PPS fiber makes it suitable for many liquid filtration applications, particularly where hot and/or corrosive liquids are filtered. The polymer can be spun into meltblown and spunbond nonwoven fabrics.

Some of the properties of PPS fiber are shown in Table 4.27.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value or level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point</td>
<td>280°C</td>
</tr>
<tr>
<td>Glass transition</td>
<td>90°C</td>
</tr>
<tr>
<td>Moisture regain</td>
<td>4%</td>
</tr>
<tr>
<td>Density</td>
<td>1.43 g/cm³</td>
</tr>
<tr>
<td>Tenacity</td>
<td>Very high</td>
</tr>
<tr>
<td>Modulus</td>
<td>Very high</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>5%</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>Excellent</td>
</tr>
<tr>
<td>Flammability</td>
<td>Does not burn, O.I.: 47</td>
</tr>
<tr>
<td>Acid/base stability</td>
<td>Fair in strong acids, good in</td>
</tr>
<tr>
<td></td>
<td>alkalis and weak acids</td>
</tr>
<tr>
<td>Oxidative/light solvents</td>
<td>Resistant to oxidation</td>
</tr>
<tr>
<td>Solvents</td>
<td>None</td>
</tr>
</tbody>
</table>
4.3.5.2.9 Polyimide

Polyimide fiber is often referred to by its trade name P-84®. The fiber was developed by Lenzing AG, Austria. It is marketed by Inspec Fibres GmbH, Austria. The fiber has a trilobal cross-section (see Figure 4.2 above), which enhances its surface area for filtration. The fiber provides unique heat resistance properties. It can be used continuously in temperature environments up to 260°C. It also has very good flame retardant properties.

The fiber is manufactured as a staple fiber ranging from 0.6 to 8.0 dtex. It is best used in needlepunch felts for high temperature air and fume applications. It also finds application as a sealant in the manufacture of oil filter cartridges because of its stability at high temperatures and its resistance to hot oil (Greisner105). This is done by melting polyimide into a polyimide felt ring.

Some typical properties of P-84® polyimide fiber are summarized in Table 4.28.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenacity</td>
<td>4.2 g/den</td>
</tr>
<tr>
<td>Elongation</td>
<td>30%</td>
</tr>
<tr>
<td>Continuous operating temperature</td>
<td>260°C</td>
</tr>
<tr>
<td>Limiting oxygen index</td>
<td>38%</td>
</tr>
<tr>
<td>Glass transition temperature</td>
<td>115°C</td>
</tr>
<tr>
<td>Density</td>
<td>1.41 g/cm³</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>&lt;1% at 250°C, 10 min</td>
</tr>
<tr>
<td>Chemical resistance</td>
<td>Good</td>
</tr>
</tbody>
</table>

4.3.5.2.1.0 Polytetrafluoroethylene

Polytetrafluoroethylene (PTFE) is one of a group of fluropolymers that have the DuPont trade name of Teflon®. There are also fluopolymer products produced by ICI under the trade name of Fluor® and by Toray under the trade name of Toyoflon®.
PTFE is the form that is most used in filtration applications. It is used as a membrane material, as a fiber coating, and as a fiber. The fiber is used in needlepunch felt filter media for hot gas filtration and in wet lay nonwovens for liquid filtration. Its monofilament form is also used for filtration products. Membrane filter materials are an important application of PTFE. PTFE is unique in its combination properties of hydrophobicity, chemical resistance, and thermal stability. “Nothing sticks to Teflon®” is also a very useful property for certain types of filter media. An example is bag house pulse jet filtration. The presence of Teflon® fiber in needlepunch and/or spunlace felts enhances the dirt release characteristics of the media. Table 4.29 lists some of the properties of PTFE fiber.

Table 4.29 Properties of PTFE fiber

<table>
<thead>
<tr>
<th>Property</th>
<th>Value or level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point</td>
<td>327°C</td>
</tr>
<tr>
<td>Moisture regain</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Density</td>
<td>2.13–2.22 g/cm³</td>
</tr>
<tr>
<td>Tenacity</td>
<td>2 g/den</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>25%</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>Excellent</td>
</tr>
<tr>
<td>Flammability</td>
<td>Extinguishes when flame is removed. L.O.I.: 95</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>260°C</td>
</tr>
<tr>
<td>Acid/base stability</td>
<td>Outstanding</td>
</tr>
<tr>
<td>Weather resistance</td>
<td>Rated at 20 years unaffected</td>
</tr>
<tr>
<td>Solvents</td>
<td>None</td>
</tr>
</tbody>
</table>

4.3.5.2.11 Polybenzimidazole

Polybenzimidazole (PBI) is an organic fiber with excellent thermal resistant properties. It does not burn in air and it does not melt. Its high LOI (loss on ignition) coupled with good chemical resistance and good moisture regain make this fiber a good candidate for flame resistant filter media such as needlefelts. Its strength properties are relatively low; however, it blends well with other fibers such as carbon and polyaramid and is sometimes used this way in flame resistant needlefelts to give very high performance, sufficient to justify its extremely high cost. The following property data on PBI are provided by Smith (106) in Table 4.30.

Table 4.30 PBI properties

<table>
<thead>
<tr>
<th>PBI property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenacity, g/de</td>
<td>2.7</td>
</tr>
<tr>
<td>Modulus, g/de</td>
<td>32</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>29</td>
</tr>
<tr>
<td>Continuous operation temperature (°F)</td>
<td>482</td>
</tr>
<tr>
<td>Limiting oxygen index (%)</td>
<td>41</td>
</tr>
<tr>
<td>Chemical resistance</td>
<td>Good – excellent</td>
</tr>
</tbody>
</table>

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4.3.5.3 Inorganic fibers

Inorganic fibers, both metal and non-metal, are more resistant, more rigid, higher melting, and more heat resistant than traditional organic fibers. Following is a comparison of typical properties of some inorganic fibers.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, g/cm³</th>
<th>Tenacity, MPa</th>
<th>Modulus, GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>2.5–2.6</td>
<td>3,400–4,500</td>
<td>70</td>
</tr>
<tr>
<td>Carbon</td>
<td>1.8–2.1</td>
<td>2,000–7,000</td>
<td>240–700</td>
</tr>
<tr>
<td>Silica carbide</td>
<td>2.6–3.5</td>
<td>2,000–3,700</td>
<td>200–420</td>
</tr>
<tr>
<td>Oxides</td>
<td>3.9</td>
<td>1,200–1,400</td>
<td>340–400</td>
</tr>
</tbody>
</table>

Source: Studio Technica, Florence, Italy.

4.3.5.3.1 Glass fibers

Glass fibers are formed, by design, to a broad range of fiber diameters. They are classified by diameter and by chemical composition. They can be produced as microfibers and as chopped strand. The process is a meltblown process related to the meltblown process for producing polymer webs (see Chapter 5, Section 5.1.3). Two primary processes for producing glass microfibers are rotary attenuation and flame attenuation. In both processes, the fibers are flame attenuated to control their diameters. From these, Scheffe[108] describes four variations as follows:

(a) Rotary process: Molten glass is charged into a rotating basket-like device having a large number of holes as centrifugal openings. Because of the centrifugal forces arising due to the rotation, the glass melt flows to the circumferential wall and is driven out through the openings as primary monofilts. A hot gas stream transverse to the direction of the monofilaments draws them to fine glass fibers (Figure 4.18).

(b) CAT process: The Controlled Attenuation Technology (CAT) process represents a modified rotary technology with less and thinner monofilts and a significantly higher gas stream (Figure 4.19).

(c) Flame attenuation process: This process is characterized by primary monofilts with diameters of 25–38 μm that are drawn from a platinum bushing and then fiberized by a highly accelerated hot gas stream (Figure 4.20).

(d) Duplex process: The starting materials are glass rods from which primary monofilts with diameters of 0.3–1.0 mm are continuously drawn mechanically and these are fiberized in a highly accelerated gas stream of high temperature (Figure 4.21).

Several glass compositions are available for the production of glass microfibers. Lauscha Fiber International lists four compositions (A, B, C, and E) in Table 4.32. Johns Manville lists two: 475 chemical composition for their 100 series of glass microfiber and 253 chemical composition for their 200 series. These compositions
are listed in Table 4.33. Evanite Corporation in Corvallis, Washington, has two compositions as listed in Table 4.34: filter glass compositions and battery glass compositions (for battery separator).

E-glass composition has a relatively high electric conductivity and is designated as electrical-grade glass. Compositions such as E-glass that have a high boron content (B₂O₃) are being specified out of clean room filters for the electronics industry.
because boron has been identified as a contaminant to some high purity electronic components.

Fiber diameter determines the filtration efficiency of filter media made from glass microfibers; the finer the diameter, the more efficient will be the medium. It is common practice to grade glass microfibers with a numbering system: the lower the number, the smaller the fiber diameter. Lauscha uses a system that identifies the glass composition...
Table 4.32 Chemical composition of Lauscha glass microfibers

<table>
<thead>
<tr>
<th>Glass composition</th>
<th>A-Glass (%)</th>
<th>B-Glass (%)</th>
<th>C-Glass (%)</th>
<th>E-Glass (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>69.0–72.0</td>
<td>55.0–65.0</td>
<td>63.0–67.0</td>
<td>50.0–56.0</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>2.5–4.0</td>
<td>4.0–7.0</td>
<td>3.0–5.0</td>
<td>13.0–16.0</td>
</tr>
<tr>
<td>B₂O₃</td>
<td>&lt;0.09</td>
<td>8.0–11.0</td>
<td>4.0–7.0</td>
<td>5.8–10.0</td>
</tr>
<tr>
<td>Na₂O</td>
<td>10.5–12.0</td>
<td>9.5–13.5</td>
<td>14.0–17.0</td>
<td>&lt;0.6</td>
</tr>
<tr>
<td>K₂O</td>
<td>4.5–6.0</td>
<td>1.0–4.0</td>
<td>0–2.0</td>
<td>&lt;0.4</td>
</tr>
<tr>
<td>CaO</td>
<td>5.0–7.0</td>
<td>1.0–5.0</td>
<td>4.0–7.0</td>
<td>15.0–24.0</td>
</tr>
<tr>
<td>MgO</td>
<td>2.0–4.0</td>
<td>0.0–2.0</td>
<td>2.0–4.0</td>
<td>&lt;5.5</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>&lt;0.02</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>ZnO</td>
<td>0–2.0</td>
<td>2.0–5.0</td>
<td>&lt;0.1</td>
<td>–</td>
</tr>
<tr>
<td>BaO</td>
<td>–</td>
<td>3.0–6.0</td>
<td>&lt;0.1</td>
<td>–</td>
</tr>
<tr>
<td>F₂</td>
<td>–</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
</tr>
</tbody>
</table>

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Table 4.33 Chemical composition of Johns Manville glass microfibers

<table>
<thead>
<tr>
<th>Glass composition</th>
<th>475 chemical composition for 100 series</th>
<th>253 chemical composition for 200 series</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>58.3</td>
<td>65.5</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>5.8</td>
<td>3.1</td>
</tr>
<tr>
<td>B₂O₃</td>
<td>11.3</td>
<td>5.3</td>
</tr>
<tr>
<td>Na₂O</td>
<td>10.1</td>
<td>16.0</td>
</tr>
<tr>
<td>K₂O</td>
<td>2.9</td>
<td>0.7</td>
</tr>
<tr>
<td>CaO</td>
<td>1.8</td>
<td>5.9</td>
</tr>
<tr>
<td>MgO</td>
<td>0.3</td>
<td>3.0</td>
</tr>
<tr>
<td>ZnO</td>
<td>4.0</td>
<td>–</td>
</tr>
<tr>
<td>BaO</td>
<td>5.0</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Reproduced with permission of Johns Manville, Denver, Colorado, USA[110].

Table 4.34 Evanite Fiber Corporation – glass fiber compositions

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Filter glass compositions</th>
<th>Battery glass compositions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EFC B-glass Wt. %</td>
<td>EF M3 Wt. %</td>
</tr>
<tr>
<td>SiO₂</td>
<td>59–65</td>
<td>60–69</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>5.0–7.0</td>
<td>3.0–6.0</td>
</tr>
<tr>
<td>B₂O₃</td>
<td>8.0–11.0</td>
<td>4.0–6.0</td>
</tr>
<tr>
<td>Na₂O</td>
<td>8.0–11.1</td>
<td>8.0–12.0</td>
</tr>
<tr>
<td>K₂O</td>
<td>1–3.5</td>
<td>0.5–3</td>
</tr>
<tr>
<td>CaO</td>
<td>2.0–4.0</td>
<td>5.0–7.0</td>
</tr>
<tr>
<td>MgO</td>
<td>0–2</td>
<td>2.5–4.5</td>
</tr>
<tr>
<td>BaO</td>
<td>2.5–5.5</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>ZnO</td>
<td>0–4.5</td>
<td>&lt;0.04</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>F₂</td>
<td>0–1</td>
<td>0–1</td>
</tr>
</tbody>
</table>

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Data provided by Pat Swoboda, Evanite Fiber Corporation.
Raw Materials for Nonwoven Filter Media

A, B, C, or E, and uses a 2-digit number from 00 to 50 for the fiber diameter code. 00 is the smallest diameter available and 50 is the largest. Their grade numbering system also includes a letter designation to identify the fiberization technology (F: flame attenuation, Fi: high speed F-technology, and R: rotary attenuation). For example, Grade B-06-F would be a glass microfiber composed of the B-glass composition in Table 4.35, having a fiber diameter code of 06, and produced by flame attenuation (F) technology. Table 4.36 lists several of the Lauscha grades along with their fiber diameters and specific surface areas (SSA). Figure 4.22 relates Lauscha grades and SSA to handsheet pressure drop. It is apparent from the Lauscha data that the finer the fiber diameter, the larger is the SSA and the larger the SSA, the more resistant will be the media to flow.

Table 4.35 Lauscha Product Designation System

<table>
<thead>
<tr>
<th>GLASS COMPOSITION</th>
<th>DIAMETER CODE</th>
<th>FIBERIZATION TECHNOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-Glass (low boron alkali silicate)</td>
<td>00–50</td>
<td>F-flame attenuation technology</td>
</tr>
<tr>
<td>B-Glass (borosilicate)</td>
<td></td>
<td>Fi-high speed F-technology</td>
</tr>
<tr>
<td>C-Glass (acid resistant borosilicate)</td>
<td></td>
<td>R-rotary attenuation technology</td>
</tr>
<tr>
<td>E-Glass (calcium aluminoborosilicate)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Example

B 06 F

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Table 4.36 Nominal fiber diameters and specific surface areas of Lauscha glass microfibers

<table>
<thead>
<tr>
<th>Grade</th>
<th>Nominal diameter</th>
<th>Nominal specific surface area (m²/gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-00-F</td>
<td>0.333</td>
<td>4.8</td>
</tr>
<tr>
<td>B-02-F</td>
<td>0.457</td>
<td>3.5</td>
</tr>
<tr>
<td>B-04-F</td>
<td>0.533</td>
<td>3.0</td>
</tr>
<tr>
<td>B-06-F</td>
<td>0.648</td>
<td>2.5</td>
</tr>
<tr>
<td>B-08-F</td>
<td>0.800</td>
<td>2.0</td>
</tr>
<tr>
<td>B-15-F</td>
<td>1.481</td>
<td>1.1</td>
</tr>
<tr>
<td>B-26-F</td>
<td>2.439</td>
<td>0.7</td>
</tr>
</tbody>
</table>

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Data provided by Wolfgang Rodigas, Lauscha Fiber International, Lauscha, Germany.
The Johns Manville system uses a digital number series; 90 and up for the 475 glass composition and 200 and up for the 253 glass composition. There is also a CX grade for the 5.5 μm diameter. Figure 4.23 plots the Johns Manville code vs. fiber diameter.

Evanite Fiber Corporation uses a three-digit code, the last two digits indicating the fiber diameter. Table 4.37 is a listing of Evanite grades by fiber diameter. The fiberizing technology is also listed.
Table 4.37  Evanite Fiber Corporation – grade designation and microfiber properties

<table>
<thead>
<tr>
<th>Grade</th>
<th>Nominal fiber diameter (microns)</th>
<th>Fiberizing technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>805</td>
<td>0.45</td>
<td>Flameblown</td>
</tr>
<tr>
<td>404</td>
<td>0.5</td>
<td>CAT</td>
</tr>
<tr>
<td>504</td>
<td>0.5</td>
<td>Rotary</td>
</tr>
<tr>
<td>604</td>
<td>0.5</td>
<td>CAT</td>
</tr>
<tr>
<td>704</td>
<td>0.5</td>
<td>Flameblown</td>
</tr>
<tr>
<td>804</td>
<td>0.5</td>
<td>Flameblown</td>
</tr>
<tr>
<td>406</td>
<td>0.6</td>
<td>CAT</td>
</tr>
<tr>
<td>506</td>
<td>0.6</td>
<td>Rotary</td>
</tr>
<tr>
<td>606</td>
<td>0.6</td>
<td>CAT</td>
</tr>
<tr>
<td>706</td>
<td>0.6</td>
<td>Flameblown</td>
</tr>
<tr>
<td>806</td>
<td>0.6</td>
<td>Flameblown</td>
</tr>
<tr>
<td>408</td>
<td>0.8</td>
<td>CAT</td>
</tr>
<tr>
<td>608</td>
<td>0.8</td>
<td>Flameblown</td>
</tr>
<tr>
<td>708</td>
<td>0.8</td>
<td>Flameblown</td>
</tr>
<tr>
<td>509</td>
<td>1.6</td>
<td>Rotary</td>
</tr>
<tr>
<td>609</td>
<td>1.4</td>
<td>CAT</td>
</tr>
<tr>
<td>709</td>
<td>2</td>
<td>Flameblown</td>
</tr>
<tr>
<td>410</td>
<td>2.5</td>
<td>Rotary</td>
</tr>
<tr>
<td>510</td>
<td>2.3</td>
<td>Rotary</td>
</tr>
<tr>
<td>610</td>
<td>2.6</td>
<td>Rotary</td>
</tr>
<tr>
<td>610</td>
<td>2.6</td>
<td>CAT</td>
</tr>
<tr>
<td>710</td>
<td>2.6</td>
<td>Rotary</td>
</tr>
<tr>
<td>810</td>
<td>2.6</td>
<td>Flameblown</td>
</tr>
<tr>
<td>411</td>
<td>3</td>
<td>Rotary</td>
</tr>
<tr>
<td>512</td>
<td>3.7</td>
<td>Rotary</td>
</tr>
<tr>
<td>612</td>
<td>3.9</td>
<td>Rotary</td>
</tr>
<tr>
<td>712</td>
<td>4.3</td>
<td>Rotary</td>
</tr>
<tr>
<td>413</td>
<td>5.2</td>
<td>Rotary</td>
</tr>
<tr>
<td>716</td>
<td>5.2</td>
<td>Rotary</td>
</tr>
<tr>
<td>716</td>
<td>5.2</td>
<td>Rotary</td>
</tr>
<tr>
<td>717</td>
<td>6.1</td>
<td>Rotary</td>
</tr>
<tr>
<td>719</td>
<td>8.5</td>
<td>Rotary</td>
</tr>
</tbody>
</table>

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4.3.5.3.2 Ceramic fibers

Ceramic fibers, produced from metal oxides or refractory oxides, are resistant to high temperatures (1,100–1,700°C). This class of fibers includes alumina, beryllia, magnesia, thoria, zirconia, silicon carbide, quartz, and high silica reinforcements. Technically, glass is also a ceramic; however, it is generally not included with the class of ceramic materials. Ceramic fibers are produced by chemical vapor deposition, melt drawing, spinning and extrusion. Refractory ceramic fibers (RCF), fibrous glass, and mineral wool belong to a group known as synthetic vitreous fibers (SVF). These are materials made from molten masses of raw material under highly controlled conditions. All these fibers possess high strength and modulus. Ceramic fibers are used in felt type filter media where high temperature resistance is required.

Nixdorf of Industrial Ceramic Solutions LLC describes a patented "Microwave-Cleaned Particulate Filter System" based on silicon carbide fiber. This fiber has a

\(^9\)Data provided by Patrick Swoboda, Evanite Fiber Corporation.
unique ability to heat at a phenomenal rate in a microwave energy field. In applications such as diesel engine exhaust filters and restaurant grease filters, they can be made to be self-cleaning. When exposed to microwave energy, trapped particulate matter is oxidized to carbon dioxide and water.

The fiber is manufactured in two stages. First an organic fiber is carbonized in an inert atmosphere to yield a carbon fiber. The carbon fiber is then subject to a high temperature carbo-thermal reduction in the presence of silicon dioxide to form the silicon carbide fiber. A fiber has been produced, $16 \times 1000 \mu m$ (1 mm) that is large enough to be nonrespirable and be safe for handling. It is also suitable for making ceramic paper for cartridge filter applications. Figure 4.24 is a scanning electron microphotograph of a silicon carbide fiber.

![Figure 4.24. Silicon carbide fiber.](image)

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4.3.5.3.3 Carbon fibers

Studio Technica\textsuperscript{(107)} reports that carbon fibers were discovered in 1879 by Thomas Edison. They can be considered as the transition between inorganic and organic fibers. There are two sources of carbon fiber: the alteration of organic fibers such as rayon, acrylics, etc.; and the remains of petroleum or tar distillation. The former is referred to as PAN-based carbon and the latter is referred to as pitch-based. Table 4.38 compares the properties of the two fiber types.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Fibers from PAN</th>
<th>Fibers from pitch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenacity (GPa)</td>
<td>1.8–7.0</td>
<td>1.4–3.0</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>230–540</td>
<td>140–820</td>
</tr>
<tr>
<td>Elongation at break (%)</td>
<td>0.4–2.4</td>
<td>0.2–1.3</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>1.75–1.95</td>
<td>2.0–2.2</td>
</tr>
</tbody>
</table>

Reproduced with permission of Bill Smith\textsuperscript{(106)}, Industrial Textiles Associates, Greer, South Carolina, USA.
The PAN-based fibers are referred to as such because fibers of PAN are most often used as the precursor. Carbon fibers are produced through heat treatment and pyrolysis of the precursor. High modulus carbon fibers are often referred to as graphite fibers. Graphite fibers are carbon fibers that have been heat treated to temperatures over 2,000°C.

The PAN- and pitch-based carbon fibers are predominantly used as a reinforcing fiber in high strength structural composites. They find use in some filter applications where high chemical and temperature resistance is desired. Since carbon fibers are conductive fibers, they are sometimes used in felt media to dissipate electric charge.

A different form of carbon fiber is activated carbon fiber (ACF) that is used in media filtration and separation applications because of its adsorption properties. It can be produced from cellulose (rayon) or acrylic precursors as well as from coal, wood and coconut shell. The fiber is produced by heat treatment at temperatures up to 300°C. After the treated fiber is formed into a web (woven or nonwoven), it is oxidized at temperatures up to 1,300°C to activate the surface into a porous structure.

### 4.3.5.3.4 Metal fibers

Metal fibers are produced as thin filaments with diameters ranging from 1 to 80 μm. Among the various forms are chopped fibers and needlefelt. Chopped fibers can be used in wet laid operations. Needlefelt forms composed of or containing metal fibers are often sintered to produce a stiff rigid media. Metal fibers are produced from a variety of metal alloys. Included are stainless steel, nickel, nickel alloy, and high temperature resistant alloys. Table 4.39 lists properties of some of the alloys used in filter media.

**Table 4.39 Properties of some metal fiber alloys**

<table>
<thead>
<tr>
<th>Alloy</th>
<th>AISI 316 SS</th>
<th>Inconel 601</th>
<th>Hastelloy*2 X</th>
<th>Haynes* Alloy HR-160*3</th>
<th>Fecralloy*4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (gm/cm³)</td>
<td>8.0</td>
<td>8.11</td>
<td>8.22</td>
<td>8.08</td>
<td>7.15</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>1375–1400</td>
<td>1160–1410</td>
<td>1260–1350</td>
<td>1300–1370</td>
<td>1500</td>
</tr>
<tr>
<td>Max. operating temp. (°C)</td>
<td>925</td>
<td>1175</td>
<td>1205</td>
<td>1205</td>
<td>1400</td>
</tr>
<tr>
<td>Thermal conductivity (W/mK)</td>
<td>14.6–15.0</td>
<td>11.2</td>
<td>9.7</td>
<td>10.9</td>
<td>16</td>
</tr>
<tr>
<td>Electrical resistance (ohm-cm)</td>
<td>.0000074</td>
<td>.000119</td>
<td>.000118</td>
<td>.000112</td>
<td>.000139</td>
</tr>
</tbody>
</table>

1. Inconel 601 is a trademark of International Nickel Co., Inc.
2. Hastelloy is a trademark of Haynes International Incorporated.
3. Haynes and Alloy HR-160 are trademarks of Haynes International Incorporated.
4. Fecralloy is a trademark of the UK Atomic Energy Authority (now AEA Technology, Harwell, England).
Metal fiber media are used in liquid and air filter applications where a high degree of heat and chemical resistance is required. They can be welded into filter shapes of high structural integrity. Metal fiber filters are cleanable and reusable. Global Material Technologies, Inc., Palatine, Illinois, USA, markets a metal fiber media under the trade name of VersaFilter®. Mott Corporation of Farmington, Connecticut, USA, produces a variety of filters from fiber metal filter media.

4.3.5.3.5 Basalt fibers
Basalt is a material produced from volcanic rock. Lisakovski et al. (112) report that continuous basalt fibers were developed in the Ukraine in the mid-1970s. The fiber is highly heat- and chemical resistant. Compared to glass microfiber, it is stiffer and has less elongation. It is mostly used as a woven fabric. In filter applications, American Felt and Filter Company (AFFCO), New Windsor, New York, use woven basalt fabrics as scrim reinforcement for needlepunch Nomex® felts to provide improved heat resistance in hot air filtration applications. AFFCO and their “The Heat Shield” product are further discussed in Chapter 8, Section 8.1.1.

4.3.5.3.6 Asbestos
Asbestos fibers are made from natural minerals that are contained within natural rock. The minerals are in the form of masses of strong flexible fibers that can be separated into individualized fibers and thin threads. The threads can be woven into fabrics that are highly heat and chemical resistant. The fibers are very fine with nanosized fiber diameters. They can easily be dispersed in the wet end of a wet laying forming system. For this reason, asbestos fibers were at one time very popular for high efficiency filter applications. Some of the original developments for military gas mask media and HEPA media utilized asbestos fibers. In the 1970s the carcinogenic dangers of asbestos became apparent and they were replaced with other fibers – mostly glass microfibers. There are still some applications of asbestos in filter media; however, this is very specialized and involve very small quantities.

4.3.5.4 Specialty fibers
4.3.5.4.1 Nanofibers
Nanofiber is a broad phrase generally referring to a fiber with a diameter less than 1 μm (Graham et al. (16)). Although nanofiber is a relatively recent term for sub-micron fibers, they have been around for a long time. One of the earliest was asbestos fiber (see Section 4.3.5.3.6). At one time, this fiber was very popular in media for high efficiency air filtration; for example HEPA media and military gas masks were originally developed from asbestos fiber. Since the carcinogenic effects of asbestos were revealed, its use in filter media has been largely discontinued. Glass microfibers (discussed in Section 4.3.5.3.1 above) are now the dominant source of nanofibers for both high efficiency air filtration and liquid filtration. Recent advances in meltblown fiber technology are producing meltblown fibers approaching the sub-micron range. Polymeric webs from the electrospun process are often produced with fibers in the sub-micron category. Bi-component fibers and multi-component fibers are a relatively recent, high-tech source of nanofibers because certain configurations can be separated into nanofiber-sized components (see Section 4.3.5.4.2).
4.3.5.4.2 Bi-component and multi-component fibers

Bi-component and multi-component fibers are spun fibers that have two or more different polymer phases in their cross-section. Each phase has its own distinct properties and contributes something to the properties of the fiber that would not be there without the presence of the phase. Figure 4.25 tabulates some of the more common fiber cross-sections. Included are:

(a) sheath–core fibers most often used to make binder fibers;
(b) side-by-side fibers used mostly to produce bulky, self-crimping fibers;
(c) tipped products mostly used in special filtration products;
(d) segmented products that can be split into small individual fibers;
(e) islands-in-a-sea products wherein the sea is normally dissolved away to leave only the small islands;
(f) mixtures of two or more fiber types to make specialized strands for yarns and fabrics having multiple cross-sections.

The most common form of bi-component fiber is the sheath–core fiber. In this cross-section, one polymer forms an outer sheath around the inner core of the second polymer. Figure 4.26 is a photomicrograph example of a sheath–core fiber with a circular sheath. This particular fiber is meltblown with a polyethylene sheath and used as thermobonding fiber. Thermobonding binder fiber is the most common use of sheath–core fibers. A number of sheath–core variations are possible as demonstrated by the top row in the tabulation of Figure 4.25. Note that the cross-sections are not necessarily circular as indicated by the inclusion of trilobal shapes.

![Figure 4.25. Various cross-sections of bi-component fiber.](http://example.com/figure425.png)

Reproduced with permission of Hills, Inc., West Melbourne, Florida, USA.
Figure 4.26. Photomicrograph of a sheath–core fiber.
Reproduced with permission of Hills, Inc., West Melbourne, Florida, USA.

Figure 4.27. 16-segment pie wedge fibers.
Reproduced with permission of Hills, Inc., West Melbourne, Florida, USA.
It becomes apparent that segmented products and island-in-a-sea are a powerful source of microfibers for high efficiency filtration. Figure 4.27 is an example of a 16-segment “pie wedge” fiber. Figure 4.28 shows how this fiber can be split into smaller wedge-shaped segments of much smaller fiber size. Figure 4.29 shows the splittable segments of the fiber. The splitting can be accomplished by thermal, chemical, or mechanical means. Dugan\(^{10}\) suggests that for filtration media, a conventional purpose would be to form a carded web of 3 dpf (denier per filament) fibers and then pass the web under hydroentanglement jets (see Chapter 5, Section 5.1.2.3.2), which simultaneously split the fibers into individual wedges and entangle the fibers to give fabric strength and integrity. The fabric will contain fibers down to 0.2 dpf and yet still maintain much of the throughput and processing advantages of a 3 dpf fiber.

---

Dugan also suggests that the alternating segments be polyester and nylon. These two polymers have little adhesion to each other and would more readily split in the hydroentanglement process.

Segmented fibers are certainly not limited to 16-segment pie wedges. Figure 4.29 is a microphotograph of a 32-segment pie wedge.

Figure 4.30 is a cross-section of an “island-in-the-sea” type fiber. In this configuration, the micro-sized nanofibers are formed by dissolving away the sea. Usually, the island portions are polyester, and the sea is composed of a water-soluble polymer. Hagewood reports that the island fiber can be produced in diameter ranges of 100–800 nm. Hagewood also indicates that the technology is capable of producing up to 1,000 islands and not even limited to that number. Figure 4.31 is a microphotograph of a 600-island-in-the-sea fiber. A variation of the islands-in-the-sea technology is hollow islands having a wall thickness of approximately 40 nm and a diameter of 300 nm.

The islands-in-the-sea technology has been commercialized for staple and filament yarns. It has not yet been applied to meltblown or spunbond nonwovens.

In Table 4.40 Hagwood compares the microfiber capabilities of bi-component and multicomponent fibers to the microfiber capabilities of other technologies (staple, spunbond, meltblown, and electrospun). It appears that only the electrospun process is capable of producing finer fibers.
Figure 4. 37 Islands-in-the-sea.
Reproduced with permission of Hills, Inc., West Melbourne, Florida, USA.

Figure 4. 31. 600 Islands-in-the-Sea.
Reproduced with permission of Hills, Inc., West Melbourne, Florida, USA.
<table>
<thead>
<tr>
<th>Fiber L.D.</th>
<th>Mfg. process</th>
<th>Fiber description</th>
<th>Fiber cross-section</th>
<th>Fiber size (microns)</th>
<th>Fiber surf. area (sq. m/Gr)</th>
<th>Prod. rate (Gr. Per min. per spin hole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional processes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Conventional staple or spunbond Conventional meltblown</td>
<td>One denier fiber, homopolymer Two micron fiber, homopolymer</td>
<td>Round</td>
<td>10.1</td>
<td>0.3</td>
<td>0.67</td>
</tr>
<tr>
<td>2</td>
<td>Conventional meltblown</td>
<td>Round</td>
<td>2.0</td>
<td>1.4</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>Conventional electrospun</td>
<td>Round</td>
<td>0.3</td>
<td>9.5</td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>Segmented pie products</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Segmented pie staple or spunbond Segmented pie meltblown</td>
<td>One denier fiber, 32-segment pie Two micron fiber, 16-segment pie</td>
<td>Pie segments</td>
<td>Ea. segment = 1.0 arc × 2 × 5.1 legs</td>
<td>Ea. segment = 3.2</td>
<td>0.67</td>
</tr>
<tr>
<td>5</td>
<td>Segmented pie meltblown</td>
<td>Pie segments</td>
<td>Ea. segment = 0.4 arc × 2 × 1.0 legs</td>
<td>Ea. segment = 8.7</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Islands-in-a-sea processes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Islands-in-a-sea staple or spunbond</td>
<td>One denier fiber, 50/50 islands/sea, 30 islands</td>
<td>Round islands</td>
<td>Ea. island = 1.3</td>
<td>Ea. island = 2.2</td>
<td>0.3</td>
</tr>
<tr>
<td>7</td>
<td>Islands-in-a-sea staple or spunbond</td>
<td>One denier fiber, 50/50 islands/sea, 600 islands</td>
<td>Round islands</td>
<td>Ea. island = 0.3</td>
<td>Ea. island = 9.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Nanotube islands</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Islands-in-a-sea staple or spunbond</td>
<td>One denier fiber, 50/50 islands/sea, 30 islands</td>
<td>Microtube islands, 50% hole</td>
<td>Ea. tube = 1.2 OD × 0.02 wall</td>
<td>Ea. tube = 7.5</td>
<td>0.15</td>
</tr>
<tr>
<td>9</td>
<td>Islands-in-a-sea staple or spunbond</td>
<td>One denier fiber, 50/50 islands/sea, 600 islands</td>
<td>Microtube islands, 50% hole</td>
<td>Ea. tube = 0.2 OD × 0.04 wall</td>
<td>Ea. tube = 33.6</td>
<td>0.15</td>
</tr>
</tbody>
</table>

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4.4 Resins and Binders

Resins for filter media usually come in one of the three forms: solvent-based solutions, water-based latex emulsions and dispersions, and water-based solution forms. Their main purpose is to strengthen the media; however, they provide for other important properties. These include stiffness, tear strength, modulus, dimensional stability, flex resistance, water resistance, downstream processability, heat and temperature resistance, resistance to chemical and environmental exposure, and durability in the end use application. Resins can also affect filtration properties. For example, some film-forming resins are undesirable because the film may form across a pore and close it to passage of fluid. Resins are available in thermoplastic form or thermosetting form. Very often both properties are desired for processing. For example, a resin may be thermoplastic so that it can be thermally softened for the pleating operation and then afterward heat cured and thermoset to provide for stiff rigid pleats in the end use application. The following is a discussion of some of the various types of resins used as binders for filter media.

4.4.1 Formaldehyde resins

Three major forms of formaldehyde resins are phenol formaldehyde and/or phenolics, melamine formaldehyde, and urea formaldehyde. In filter medium applications, all three can be used as cross-linkers with other resin systems. Melamine-formaldehyde, and urea-formaldehyde play important roles as wet strength agents for wet laid media (see Sections 4.4.1.2 and 4.4.1.3). Solvent-based phenol-formaldehyde resin is a very important saturant for wet laid filter paper particularly for engine lube oil filter applications.

4.4.1.1 Phenolic resins

Phenol formaldehyde resins and phenolic resins are not necessarily synonymous. Phenol formaldehyde resins are formed from the specific reactions of phenol with formaldehyde, whereas the definition of phenolic resins includes the reaction of phenol with other aldehydes as well. Most of the phenolic resins used for the treatment of filter paper are of the phenol formaldehyde form; however, there are some variations. Phenolic resins are thermosetting resins available in both solvent-based and water-based form. The solvent-based forms can be built to higher molecular weights and impart far superior properties. The solvent-based phenolics are thermosetting resins and they come in two different chemical structures: resole and novolak. Both are used in filter medium applications; however, the resole form is a more widely used resin in the USA. Often the two are blended together to optimize properties.

Resoles are formed from the base catalyzed reaction of phenol and formaldehyde and requires an excess of formaldehyde. For solution resins, they are reacted to a low molecular weight of 300–700 (Stille90), so that the polymer is still soluble. The polymer contains hydroxymethyl (–CH₂OH) side groups and possibly some ether linkages (–O–CH₂–). Further heating will cause condensation reactions and result in a high molecular weight cross-linked polymer.
Novolaks are formed from acid catalyzed reactions requiring an excess of phenol and usually result in a linear polymer of molecular weight 1,000–1,500 (Stille\textsuperscript{(90)}). Hydroxymethyl groups are not present because under the acid condition, they are unstable and decompose to a methylene group. The methylene groups react with phenol to give methylene bridges (Intelligensys Ltd.\textsuperscript{(113)}). Further cross-linking can only take place by the addition of more formaldehyde, usually in the form of hexamine. In Figure 4.32, Bell and Cove\textsuperscript{(116)} have compared the relative cure times.

Figure 4.32. Typical cure schedules of impregnated paper.
of impregnated filter paper treated with resole and novolak resins. At 130°C, the resole cures considerably faster than the novolak; however at 150°C they both cure at roughly the same rate.

Phenolic resins have unique properties that make them ideal for filter paper used in hot oil filter applications such as the lube oil filters of automobiles. First, they are "B-stageable", meaning they can be applied to the base paper, then dried but not cured or thermoset. At this point, the resin in the treated paper is considered as thermoplastic. It makes the paper amenable to such converting operations as corrugating and embossing. When shipped to the filter manufacturer, the paper is soft and pliable for the pleating operation. Once formed into pleated filter elements, the resin treated filter paper is heat cured to its final state. Full cure is essentially achieved in 10 min at 150°C; less time at higher temperatures. The cured filter paper has good heat resistance up to 200°C. The resin provides for good dimensional stability so that the medium will not seriously change dimensions with changes in humidity. It provides for hot oil stiffness, a property determined by measuring the stiffness of the paper after soaking in hot oil. The phenol treated paper is well designed to stand up to the prolonged rigors of hot oil. Water resistance is excellent. Wet: dry ratio properties of tensile strength, stiffness, and burst strength are better than most other types of resins. The solvent-based resin has little tendency to form films across the pores. Filter media made from phenolic resin generally have better filtration properties than comparable water-based resins.

Environmental concerns have stimulated new technologies in the manufacture and processing of phenolic resins. Manufacturers of filter media now use high tech incinerator technology to destroy methanol, formaldehyde, and phenol emissions. Resin manufacturers have developed lower emission and faster curing resins. Dupré117 reports that free phenol contents of solvent phenolics were reduced from approximately 10% in 1986 to 3% in 1996. Hollingsworth & Vose Company has developed filter media with advance cure resin systems that greatly reduce phenol and formaldehyde emissions at customers pleating sites. In Figures 4.33 and 4.34, Murphey and Raval118 demonstrated how advance curing reduces free formaldehyde and free phenol levels.

![Free formaldehyde levels](image)

*Figure 4.33, Free formaldehyde levels.*

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Usually the water-based phenolics are formulated with other water-based polymer resins to provide thermosetting and cross-linking properties. Usually they come in solution form and have a water tolerance, meaning that if diluted beyond a certain point, the resin kicks out of solution. This will happen even when formulated with other resins and the whole resin mix is diluted. When this happens, the resin sometimes agglomerates into a very unusable sludge. One manufacturer of phenolic resins, Ashland Chemicals, produces a water dispersible version (Arotap® 1090) that is less prone to instability due to water dilution.

4.4.1.2 Melamine formaldehyde
Melamine formaldehyde resins find use in filter media as a cross-linking agent for latex resins. Cationic forms of the resin are used in wet lay systems as wet strength agents. In this application, they are added to the fiber slurry.

4.4.1.3 Urea formaldehyde
Like melamine formaldehyde, urea formaldehyde (UF) is used as a wet strength additive in wet lay systems and as a cross-linking agent in latex systems. UF resin is often blended with acrylic resins in glass mat materials (Bell et al.\(^{(119)}\)).

4.4.2 Latex resins
4.4.2.1 Introduction to latex resins
Latex resins are emulsions of polymer particles in water. In addition to the base polymer, the emulsion will include a surfactant system to stabilize the emulsion. Other additives are added to enhance the polymer and provide for additional properties when applied to the nonwoven filter media. Examples are water repellent agents, cross-linking mechanisms, flame retardants, viscosity control agents, and additives for pH stabilization. Often, more than one resin is blended together to achieve desired properties. When applied to filter media, latex resins are expected to impart fiber-to-fiber bonding strength and possibly stiffness. Stiffness is of particular importance to media that are pleated.
Other properties that result from the latex resin system are water resistance, dimensional stability, long-term durability, chemical and environmental resistance, flame retardancy, resistance to oils and chemicals, heat resistance, and processability in downstream mechanical processing operations. Downstream mechanical operations, which may be in-line or off-line, include corrugating, creping, slitting, and pleating.

There are filter applications where low $T_g$ lattices are desired. For example, industrial and medical face mask filters are bonded with softer resins to provide greater comfort for skin contact. Chemically bonded filter medium bag filters will utilize lower $T_g$ resins.

Latex resins tend to be thermoplastic; however, cross-linking agents are often added to provide cure-related properties. Blending with a thermosetting resin such as a water-based phenolic or melamine formaldehyde greatly enhances the cured properties of a medium. The improvements may show in medium strength, modulus, stiffness, and Mullen burst. The effects of curing are much more evident when measuring some form of water resistance. To illustrate, the uncured tensile strength of a latex treated medium may be little different than its cured tensile strength. On the other hand, the wet tensile strength of the cured medium usually is much greater than the uncured wet tensile strength. The ratio of wet uncured property to wet cured property is sometimes used as an indicator of cure. If the ratio is one, the medium is presumed to be fully cured.

Sometimes the application of a resin to a nonwoven filter medium is referred to as a coating. This is exactly what a filter resin is not. The resin is applied as a saturant (sometimes referred to as an impregnate). Unlike a coating, which is intended to cover the surface of the substrate, a saturant is expected to penetrate the media and form bond points in the interior as well as at the surfaces. Because of the need for penetration, low viscosity is a very desirable property in liquid resin systems for filter media. The latex producer has some control of this by the choice of surfactant systems, particle size, and polymer type. The user may reduce viscosity by diluting the resin to a lower viscosity and/or by preheating the resin. Preheating the resin requires a strong temperature control system; otherwise there is potential for overheating. Overheated resin can agglomerate and solidify in the mix tank and cause a disastrous mess. Control of resin solids is probably the most common way to regulate viscosity. However, this approach has to be compromised with the need to maintain a certain resin content in the finished web. Diluting the resin with more water to maximize penetration will increase the drying burden for removing the water, resulting in increased energy costs and possible loss of productivity.

In most nonwoven applications, especially those for wipes and covers for absorbent materials, hand and softness are desired properties. For these products, a soft, low $T_g$ (glass transition temperature) resin is preferred. Resins for many filter media are just the opposite, particularly if the medium is to be pleated. The resin has to impart stiffness and rigidity to the medium enabling the pleats to stand up to the “wind” force of the fluid flowing through it. Generally high $T_g$ resins, $>30^\circ C$, are the chosen binders for media to be pleated. In bulkier media, such as high loft media, the resin would have to provide for compression resistance and compression recovery. To illustrate, Table 4.41 is a compilation of filter resin binders marketed by Omnova Solutions Inc., a major producer of latex binders for the filter medium industry. Note that the two Sequabond* resins (Sequabond* FVAC and Sequabond* FCS) are designed for vacuum
bag applications and therefore, have a lower $T_g$ to provide for flexibility and resilience. The Sunbond® (FN, FS, and FW) resins are intended for more rigid media to be used in pleated applications and have higher glass transition temperatures.

Note from Table 4.41 that the polymers listed are copolymers, i.e. the polymer structure includes two monomer species. If there is only monomer species, the polymer is a homopolymer. Generally, the resins in filter media lattices are copolymers; however there are exceptions. For example, homopolymer PVAc latex has been widely used as a saturant for wet laid filter media (see Section 4.4.2.2.1 below). There are also terpolymers that are made up from three monomer species. Graft polymers are another way of combining different polymer species to achieve desired properties. A graft polymer is one polymer structure that is attached to the backbone of another polymer structure. A water-soluble polymer such as starch or poly(vinyl alcohol) (PVOH) is often used as the backbone polymer.

Table 4.41 lists other properties that are important to latex binders. Viscosity has been discussed above in the way it affects penetration. Solids content is of economic importance because the more water there is in the neat resin, the more will be its shipping costs. Typical solids contents of latex resins shipped to the customer are 40%–50%. Depending on the complexities of the resin system it may sometimes be higher and sometimes lower. Rarely is the neat latex resin used “as is” by the filter medium manufacturer. The medium manufacturer will blend in other ingredients, such as other resins, cross-linking agents, water repellents, plasticizers, and flame retardants. The resin blend will be diluted to a solids content as demanded by the process. The solids content determines the amount or percentage of resin content in the finished product. It affects the viscosity of the resin as applied and the degree of penetration into the web. Lowering the solids content of the resin will increase the amount of water applied to the web and result in a higher thermal load for drying the web. This may be evidenced

<table>
<thead>
<tr>
<th></th>
<th>Sequabond®</th>
<th>Sequabond®</th>
<th>Sunbond®</th>
<th>Sunbond®</th>
<th>Sunbond®</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FVAC</td>
<td>FGS</td>
<td>FN</td>
<td>FS</td>
<td>FW</td>
</tr>
<tr>
<td>Solids (%)</td>
<td>42</td>
<td>41</td>
<td>45</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>pH</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Viscosity (cps)</td>
<td>100</td>
<td>75</td>
<td>100</td>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td>Polymer type</td>
<td>Poly (vinyl acetate)</td>
<td>Poly (vinyl lactate)</td>
<td>Poly (vinyl acetate)</td>
<td>Poly (styrene vinyl acetate)</td>
<td>Poly (styrene vinyl acetate)</td>
</tr>
<tr>
<td>$T_g$ (°C)</td>
<td>+15</td>
<td>+25</td>
<td>+30</td>
<td>+45</td>
<td>+35</td>
</tr>
<tr>
<td>Recommended use</td>
<td>Paper saturants, vacuum bags</td>
<td>Paper saturants, vacuum bags, high temp and humidity resistance</td>
<td>General purpose and auto air</td>
<td>Heavy duty, highest stiffness</td>
<td>Washable and/or humid environments</td>
</tr>
<tr>
<td>Pleatable</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes (requires high temperatures)</td>
<td>Yes (requires high temperatures)</td>
</tr>
</tbody>
</table>

Reproduced with permission of OMNOVA Solutions Inc. Chester, South Carolina, USA.
by increased energy costs and/or lower production rates. Dilution may also increase pot life; however there are some resins such as water-based phenolics that have a water tolerance. They will kick out if diluted below a certain point.

pH helps to determine how other ingredients may be formulated with the latex. For example, all the latex binders listed in Table 4.41 are acidic (low pH). If they are blended with basic (high pH) materials pot life may be shortened. At worst, they may kick out of emulsion and agglomerate into a gummy sludge.

Shelf life and pot life are two very important considerations in choosing a latex resin. Latex resins are limited in their stability. Shelf life is a measure of how long the resin will last in ambient storage conditions. This period can be a matter of weeks or it can be years. Generally if the latex has been around for over a year it is probably not wise to use it. Storage instability will usually be indicated by a build-up of sludge in the bottom of the container or storage tank. The user has means to optimize shelf life.

1. Store in a cool place. Cold rooms are preferable; however, do not freeze.
2. Do not store outside in hot climates.
3. Use agitated storage tanks.
4. Take care that the order rate is consistent with usage.
5. Be aware of how long the resin has been stored at the suppliers site before it was shipped.
6. Be conscious of the weather conditions during shipment. For example, if the shipment is in winter during below 0° weather, the possibility of the latex freezing has to be considered.

Pot life is how long the resin formulation will last after it has been prepared. The addition of reactive ingredients and possible heat may greatly increase resin instability. The criterion is that the resin has to remain stable till it is used in process. When considering this timing, allowance has to be made for unexpected process shutdowns.

Formaldehyde (HCHO) and alkyl phenol ethoxylate surfactants (APEs) are two environmental concerns related to latex emulsions. Formaldehyde is released by cross-linking components built into the latex system. Formaldehyde is a by-product of the cross-linking mechanism. It is reported to be a carcinogen and is of concern both as an environmental contaminant and as an occupational health and safety hazard. There is intense effort to produce low formaldehyde or formaldehyde free lattices. Ways of doing this are:

1. Use nonformaldehyde cross-linking agents – see Section 4.6.6.4 below.
2. Incorporate a formaldehyde scavenger into the resin mix. These are specific ureas that bind to formaldehyde and prevent it from volatilizing.

APEs are nonionic surfactants that are primary components in latex surfactant systems. There is some evidence to suggest that they may “affect the reproductive or development health of wildlife or humans” (Mlynarcik). There is a possibility that they may have an impact on life in aquatic systems.

Rohm and Haas Company has introduced a line of environment friendly resins for textile and nonwoven applications. These are tabulated in Table 4.42. Note that all of the resins feature low or ultra low formaldehyde and are APE-free.
### Table 4.42 Rohm and Haas environment-friendly products

Summary table binders for nonwoven and textile applications

<table>
<thead>
<tr>
<th></th>
<th>Type</th>
<th>% Solids</th>
<th>T_d (°C)</th>
<th>Hand</th>
<th>Features and benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nonionic self-cross-linking</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rhoplex ECO-3960</td>
<td>Acrylic</td>
<td>46</td>
<td>-16</td>
<td>Soft</td>
<td>Low HCHO, APE-free binder offering superior water resistance and good solvent resistance</td>
</tr>
<tr>
<td>Rhoplex ECO-3988</td>
<td>Acrylic</td>
<td>58</td>
<td>+7</td>
<td>Medium</td>
<td>Low HCHO, APE-free, high solids binder providing outstanding solvent and water resistance</td>
</tr>
<tr>
<td><strong>Anionic self-cross-linking</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rhoplex ECO-3205PN</td>
<td>Acrylic</td>
<td>41.5</td>
<td>-27</td>
<td>Very soft</td>
<td>Ultra low HCHO binder offering excellent elasticity and durability</td>
</tr>
<tr>
<td>Rhoplex ECO-2839</td>
<td>Acrylic</td>
<td>45</td>
<td>+34</td>
<td>Firm</td>
<td>Low HCHO, APE-free binder providing excellent mechanical stability and runoff ability</td>
</tr>
<tr>
<td>Rhoplex ECO-100</td>
<td>Acrylic</td>
<td>44</td>
<td>+35</td>
<td>Firm</td>
<td>Ultra low HCHO, APE-free binder offering a firm hand and excellent durability</td>
</tr>
<tr>
<td><strong>Nonionic cross-linkable</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rhoplex ECO-15</td>
<td>Acrylic</td>
<td>46</td>
<td>+1</td>
<td>Medium</td>
<td>Low HCHO, APE-free, general purpose binder with excellent heat scalability</td>
</tr>
<tr>
<td>Rhoplex ECO-4015</td>
<td>Acrylic</td>
<td>42.5</td>
<td>+91</td>
<td>Very Firm</td>
<td>Low HCHO, APE-free, stiff binder used to modify the hand</td>
</tr>
<tr>
<td><strong>Anionic cross-linkable</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rhoplex ECO-3045</td>
<td>Acrylic</td>
<td>56</td>
<td>-35</td>
<td>Very soft</td>
<td>Ultra low HCHO, APE-free, high solids binder offering excellent elasticity</td>
</tr>
<tr>
<td>Rhoplex NW-1845K</td>
<td>Styrenated acrylic</td>
<td>44</td>
<td>-21</td>
<td>Soft</td>
<td>Ultra low HCHO, APE-free binder for wood pulp and rayon applications. Provides good salt stability, excellent water, and fair solvent resistance</td>
</tr>
<tr>
<td>Rhoplex NW-1715K</td>
<td>Styrenated acrylic</td>
<td>44</td>
<td>-6</td>
<td>Medium</td>
<td>Ultra low HCHO, APE-free binder for polyester applications. Salt stable, hydrophobic, excellent water, and fair solvent resistance</td>
</tr>
<tr>
<td>Rhoplex ECO-4032</td>
<td>Acrylic</td>
<td>48</td>
<td>+32</td>
<td>Firm</td>
<td>Ultra low HCHO, stiff binder providing excellent color, crispness and pleatability</td>
</tr>
<tr>
<td>Polyco 2149A</td>
<td>Vinyl acetate</td>
<td>48</td>
<td>+48</td>
<td>Firm</td>
<td>Ultra low HCHO, APE-free binder recommended for shoddy applications; excellent mechanical stability</td>
</tr>
</tbody>
</table>

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4.4.2.2 Polymer systems for latex resins

The following is a discussion of various polymer systems used in latex emulsion resins.

4.4.2.2.1 Poly(vinyl acetate)

Poly(vinyl acetate) (PVAc) latex emulsions are common and low cost. DeVry\textsuperscript{121} advises that PVAc is not a popular binder for many nonwoven materials because of its stiffness. On the other hand, it is for this very reason of stiffness that PVAc is a desired latex resin for filter media. It is often used in wet laid media for pleated filters in engine air intake filtration applications. Often it is formulated with a cross-linking agent such as melamine formaldehyde. Since PVAc is alcohol soluble it is sometimes blended into phenolic resin solutions as a plasticizer to reduce the brittleness of the cured media.

PVAc comes in many copolymer forms; however, a homopolymer version has been very popular for intake air filters for automotive and heavy duty vehicles. For many years, National Starch, Bridgewater, New Jersey, USA, has marketed Dur-o-set\textsuperscript{® C310}\textsuperscript{11}, a PVAc homopolymer latex, widely used as a saturant for wet laid filter media.

4.4.2.2.2 Ethylene vinyl chloride

Ethylene vinyl chloride (EVCl) emulsions are terpolymers of vinyl chloride, ethylene, and a third monomer which imparts amide functionality.

EVCl emulsions are major players in the production of filter media, particularly those used in cartridges for high efficiency air filter applications. They provide a high level of water and moisture resistance, alkali resistance, and dimensional stability. They can be readily formulated and compounded with plasticizers, coalescing agents, and the same types of solvents commonly used with acrylic and PVAc systems. They are film formers and provide good moisture barrier properties and abrasion resistance. Because they contain chlorine, they are an excellent polymer base for flame retardant formulations. They are environmentally friendly because they have low emissions of VOCs, phenols, and formaldehyde.

Air Products Polymers (APP), a joint venture between Air Products and Chemicals, Inc. and Wacker-Chemie GmbH, produces the Airflex\textsuperscript{®} line of EVCl emulsions. Table 4.43 lists properties of three products: Airflex\textsuperscript{®} 4500, Airflex\textsuperscript{®} 4514, and Airflex\textsuperscript{®} 4530. Table 4.44 illustrates how these lattices relate to each other.

4.4.2.2.3 Poly(vinyl chloride) and poly(vinylidene chloride)

Poly(vinyl chloride) (PVC) and poly(vinylidene chloride) (PVDC) are of interest for filter media because of the inherent flame retardancy provided by their chlorine content (see Section 4.5.2). PVDC contains twice as many chlorine atoms per repeat unit of polymer than does PVC and therefore is even more flame retardant. Nevertheless, a filter medium containing PVC or PVDC will still not be flame retardant unless it contains excessive amounts of the resin or it contains additional amounts of supplementary flame retardant.

\textsuperscript{11}At the time of writing this book, National Starch's specialty polymer business was purchased by Celanese Corporation of Dallas, Texas, USA. The Dur-o-set\textsuperscript{®} resin line was included in this transaction.
Table 4.43  Typical properties of Airflex® EVCL emulsions

<table>
<thead>
<tr>
<th>Copolymer type</th>
<th>Airflex® 4500</th>
<th>Airflex® 4514</th>
<th>Airflex® 4530</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethylene-Vinyl chloride</td>
<td>Ethylene-Vinyl chloride</td>
<td>Ethylene-Vinyl chloride</td>
<td></td>
</tr>
</tbody>
</table>

**Emulsion properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Airflex® 4500</th>
<th>Airflex® 4514</th>
<th>Airflex® 4530</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solids</strong>, %</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>pH</td>
<td>7–9</td>
<td>7–9</td>
<td>7–9</td>
</tr>
<tr>
<td>Particle size range, μm</td>
<td>0.11–0.19</td>
<td>0.11–0.19</td>
<td>0.11–0.19</td>
</tr>
<tr>
<td>Surfactant type</td>
<td>Anionic</td>
<td>Anionic</td>
<td></td>
</tr>
<tr>
<td>Density**, lb/gal</td>
<td>9.2</td>
<td>9.2</td>
<td>9.4</td>
</tr>
<tr>
<td>Mechanical stability**</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>(pH range of 4.0–11.0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MFFT, °C</td>
<td>4</td>
<td>14</td>
<td>50</td>
</tr>
<tr>
<td>MVTR, g/m²/24 h</td>
<td>0.13</td>
<td>0.17</td>
<td>N/A</td>
</tr>
<tr>
<td>pH stability**</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Functional group</td>
<td>Amide</td>
<td>Amide</td>
<td>Amide</td>
</tr>
</tbody>
</table>

**Film properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Airflex® 4500</th>
<th>Airflex® 4514</th>
<th>Airflex® 4530</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexibility</td>
<td>Excellent</td>
<td>Good</td>
<td>Fair</td>
</tr>
<tr>
<td>Tensile strength, psi</td>
<td>600</td>
<td>1,100</td>
<td>2,100</td>
</tr>
<tr>
<td>Elongation, %</td>
<td>1,700</td>
<td>675</td>
<td>140</td>
</tr>
<tr>
<td>Reactivity</td>
<td>Cross-linkable</td>
<td>Cross-linkable</td>
<td>Cross-linkable</td>
</tr>
<tr>
<td>Water resistance</td>
<td>Good</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Oil resistance</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Tₘ, °C</td>
<td>3</td>
<td>12</td>
<td>29</td>
</tr>
</tbody>
</table>

*a Cenco Moisture Balance.
*b Brookfield LVT Viscometer, 60 rpm #2 spindle @ 25°C.
*c Foam free at 25°C.
*d Does not break after 30 min at high speed in a Hamilton mixer.
*e If adjusted with dilute acids or alkalis.
*f Differential thermal analysis.

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4.4.2.2.4 Styrene butadiene

Styrene butadiene (SBR) is one of several polymers with elastomeric or rubber-like properties. It is often referred to as synthetic rubber. Other “rubber” polymers are natural rubber from gum trees in Asia and Africa, polybutadiene rubber (BR), butyl rubber (IIR), hydrogenated nitrile butadiene rubber (NHBR), styrenic block copolymer (SBC), fluoroelastomers, silicone rubber, nitrile rubber, and polyolefin elastomer. SBR is the largest volume. The latex form finds broad use in nonwovens and paper.

SBR is a copolymer of styrene and butadiene, the greater is the proportion of styrene in the molecular chain, the stiffer is the resin. It finds application in both dry laid and wet laid nonwovens. It is used as a binder for high loft filter media. It is used as a rubber coating on the fibers of natural filter media (hog’s hair and coir). Tacky forms of SBR have been used as a sticky fiber surface to trap air borne particles.
Table 4.44 Comparison of Airflex Resins

<table>
<thead>
<tr>
<th>Resin</th>
<th>Increasing ethylene content</th>
<th>Increasing T&lt;sub&gt;n&lt;/sub&gt;</th>
<th>Increasing solvent resistance</th>
<th>Increasing water resistance</th>
<th>Increasing stiffness</th>
<th>Increasing tensile</th>
<th>Increasing flame retardancy</th>
<th>Increasing gloss</th>
<th>Increasing fold</th>
<th>Increasing flexibility</th>
<th>Increasing elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-4500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-4514</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-4530</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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4.4.2.2.5 Acrylics
Acrylic polymers are loosely defined as being the polymers or copolymers formed from the esters of acrylic or methacrylic acid. Usually they are used in copolymer form with each other and with other monomers such as styrene (styrene acrylics) and PVAc (vinyl acrylics). Common acrylic monomers used in the copolymer systems of latex resins are ethyl acrylate, butyl acrylate, and methyl methacrylate. Polymers of acrylonitrile are often referred to as acrylics (see Section 4.3.5.2.4).

Noveon Inc. (now part of The Lubrizol Corporation) is one of the largest suppliers of acrylic emulsions to the specialty paper and nonwovens industry. Table 4.45 is a listing of their resin emulsions recommended for filter media.

4.4.2.3 Solution polymers
Solution polymers are made by connecting monomer units together to make a long polymer chain that carries an ionic charge along the chain itself. During the manufacturing process, the chains curl around and into one another. These products dissolve in water in a fashion similar to salt and sugar. When water comes into contact with the molecule, the polymer chains uncurl and lengthen.

Solution polymers can be anionic, cationic, or nonionic depending upon the monomers used in the production process. They are available in a wide range of molecular weights and charge densities. They act as solid–liquid separating agents, otherwise known as flocculants, or they can be dispersing agents. In wet lay operations they are used to enhance the strength of a medium. Certain types of charged
<table>
<thead>
<tr>
<th>Identification</th>
<th>T &lt;sub&gt;g&lt;/sub&gt; (°C)</th>
<th>Charge</th>
<th>Solids (%)</th>
<th>pH</th>
<th>Viscosity (cP)</th>
<th>Specific gravity</th>
<th>Heat reactive</th>
<th>Solvent resistance</th>
<th>Water resistance</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbocure® TSR-72</td>
<td>72</td>
<td>-</td>
<td>35</td>
<td>4.6</td>
<td>50</td>
<td>1.07</td>
<td>Yes</td>
<td>VG</td>
<td>G</td>
<td>Stiff, high cross-link density polymer with excellent oil and solvent resistance; high temperature dimensional stability, moldability; saturation and spray bond</td>
</tr>
<tr>
<td>Hycar® 2671</td>
<td>-11</td>
<td>A</td>
<td>53</td>
<td>5.0</td>
<td>170</td>
<td>1.07</td>
<td>Yes</td>
<td>G</td>
<td>G</td>
<td>General-purpose coatings; saturation or wet end addition</td>
</tr>
<tr>
<td>Hycar® 2679</td>
<td>-3</td>
<td>A</td>
<td>49</td>
<td>3.7</td>
<td>100</td>
<td>1.06</td>
<td>Yes</td>
<td>VG</td>
<td>G</td>
<td>Good general-purpose acrylic for saturation, filter paper</td>
</tr>
<tr>
<td>Hycar® 26084</td>
<td>+8</td>
<td>A</td>
<td>48</td>
<td>6.1</td>
<td>110</td>
<td>1.07</td>
<td>Yes</td>
<td>G</td>
<td>G</td>
<td>Heat seal adhesive with excellent solvent and plasticizer resistance; paper coating</td>
</tr>
<tr>
<td>Hycar® 26106</td>
<td>+66</td>
<td>A</td>
<td>50</td>
<td>5.0</td>
<td>80</td>
<td>1.05</td>
<td>Yes</td>
<td>G</td>
<td>VG</td>
<td>Hand builder; hydrophobic; film former at 75°C; saturant/paper coating</td>
</tr>
<tr>
<td>Hycar® 26120</td>
<td>-11</td>
<td>A</td>
<td>50</td>
<td>3.8</td>
<td>115</td>
<td>1.07</td>
<td>Yes</td>
<td>G</td>
<td>VG</td>
<td>Highly redispersible, excellent heat stability, saturation and wet end addition; medical</td>
</tr>
<tr>
<td>Hycar® 26138</td>
<td>+25</td>
<td>A</td>
<td>49</td>
<td>5.5</td>
<td>60</td>
<td>1.07</td>
<td>Yes</td>
<td>VG</td>
<td>G</td>
<td>Durable, excellent paper coating binder, excellent solvent resistance</td>
</tr>
<tr>
<td>Hycar® 26315</td>
<td>+55</td>
<td>A</td>
<td>49.5</td>
<td>2.1</td>
<td>36</td>
<td>1.07</td>
<td>Yes</td>
<td>G</td>
<td>VG</td>
<td>Heat sealable; FDA compliant for direct food contact; excellent water resistance</td>
</tr>
<tr>
<td>Hycar® 26349</td>
<td>+12</td>
<td>A</td>
<td>49</td>
<td>4.6</td>
<td>135</td>
<td>1.07</td>
<td>Yes</td>
<td>VG</td>
<td>G</td>
<td>Extremely durable coatings; firm but flexible hand; solvent and plasticizer resistant</td>
</tr>
<tr>
<td>Hycar® 26391</td>
<td>+36</td>
<td>A</td>
<td>50</td>
<td>3.6</td>
<td>125</td>
<td>1.09</td>
<td>Yes</td>
<td>G</td>
<td>VG</td>
<td>Highly water resistant; very good color</td>
</tr>
<tr>
<td>Hycar® 26450</td>
<td>+32</td>
<td>A</td>
<td>46</td>
<td>4.0</td>
<td>25</td>
<td>1.06</td>
<td>Yes</td>
<td>VG</td>
<td>G</td>
<td>High cross-link density; oil resistant; FDA compliant for direct food contact</td>
</tr>
</tbody>
</table>

<sup>a</sup>A = anionic. <sup>A-N</sup> = anionic/nonionic.

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polymers are added to the wet end of the wet lay process to provide for the retention of particulate matter such as diatomaceous earth.

Solution polymers usually form very viscous solutions even at low polymer contents in the water (<5%). They are most often used in the wet end of wet lay filter media. They are also used in saturation applications, usually as a component of the latex system.

4.4.2.3.1 Starch
Starch is a natural polymer with a very high molecular weight. Brouwer et al.¹¹²² state that it is the most widely used chemical in the paper industry. It is used in synthetic fiber manufacture as a finish for fibers. For wet lay systems it helps make the fiber (synthetic and glass) more dispersible in water. It is also used as a finish for dry-formed nonwovens. Starch is used as a backbone for grafted polymer systems.

Starch is sourced from agricultural plant products such as sugar cane, corn, or potato. Starch solution is prepared by dispersing starch powder in water and "cooking" the mixture at temperatures approaching 100°C. The solution formed is very viscous and usually cannot be used at concentrations above 5%–10%. Starch can be prepared in cationic, anionic, or nonionic forms. In wet lay systems it is mostly used in the cationic form. Although the purpose of Brouwer et al.¹¹²² was to justify some advantages of the anionic form, in wet lay systems, starch is mostly used as an additive to the fiber slurry. It can be used for adding dry strength to the wet lay product. It is also used in polymer retention systems to retain other additives such as activated carbon, fillers, wet strength agents, etc. into the fiber structure.

4.4.2.3.2 Poly(vinyl alcohol)
PVOH is a water-soluble, film-forming resin that has very strong bonding properties for nonwoven filter media. Its biggest use is as oil and grease proof coatings for packaging materials such as paper and board. It is chemically resistant to oils, grease, hydrocarbon solvents and when fully hydrolyzed, very resistant to water. It is available in white flake, powder, or pellet form. It is produced by first forming polyvinyl acetate and then hydrolyzing the resultant chemical structure. The properties of the polymer are very dependent on the degree of hydrolysis. The ranges for degree of hydrolysis¹² are as follows:

- Fully hydrolyzed 98%–99.5%.
- Intermediate hydrolyzed 90%–97%.
- Partially hydrolyzed 86%–89%.
- Specialty grades 76%–87.6%.

PVOH is also dependent on its degree of polymerization for its properties. Table 4.46 indicates how hydrolysis and degree of polymerization affect some of the properties of PVOH.

¹²Hydrolysis is expressed as the mole percentage of acetate groups hydrolyzed (dry basis).
## Table 4.46 The effect of degree of hydrolysis and degree of polymerization on the properties of PVOH resin

<table>
<thead>
<tr>
<th>Property effect on</th>
<th>Degree of hydrolysis</th>
<th>Degree of polymerization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Solvent resistance</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Water resistance</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Solubility</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Hygroscopicity</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Flexibility</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Viscosity</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: “+” indicates the property gets higher or stronger. “−” indicates that the property gets lower or weaker.

Preparation of PVOH solution is similar to the preparation of starch solution. The resin solids have to be added carefully to cold water and heated with agitation to >90°C. Like starch, the solubilized resin is very viscous, even at solids contents less than 10%. The high viscosity makes it difficult to use the resin as a saturant because of penetration difficulties. Because of the high viscosity, wet pickup and corresponding dry pickup is high. This means the resin has to be applied at lower solids, and therefore more water to dry off.

When formulated with the right kind of cross-linking or thermosetting agent PVOH can produce a web with outstanding heat resistance, water resistance, and strength properties. The use of the thermoset curing mechanism allows the properties to be achieved even with a low hydrolysis PVOH. The polymer is very stable and shows little tendency to oxidize or degrade with time.

### 4.4.2.4 Cross-linking agents for water-based resins

Thermosetting resins such as phenolics described above have their own built-in cross-linking mechanisms that build rigidity, strength, heat resistance, water resistance, and chemical resistance to the media when fully cured. Many water-based latexes and resins are formulated with cross-linking agents to impart these properties. Typical cross-linking agents are UF, melamine formaldehyde, water-based phenolics, and various dialdehydes. Glyoxal, the simplest of the dialdehydes, is often used. In recent years, there has been a movement to incorporate formaldehyde free cross-linking agents. Polyamide epichlorohydrin resins and salts of zirconium ammonium carbonates are two that have been considered.

### 4.5 Additives and Finishes

#### 4.5.1 Adsorbent materials

The following are some adsorbent materials that may be may be used in nonwoven filters:

(a) Activated carbon.
(b) Activated alumina: Lower surface area but good base for certain impregnations.
(c)  *Zeolite*: Man-made, pore sizes can be designed for specialty separations.

(d)  *Zeolite*: Natural.

(e)  *Ion exchange resins*: Can be produced with controlled pore sizes and high chemical capacities.

(f)  *Silica gel*.

(g)  In addition to points (a)–(e) above, Flanders Filters is marketing a residence ventilation filter containing baking soda (sodium bicarbonate, NaHCO₃) for odor removal.

Middlebrooks suggests that activated carbon is by far the preferred adsorbent for nonwoven filter medium applications. Generally it is the adsorbent with the largest total surface area depending on source. The most common sources are coal, wood, and coconut. Figure 4.35 is a microphotograph of the extended surface of an activated coconut carbon granule. Any organic material that can be charred and activated to a carbon can be used for producing some form of activated carbon. Synthetic polymer fibers such as PAN have been used for producing ACE. The choice depends on pore size and distribution. Generally, coconut sourced activated carbons are used for air filtration applications while coal-based carbons are preferred for water filtration. There are also carbons impregnated with some form of chemical to develop and enhance chemisorption properties.

One type of impregnated activated carbon, ASZM-TEDA carbon, has been used in US military nuclear, biological, and chemical (NBC) filters since 1993. This material, manufactured by Calgon Carbon Corporation, is a coal-based activated carbon that has been named for its impregnates: copper (A), silver (S), zinc (Z), molybdenum (M)
compounds, and triethylene diamine (TEDA). ASZM-TEDA carbon provides a high level of protection against a wide range of toxic chemicals. Table 4.47 provides a list of the chemical impregnates and the air contaminants against which they are effective.

<table>
<thead>
<tr>
<th>Impregnate</th>
<th>Chemical contaminant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper/silver salts</td>
<td>Phosgene, chlorine, arsine</td>
</tr>
<tr>
<td>Iron oxide</td>
<td>Hydrogen sulfide, mercaptans</td>
</tr>
<tr>
<td>Manganese IV oxide</td>
<td>Aldehydes</td>
</tr>
<tr>
<td>Phosphoric acid</td>
<td>Ammonia</td>
</tr>
<tr>
<td>Potassium carbonate</td>
<td>Acid gases, carbon disulfide</td>
</tr>
<tr>
<td>Potassium iodide</td>
<td>Hydrogen sulfide, phosphine, mercury, arsenic, radioactive methyl iodide</td>
</tr>
<tr>
<td>Potassium permanganate</td>
<td>Hydrogen sulfide</td>
</tr>
<tr>
<td>Silver</td>
<td>Arsine, phosphine</td>
</tr>
<tr>
<td>Sulfur</td>
<td>Mercury</td>
</tr>
<tr>
<td>Sulfuric acid</td>
<td>Ammonia, amine, mercury</td>
</tr>
<tr>
<td>Triethylene diamine (TEDA)</td>
<td>Radioactive methyl iodide</td>
</tr>
<tr>
<td>Zinc oxide</td>
<td>Hydrogen cyanide</td>
</tr>
</tbody>
</table>

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### 4.5.2 Flame retardants

A flame retardant is a chemical used to impart flame resistance to a nonwoven web. In many air filtration systems it is desired and/or required that the filter medium be flame resistant. The general requirement is that the medium is not able to sustain a flame after the heat or ignition source is withdrawn. Fiber materials such as polyester accomplish this by melting and shrinking away from the heat source so that combustion does not occur. Inorganic fibers such as glass are fire resistant and do not burn because they do not contain a component that will react with oxygen to produce a flame. Halogenated polymers such as PVC and PVDC are inherently flame resistant because of their chlorine atom content. Most organic filter media, particularly cellulose, will burn and require a flame retardant additive to inhibit the oxidation effect after the flame is withdrawn.

The flame resistance of a material is usually determined by some form of ignition test (vertical, 45°, or horizontal). Generally a flame is applied to the material and observation is made as how far the flame spreads before extinguishing. Another method of measuring flame resistance is the limiting oxygen index, which determines the minimum oxygen content (LOI) in air that will sustain combustion of a material.

Materials burn because they are decomposed by heat to release flammable gases. Visible flames appear when the gases combine with oxygen. The carbon–hydrogen chemical structure of the organic material reacts with oxygen in the atmosphere to produce carbon dioxide (CO₂) and water (H₂O). The oxidation is endothermic and releases energy. If sufficient energy is generated, the oxidation is maintained and
Flame retardants act in such a way as to inhibit the oxidation reaction that causes flame. For example, halogenated compounds (containing chlorine or bromine) when exposed to high temperatures will release the halogen as a free-radical \( \{\text{Cl}^+ \text{ or Br}^+\} \). These will then react with hydrocarbon molecules to form HBr and/or HCl and inhibit the oxidation process. The effectiveness depends on the quantity of halogen atoms and how well their halogen release is controlled. For example, the chlorine content of PVC resin may be enough to make the polymer flame retardant; however, if the resin is used as a binder in a filter medium it is insufficient to make the whole web flame retardant. Additional flame retardant will have to be added to the formulation. The advantage of a halogenated compound such as PVC is that it reduces the amount of additional flame retardant.

The market place has flame retardants based on bromine as well as chlorine. Brominated flame retardants are generally more expensive, but have the advantage of releasing over a narrower temperature range, thus resulting in more optimal concentrations in the flame zone.

Antimony trioxide (Sb\(_2\)O\(_3\)) is not a flame retardant; however, it has a synergistic effect for halogenated flame retardants. It serves as a catalyst, facilitating the breakdown of the flame retardants to active molecules. It also reacts with halogens to produce antimony–halogen compounds, which in themselves are effective flame retardants.

Para-Chem, of Simpsonville, South Carolina, USA, produces a line of flame retardant dispersions under the trade name of Paranol\(^\text{®}\). Several are brominated materials, usually in the form of decarbromodiphenyl oxide. Some of these are formulated with antimony oxide. Table 4.48 is a tabulation (including description) of their flame retardant dispersions.

Phosphorous containing compounds usually act in the solid phase of burning materials. When heated these compounds break down to release polymeric forms of phosphoric acid that chars the media. The charring effect inhibits the “pyrolysis” process that releuses flammable gases to feed the flames.
Table 4.48 Para-Chem flame retardants

<table>
<thead>
<tr>
<th>Product</th>
<th>Solids (%)</th>
<th>pH</th>
<th>Viscosity (cP)</th>
<th>Density (lb/gal/g/cc)</th>
<th>Suggested applications and description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRD-002</td>
<td>53</td>
<td>9.0</td>
<td>300</td>
<td>9/1.08</td>
<td>Environment-friendly system to provide flame retardancy and maintain film integrity. Can be used with woven, nonwoven, and print bonders</td>
</tr>
<tr>
<td>FRD-003</td>
<td>35</td>
<td>8.5</td>
<td>100</td>
<td>9/1.08</td>
<td>Environment-friendly system that provides a finish that is durable to home laundry, water soaks, and commercial cleaning</td>
</tr>
<tr>
<td>FRD-004</td>
<td>65</td>
<td>8.5</td>
<td>3,000</td>
<td>12/1.44</td>
<td>Aqueous dispersion of decarbromodiphenyl oxide. Designed for a variety of fabrics and applications</td>
</tr>
<tr>
<td>FRD-005</td>
<td>65</td>
<td>8.5</td>
<td>4,000</td>
<td>15/1.80</td>
<td>Aqueous dispersion of decarbromodiphenyl oxide and antimony oxide in a 4.5:1 ratio. Designed for a variety of fabrics and applications</td>
</tr>
<tr>
<td>FRD-006</td>
<td>55</td>
<td>8.5</td>
<td>4,000</td>
<td>12/1.44</td>
<td>Environment-friendly brominated system that provides a &quot;clean&quot; MSDS for use in a variety of latex systems</td>
</tr>
<tr>
<td>FRD-007</td>
<td>65</td>
<td>8.5</td>
<td>4,000</td>
<td>15/1.80</td>
<td>Aqueous dispersion of decarbromodiphenyl oxide and antimony oxide in a 2:1 ratio. Designed for a variety of fabrics and applications</td>
</tr>
<tr>
<td>FRD-008</td>
<td>70</td>
<td>9.0</td>
<td>4,000</td>
<td>15/1.80</td>
<td>Aqueous dispersion of decarbromodiphenyl oxide and antimony oxide in a 4.7:1 ratio. Designed for a variety of fabrics and applications</td>
</tr>
<tr>
<td>FRD-009</td>
<td>62</td>
<td>9.0</td>
<td>6,000</td>
<td>15/1.80</td>
<td>Aqueous dispersion of decarbromodiphenyl oxide and antimony oxide in a 2:1 ratio. Designed for a variety of fabrics and applications</td>
</tr>
<tr>
<td>FRD-010</td>
<td>65</td>
<td>8.5</td>
<td>4,000</td>
<td>15/1.80</td>
<td>Aqueous dispersion of decarbromodiphenyl oxide and antimony oxide in a 10:1 ratio. Designed for a variety of fabrics and applications</td>
</tr>
<tr>
<td>FRD-011</td>
<td>65</td>
<td>9.5</td>
<td>4,000</td>
<td>15/1.80</td>
<td>Aqueous dispersion of decarbromodiphenyl oxide and antimony oxide in a 5:1 ratio. Designed for a variety of fabrics and applications</td>
</tr>
<tr>
<td>FRD-012</td>
<td>65</td>
<td>9.5</td>
<td>4,000</td>
<td>15/1.80</td>
<td>Aqueous dispersion of decarbromodiphenyl oxide and antimony oxide in a 4.5:1 ratio. Designed for a variety of fabrics and applications</td>
</tr>
<tr>
<td>FRD-013</td>
<td>65</td>
<td>9.0</td>
<td>5,000</td>
<td>15/1.80</td>
<td>Aqueous dispersion of supermicronized decarbromodiphenyl oxide and antimony oxide in a 2.1 ratio. Designed for a variety of fabrics and applications</td>
</tr>
</tbody>
</table>

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Diammonium phosphate (DAP) is a common form of phosphorous containing flame retardant because it is inexpensive and it is effective. There are several caveats associated with its use:

1. It decomposes over time and accelerates the degradation and discoloration of the medium.
2. It has a relatively low decomposition temperature; therefore, medium containing this additive will have very poor heat and temperature resistance.
3. It is very hygroscopic and will adversely affect the moisture resistance of the medium. The dimensional instability of the medium will be increased.
4. DAP is water soluble and cannot be used in washable filter media.

Other forms of phosphorous containing compounds include phosphate esters, phosphonates, and halogenated esters of phosphates, etc. THPC, the “Cadillac of fabric flame retardant finishes” (EFP, A t 123~) is a phosphine formaldehyde derivative precondensed with urea to make a water-soluble prepolymer. When applied as a finish to fabrics, it produces a flame retardant medium that is resistant to multiple launderings. Nitrogen flame retardants are believed to act in the following manner:

1. They form cross-linked polymer structures, stable at high temperatures, and thereby, physically inhibit the decomposition of materials to flammable gases.
2. They release nitrogen which reduces the flammable gases and thus reduces flames.
3. They are synergistic with phosphorous containing flame retardants and reinforce their function.

Nitrogen-based flame retardants are used at high concentrations, or in conjunction with other flame retardants. Melamine-based products are the most widely used type nitrogen flame retardants.

There are a number of inorganic products that serve as flame retardants. These include aluminum trihydrate, magnesium hydroxide, boron compounds, and zinc borate. Other zinc and tin compounds act in a way to reduce smoke emissions.

### 4.5.3 Water repellents

Water repellency is important to a filter medium, particularly air filtration media, because it helps prevents it from being wetted out and damaged when exposed to water. For example, Juroff and Sławski point out that “Thoroughly wetting HEPA filter media, even once, substantially degrades filter strength and could reduce resistance to medium breach”.

Water repellency is incorporated into a filter medium by the use of hydrophobic materials in the media surface. This can be done by the use of water repellant fibers or by water repellant coatings. Water repellent materials have low surface energies, meaning that the surface lacks the energy to hold on to a liquid droplet. This is analogous to the freshly waxed surface of an automobile. The driver will note that when raindrops strike the hood of the automobile they ball up and simply roll off, an example of a low energy
surface. On the other hand, if the surface has aged and become worn since the last waxing, its surface energy has increased. When the hood of such an automobile is struck by raindrops, they will spread and wet out the surface with a continuous film of water.

Polyester and polyolefin are examples of fibers that are hydrophobic and will help impart water repellency to a filter medium. Waxes, silicones, and fluorocarbon resins are examples of water repellent coatings that can be applied to a filter media. Some binders such as styrene acrylates also impart a degree of water repellency.

4.5.4 Antimicrobial agents

Antimicrobial agents inhibit microbial growth (bacteria, fungus, and mildew) on the surface and/or interior fiber surface of a filter medium. Their functions are as follows:

1. Protect the filter medium from biological degradation while in service.
2. Inhibit the biological growth of microbes downstream of the filter.
3. Serve as a means of odor control.

SpecialChem S. A., an online Internet service for specialty chemicals, identifies the following as antimicrobial chemicals:

- 10,10'-oxybisphenoxarsine (OBPA),
- trichlorohydroxydiphenylether (triclosan),
- n-octyl-isothiazolinone (OIT),
- 4,5-di-chloro-isothiazolinone (DCOIT),
- mercaptopyridine-n-oxide (pyrithione),
- butyl-benzisothiazolinone (butyl-BIT),
- metal-based biocides, such as organo-tin and silver,
- nonbiocide additives, including inherently antimicrobial polymers and photocatalytic ingredients, which when exposed to light generate free radicals.

In general, antimicrobial agents are either organic or contain a metal component such as silver, zinc, copper. Ciba Specialty Chemicals markets both organic and inorganic under their Irgaguard® trade name.

Antimicrobial agents can be incorporated into the medium as a surface treatment or they can be formulated into fibers that make up the nonwoven. Foss Manufacturing Co. Inc of Hampton, New Hampshire, USA, has patented a fiber technology incorporating a silver zeolite. The additive can be included in monocomponent and bi-component fibers. The technology is being traded as Fossguard®. Hollingsworth & Vose Co., Inc., East Walpole, Massachusetts, USA, is incorporating this technology in their antimicrobial swimming poll filter medium trade named AquaSure® AG.
Chapter 1 Section 1.7 classified nonwovens by process and presented brief descriptions of each process. More detailed discussions of each process follow.

5.1 Dry Formed

5.1.1 Air laid

The fundamental process for air laying a web is to hammer mill dry pulp fibers into an air stream and deposit it onto a moving collector fabric. The important products of this process are wipes and absorbent materials for hygienic products, incontinence pads, and diapers. The absorbent products may incorporate superabsorbent (SAP) materials to be blended with the fibers. Figure 1.1 of Chapter 1 diagrammed the MTS pilot process for producing air laid products. The web former is a Dan-Web dual head former produced by Dan-Webformin in Denmark. The process also provides fiber metering systems to feed long synthetic fibers to the air laid forming device. SAP powder is added through “dosers” at the forming heads. A latex spray provides for web bonding. The wet resin treated web is dried by a flat bed through-dryer.

Air laid webs can also be bonded by thermal bonding, hydroentanglement, and needle punching. Pittman and Irish\(^{126}\) examined the effects of thermal bonding air laid webs with bicomponent sheath–core fibers.

At one time the air laid process was reported as producing an automotive carburetor air filter for Fram Filters\(^{127,128}\). This product has since been discontinued. The author is unaware of any other filter media produced by the air laid process.

A variation of the air laid process is the use of formers such as the Rando Webber\(^{8}\) to form webs directly from bale opening equipment. Since this is more of a mechanical forming process rather than an aerodynamic process, the Rando Webber\(^{8}\) is included as part of the discussion of dry laid processes in Section 5.1.2.1.
5.1.2 Dry laid webs and felts

5.1.2.1 Forming of dry laid webs

Figure 1.2 (Crook\cite{13}), in Chapter 1 is a layout of a typical dry-laid line. The core of the dry laid process is the card or a related machine called the garnett. Cards and garnetts were originally designed to produce slivers for yarn manufacture. Modified versions were developed for nonwoven manufacture. Figure 5.1 is a diagram of a roller-top card. It consists of a series of rolls coated with spirally wound saw-tooth wire often referred to as metallic clothing. The saw-tooth points are engineered to have specified heights, pitches, and angles. Fiber is carded when it passes between two such rolls (or two metallic clothed surfaces) moving at different speeds. If the points of the metallic clothing are opposite a combing action takes place that parallelizes the fiber. It is not necessary that both metallic coated surfaces be rolls. Generally one surface is the master cylinder roll, however the other could be a stationary surface such as depicted in Figure 5.2.

![Figure 5.1. Chute feed and roller-top card.](image)

Reproduced with permission of TAPPI Press, Atlanta, Georgia USA\cite{13}, p. 160.

Figure 5.3 is a diagram of a garnett. Note the similarity between the garnett and the roller-top card of Figure 5.1. In general, garnetts differ from cards in that they form more randomized webs. They also produce higher loft webs for filter applications. Garnetts are considered as an older technology. More and more of garnett produced products are being replaced by carded webs and felts.

\footnote{Much of the description of the dry laid process presented here is based on a publication by LeGrande Crook\cite{13} and subsequent conversations with Mr. Crook.}
Following are the types of metallic coated rolls found on a card or garnett:

1. **Master cylinder**: The master cylinder is the main roll in a card or garnett. Its function is to transfer the web from one point in the process to the next. It also provides the surface on which other rolls such as stripper rolls and worker rolls can do their work.

2. **Likerin roll**: The likerin roll accepts lap or batting that are condensed from fibers fed from a chute or hopper, opens them into small tufts, and feeds them to the master cylinder.

3. **Stripper rolls**: Stripper rolls have the wire points in the same direction as the master cylinder. They are used to transfer the web from one roll to another.

4. **Worker rolls**: Worker rolls act in conjunction with the master cylinder to do the fundamental carding action. In Figure 5.4 carding takes place between the tangent point of the master cylinder and the worker roll. The stripper roll which has points in the same direction as the worker roll strips fiber tufts from the worker roll and puts the fiber back on the web ahead of the carding plane.
This allows the fiber to be reworked again and again until the tufts are reduced to individualized fibers.

5. *Doffer rolls*: Doffer rolls are used to transfer the web from the master cylinder to a moving bed. They rotate counter to the direction of the master cylinder, although the points are in the same direction.

6. *Condensing rolls*: The carded webs off the master cylinder are very linear in the machine direction. The $MD:CD$ (machine direction:cross direction) ratio of fiber orientation is in the range of 10:1. Condensing rolls work with the doffer rolls to randomize the structure and put more fibers in the cross direction. This is done by using the condensing roll to doff fibers from the doffing roll. The condensing roll runs slower than the doffer roll and rotates in an opposite direction than the doffer roll and in the same direction as the master cylinder. Its wire points are in an opposite direction to both the wire points of the master cylinder and the doffer roll. The transfer action allows the doffing roll to push fiber into the teeth of the condensing roll. The result is a more isotropic web. Figure 5.5 demonstrates the activity between the master cylinder, the condensing roll and the doffer roll.

7. *Randomizing rolls*: Randomizing rolls are high speed rolls inserted between the master cylinder and the doffing roll. The randomizing roll doffs the web from the master cylinder and by centrifugal force transfers the fibers to the doffing roll. Random webs with $MD:CD$ ratios of 4:1 are obtainable with this arrangement.

8. *Fancy rolls*: A roll associated with a garnett used to help produce high loft mats.
In addition to cards and garnets, a dry-laid line will include bale opening machines, blending machines, and machines to feed the cards (or garnets). In a carding line there may be two or more cards as shown in Figure 5.6, each one forming a separate layer that is combined with the previously formed layers. The layering allows for thicker webs and higher grammages.

Cross layering is a process step for producing thicker and heavier webs by lapping them back and forth unto a conveyor moving at a right angle to the cross-layering motion. The cross-layering operation is diagrammed in Figure 5.7. Cross layering or cross lapping is the method of building a web for the needle punching operation described in 5.1.2.3.1.
The process requires a device for forming the final web. This could be the output of the cards or garnetts. There are also air laid formers fed by carded fibers from the cards. A very popular such former is the Rando Webber® produced by Rando Machine Corporation. This device is depicted in Figure 5.8. A variation on the dry laid process is to use bale opening equipment to feed fibers directly to a forming device such as the Rando Webber®.

![Diagram of Rando Webber®](image)

**Figure 5.8. Rando Webber.**
Reproduced with permission of TAPPI Press, Atlanta, Georgia USA (13), p. 164.

5.1.2.2 Bale opening, feeding, and blending
A number of steps are necessary to process fibers on their way to the forming process. This includes bale opening, blending, and feeding. Figure 5.9 is a diagram of the head of a bale opening device called an OPTIMIX® bale opener. It traverses over the top of a lay-down of bales of fiber and picks up the fibers with two opening rolls.

![Diagram of OPTIMIX® head](image)

**Figure 5.9. OPTIMIX® head.**
Reproduced with permission of TAPPI Press, Atlanta, Georgia, USA (13), p. 156.
that create an air vacuum. The picked fibers are aerodynamically guided to a pneumatic plenum and channeled to a blending hopper.

The blending hopper feeds to a blend roll which opens the tufts of fiber and aerodynamically feeds them to a fine opener. The blend roll diagrammed in Figure 5.10 is a Kirschner beater type that has a three lag pin beater. There are also roll type beater rolls, which are fully metallic clothed.

![Blend roll diagram](image)

*Figure 5.10. Blend roll.*
Reproduced with permission of TAPPI Press, Atlanta, Georgia USA, p. 156.

The fine opener is depicted in Figure 5.11. This is a Micro-Tuft Opener (MTO) that uses carding roll principles in further reducing the tuft size. The carding occurs between

![Micro-Tuft opener diagram](image)

*Figure 5.11. Micro-Tuft opener, FS/52, KD condenser.*
Reproduced with permission of TAPPI Press, Atlanta, Georgia USA, p. 157.
rolls A and B and between rolls B and C, all of which are metallic clothed. Depending on
the degree of tuft size reduction required, more openers may be added in line.

Once the fibers are satisfactorily opened, they are fed to the former. There are two
types of feeding devices: a chute feeder and a hopper feeder. A chute feeder called the
MASTERCHUTE® is depicted in Figure 5.12. Opened fibers blown into the transition,
located at the top of the chute are fed into a feed roll and feed plate arrangement.
This arrangement meters the fiber into the nip point of the pin beater roll and feed
plate, which provides for gentle opening of the fiber. Air introduced at this point car-
ries the fiber down into the forming chamber of the chute. A spanker plate at this
point helps to distribute the fiber uniformly and evenly in both the MD and CD direc-
tions. A feed mat of uniform consistency is created to feed the web former.

![Diagram of MASTERCHUTE®](image)

Figure 5.12. MASTERCHUTE®.
Reproduced with permission of TAPPI Press, Atlanta, Georgia USA131, p. 158.

5.1.2.3 Bonding of dry laid webs
5.1.2.3.1 Needle punch
Needle punch webs are the most dominant form of nonwoven used as filter medium.
It is a prominent medium for baghouse filtration operations. Needle punching is a
process by which fibers are entangled and mechanically interlocked by puncturing
the web with a series of barbed needles. The density and strength of the web can be
regulated by the strokes per minute of the web, the advance rate of the web, and the
degree of penetration of the needles. Figure 5.13 is a diagram of the needle felting
operation and of a typical needle.
Figure 5.13. Needle felting and an example of a barbed needle.
Reproduced with permission of Reifenhäuser REICOFIL GmbH & Co. KG Machine Fabric, Troisdorf, Germany.

Figure 5.14. Cross-section through a needle felt showing the scrim and also the fiber re-orientation cause by the needling, at ×6.2 magnification.

Figure 5.14 is a side view photograph of a needlefelt web. The locations of the needle penetrations are quite visible.
Crook13 describes 5 components to a needle loom:

1. Feed apron carries the formed web to the needle punching operation.
2. Bed plate supports the web during the needling action. The bed plate has holes that match the needle pattern.
3. Stripper strips the fiber off the needles if tagging occurs when the needle is withdrawn from the felted web. The stripper is a plate aligned with the bed plate. It also has holes that match the needle pattern.
4. Needle beam houses the needle board and moves up and down to perform the needling action.
5. Draw rolls control the advance rate of the needled fabric in relationship to the strokes of the needle board. These rolls are at the delivery point of the needled fabric.
5.1.2.3.2 Spunlace (hydroentanglement)

Spunlace is the generic terminology for hydroentanglement. The process was first introduced by DuPont in 1973 along with the spunlaced product, trade named Sontara®. Figure 5.15 (Israel et al. 129) is a general schematic of the process. The process uses very fine high velocity jets of water instead of barbed needles to entangle the fibers. The jets are applied from high pressure headers. The header pressures generally range from 0.5 to 2.5 MPa. The jet holes in the headers range from 100 to 120 μm in diameter. The jets are arranged in rows across the header. Spacing between rolls are 3–5 mm. Along each row there may be 30–80 holes per 2.5 cm.

Figure 5.15. The spunlace (hydroentangling) process.
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The process for hydroentanglement involves the following steps:

1. The formation of a precursor nonwoven web.
2. Entanglement of the web with water jets.
3. A vacuum system to remove excess water.
4. Recirculation and filtration of the water.
5. Drying of the web.
6. Wind-up of the web into rolls for shipment or further processing.

The webs may be hydroentangled from one side or two sides. This usually a stepwise, two-stage process where the web is first entangled on one side and then entangled from the other side. Important to the product is the woven support fabric. The design of the fabric will affect where and how the web is hydroentangled. The mesh and structure of this fabric will affect the appearance and physical properties of the web. For example, a coarse mesh support fabric may result in a hydroentangled web patterned with a number of large holes whereas a fine mesh fabric may result in a larger number of smaller holes. It should be noted that the holes in the web are not formed at the holes in the support fabric, but rather at the knuckles created by the fiber intersections of the support fabric.

Other factors that may affect the properties of the hydroentangled web are jet velocity and pressure, web speed, the number of manifolds or headers, and the angle of the jets as they strike the web. The best web properties are not necessarily achieved from a vertical jet strike. Better properties may result if the jets are directed at some angle from the vertical when they strike the web.

Properties of the fiber in the web will affect how well they entangle. Generally soft longer fibers will entangle better than rigid shorter fibers. Thin fibers will entangle
better than coarse fibers. The properties of the web will affect the entanglement performance. Basis weight, air permeability, and fiber orientation are factors that may affect how the web is entangled. Usually the best webs for hydroentanglement will have a grammage of 25–250 g/m² and composed of fibers in the range of 1.5–3.3 denier.

The water recirculation and filtration system is critical to process performance. Depending on jet velocity and the types of fibers, used, there will be some tendency for small fiber segments to break off as “fines”. The fines are in the micron size category and could easily cause plugging of the water jet holes. A very efficient filtration system is required. It can be quite surprising as to how much fines may be generated. If the filtration system is not well designed, early plugging and short filter life will occur.

The sketch of Figure 5.15 indicates a flat hydroentanglement area. There are also units in the market place based on a round configuration. Figure 5.16 illustrates a unit based on Honeycomb hydroentanglement rolls.

![Figure 5.16. Hydroentanglement with Honeycomb rolls. Reproduced with permission of Metso Paper USA Inc.]()
Sächsisches Textil Forschung Institut (STFI) e.V., Chemnitz, Germany has introduced Hycoknit®, a stitch-bonded nonwoven composite, as a depth filter medium. Schmalz et al.\textsuperscript{11,12} report that the product is made in two steps. In the first step a pile stitch-bonded nonwoven with a one loop surface is manufactured. In the second step the one loop surface of pile stitch-bonded nonwoven is compressed by putting a hydroentangled nonwoven on it. The result is a gradient density medium as shown in Figure 5.18. The product is unique in that the fibers of the upper pile surface are oriented in the direction of flow. This is in contrast to conventional filter media where the fibers are generally perpendicular to the direction of flow.

\footnote{Photographs and layout provided by Dr.-Ing. Elke Schmalz of STFI}
5.1.2.3.4 Thermal bonding
Webs containing low melting thermoplastic material can be thermal bonded to consolidate the web. Usually the low melting material is fibers or bicomponent fibers, however thermoplastic powders are used in some applications. Following are some forms of thermal bonding:

1. **Calendering or embossing:** The heated web is squeezed between two rolls (either smooth or patterned) which forces intimate contact of the molten fibers with other fibers in the web. If the rolls are smooth (calendaring), the web is uniformly bonded. If the rolls are patterned, an embossed web results where bonding is most intense in the dense areas of the embossed structure. Embossing results in a softer web. It is also a way of providing spot bonding to the web.

2. **Through air bonding:** The web is thermally bonded by passing the web through an air dryer or heater. This type of thermal bonding results in a bulkier and loftier web. High loft webs used in HVAC (heat, ventilation, air conditioning) filters are often bonded in this manner.

3. **Ultrasonic bonding:** This relatively new technology utilizes high intensity ultrasonic energy to melt and form bonds from thermoplastic fiber. The ultrasonic bonding is like stitch bonding in that it takes place along narrow lines in the web. It is also a way of producing quilted structures.

4. **Hot melt bonding:** A hot melt thermoplastic is extruded unto the web and while still in the molten stage, penetrates and bonds the web.

5.1.2.3.5 Chemical bonding
Chemical bonding involves the use of a chemical binder or resin to bond the web. It should be noted that the author will use the term “resin” as a generic for all chemical binders. Latex binders are a form of resin emulsified in water. Other types of resin forms include dispersions, solution resins and solvent based resins. Latex is the most commonly used resin binder for dry laid webs. Many wet laid products use solvent (hydrocarbon or non-aqueous) based resins. It is implicit in a wet resin bonding process that a drying step follow the application of wet resin to the web. In addition, heat to cure or thermoset the resin may follow the drying step. Following are ways of applying the latex:

1. **Saturation:** To saturate a web with latex binder it is usually applied from a padder, which uses an applicator roll to apply resin from a resin bath. One form of padder is illustrated in Figure 5.19. In this simple mode an applicator roll passes through the bath and coats the resin unto the web as it passes through the squeeze rolls. The squeeze rolls force the resin to the interior of the web and helps achieve uniform depth bonding.

   Another form of saturator is an impregnator, which immerses the web into the resin bath prior to the squeeze rolls. The squeeze rolls serve to remove excess resin from the web. This method of application assures a uniform resin

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1 See Chapter 4, Section 4.4.1.1 for a discussion of solvent based phenol-formaldehyde resins.
distribution through the depth of the media. However, the web pick-up is far greater than other application methods such as padding. This forces a more dilute resin mix to achieve the desired web resin content. The more water, that has to be removed in the drying process, results in higher energy costs and possible lower production rates.

2. **Spray bonding**: Spray nozzles are used to spray chemical binder onto the web. Spray bonding is an effective way of bonding very thin webs or for low strength webs where bulk is desired. However, for thick webs the process becomes inefficient because of the difficulty of the sprayed resin droplets to penetrate into the interior of the web.

3. **Gravure bonding**: A gravure press is used to apply liquid binder to the web. The press roll is patterned to hold a fixed volume of liquid that is applied to the surface of the web. For saturated products squeezing and resin migration into the web is required. In many applications two gravure rolls are necessary: one to apply resin to the bottom surface of the web and the other to apply it to the top surface.

4. **Spot bonding**: Gravure presses and rotary screen printers are used to apply resin to specific areas of the web and leave other areas unbonded. It is a way of providing strength to a nonwoven structure and still leave a bulky or lofty structure between bond points. The process is most often used for wipes; however it has application for media used in filter bag applications.

5. **Foam binder application (foam bonding)**: Surfactants are applied to a latex so that it can be agitated to a stable froth or foam. The latex is applied as foam to the media. One method of applying the foam is from a padder similar to the one depicted in Figure 5.19. Another method of application is to apply the foam from an applicator to the top side of the web and use a vacuum suction device from underneath the web to pull the foamed latex into and through the thickness of the web. The vacuum force also serves to collapse the foam bubbles.

6. **Curtain coating**: In this method of application the resin overflows from a reservoir and down an inclined flat surface. It then flows unto the web as a thin film or curtain. For web saturation, vacuum suction devices underneath the web may be necessary to pull the resin through the web.
5.1.3 Spunbonded webs

Jirsák and Wadsworth\textsuperscript{11}\textsuperscript{11} define the spunbond process as consisting of the following integrated operations:

1. Polymer melting, transportation of polymer melt, and filtration of polymer melt.
2. Filament extrusion.
3. Filament drawing.
4. Filament deposition.
5. Bonding.

The types of polymers used in the spunbond process include polyester, polypropylene, nylon, and any other polymer that can be considered as a fiber forming polymer. Flash spinning is a variation of the spunbond process in that the polymer is spun from a solution rather than a hot melt. High molecular weight polyethylene is used in this process to produce the spunbond known as Tyvek®.

A schematic of the REICOFIL system developed by Reifenhäuser GmbH of Germany is presented as Figure 5.20. Figures 5.21a–p are a pictorial displaying parts of a REICOFIL spunbond line, sequenced to illustrate its operation\textsuperscript{5}.

The process begins with polymer, in either powder, granular, or pellet form, that is pneumatically conveyed from its container through a long hose into the dosing

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\textsuperscript{1} A thorough discussion of both spunbond and melt blown processes by Malkan and Wadsworth\textsuperscript{11}\textsuperscript{11} is be found in "Nonwovens: Theory, Process, Performance, and Testing", Albin E. Turbak editor, TAPPI Press, 1993 Chapter 8: Polymer-laid Systems. Page 171.

\textsuperscript{5} A 30-in. wide version of this process is used as a research pilot machine by TANDEC (Textile and Nonwoven Development Center) at the University of Tennessee in Knoxville, Tennessee.
Figure 5.21. Parts of a REICOFIL spunbond line

Reproduced with permission of Reifenhäuser, REICOFIL GmbH, Germany.

Pictures provided by Hans-Georg Geus, Reifenhäuser, REICOFIL GmbH, Germany.
Figure 5.24. Continued
system vessel of Figure 5.21a. The vessel is an air-solid separator. The pneumatic air carrying the polymer is exhausted to a vacuum pump through a tube at the top of the vessel. The heavier polymer gravity settles to the bottom of the vessel and into the hopper depicted in Figure 5.21b. The hopper is a water-cooled vessel that feeds the polymer into the throat of the extruder. After a run, a hot air tube feeds hot air into the hopper to clean out any residual polymer. The extruder depicted in Figure 5.21c contains four heating zones. A schematic of an extruder is diagrammed in Figure 5.22. Inside the extruder is a rotating screw shaft that forces the polymer through the heating zones. The polymer is in a molten state by the time it reaches the filter screen inside the screen changer of Figure 5.21d. The filter screen removes solid contaminants from the molten liquid polymer. The molten polymer is then forced into the die block by the gear pump (often referred to as a spin pump) of Figure 5.21e. Figure 5.23 is a schematic of the gear pump mechanism.

![Schematic of an extruder](image1)

*Figure 5.22. Schematic of an extruder.*

![Schematic of a gear pump](image2)

*Figure 5.23. Schematic of a gear pump.*
Reproduced with permission of TAPP! Press Atlanta, Georgia, USA(4), p. 173.
The die block has two critical components: the polymer feed distributor and the spinnerette. The purpose of the distributor is to provide for a uniform feed of polymer across the entire block. The distributor balances both flow and residence time across the width of the die. Two types of distributors that have been employed in the spun-bond process are T-type (tapered and untapered) and coat hanger-type. The coat hanger-type is referred to as a coat hanger, because the parabolic shape of the wall around the distributor chamber looks like a coat hanger. Figure 5.29 depicts a coat hanger distributor. Although the one depicted is used in a melt-blown line, the configuration is very similar to those used in spunbond lines.

The spinnerette is the underside of the die block as depicted in Figure 5.21 g. It is a block of metal containing thousands of holes. The one at TANDEC has 4036 holes which are 0.6 mm in diameter. The holes are usually circular, however they can also be rectangular. The forming of filament fibers from the molten polymer forced through the spinnerette is shown in Figure 5.21 g. The filaments or die formed fiber are shown in Figure 5.21 h as they travel through a long, vertical, enclosed chamber (generally 30 feet or longer). Airflow is forced through the chamber by a vacuum suction device underneath the web collection belt at the bottom of the chamber. A lot happens to the fibers as they travel through the chamber. First they are rapidly cooled by a cross flow of cold quenching air. The cross flow of air also creates a disorientation and randomization of the filaments. This is apparent in the forming filaments of Figure 5.21 g. This is the first of two air-cooling zones. It is the primary zone, just below the spinnerette, that quenches the filaments with conditioned air. Below the primary zone is an auxiliary zone that blows a stream of room temperature air.

Several feet below the quench zones, the filaments are sucked through a pneumatic venturi that accelerates the filament flow and draws the fibers. The venturi chamber is depicted in Figure 5.21 j and k. The venturi consists of steel plates extending across the machine. Figure 5.21 j and k only show the edges of these plates. A better perspective of the venturi structure is shown in Figure 5.24. The angle and relative location of the plates can be adjusted to optimize the flow conditions through the venturi. The rotary wheel handles depicted in Figure 5.21 j are used to make fine adjustments. In operation, the filament fiber coming down from the spinnerette is funneled through the converging plates of the venturi shown in Figure 5.24 and necked into the narrowed gap between the plates. On either side of the converging plates is a second set of converging plates forming an annulus through which air is introduced. The air merges with the filament flow and carries it into the distribution chamber beneath.

The air in the distribution chamber becomes turbulent and causes fanning and entangling of the filaments. The randomness of the web is greatly affected by the turbulence. The entangled fibers are then suction deposited onto a foraminous belt collector to form the web. The formed web is carried by the belt as it moves more or less horizontally between two support rollers. The entangled filaments lay down on the belt more or less vertically. They leave the web-forming zone with the belt and pass underneath a contact roll. Figure 5.21 m shows the exit side of the contact roll. The roll serves to consolidate the web and provide a seal to the negative-pressure forming zone.
The formed web is passed through heated calendar rolls to densify and bond it (Figure 5.21n). The heated web is transferred around a chiller roll (Figure 5.21o) and then to the winder.

In addition to the REICOFIL® system described above there are other producers or licensers of spunbond lines. Lurgi Kohle & Mineralotechnik GmbH of Germany developed the Docan® system which like the REICOFIL® system is based on melt spinning. Another melt spinning line is the Lutravil® system developed by Carl Freudenberg Co. of Germany.

Mentioned above is the DuPont flash-spun system that produces the high density polyethylene web known as Tyvek®. SoloFlo® is a DuPont filter medium based on the flash spun technology.

A developing variation of the spunbond process is the Nanoval® process which splits the molten or liquid filament out of the spinnerette into a multitude of finer fibers. The splitting of polyester (PET) filaments is depicted in Figure 5.25. Dr. L. Gerking, President of Nanoval GmbH & Co. KG, Germany reports that the Nanoval® process is capable of splitting spunbond fibers down to a range of 0.7–4.0 μm which is approaching the capability of melt-blown fibers. He also reports the process works

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7 Photograph provided by Chris Eash of TANDEC.
with solution polymers as well as molten polymers. Cellulose polymers such as lyocell can be converted to filament form by this process.

5.1.4 Melt-blown webs

A schematic of the melt-blown process is diagrammed in Figure 5.26. The line as diagrammed is blowing the fibers in a horizontal path to the collector. Commercial lines with vertical fiber flow are also in operation.

The key difference between the spunbonded process and melt-blowing is in the die assembly. In the melt-blown process hot air converges with the fiber as it emerges from the die, whereas in the spunbond process the hot air flow is at a cross flow to the emerging fiber. The converging flow of the melt-blown process, diagrammed in
Figure 5.26. The melt-blowing process.
Reproduced with permission of Dr. Randall R. Bresee, University of Tennessee, Knoxville, Tennessee, USA.

Figure 5.27. Airflows in the melt-blowing process.
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The collage of Figure 5.28 is a photo display of the 6-in. pilot melt-blowing line at TANDEC, University of Tennessee. The process starts with polymer in the form of pallets, granules, powder that is poured into the hopper of Figure 5.28a. From the hopper the polymer gravity drops into the feed throat of the extruder. Inside the extruder is a rotating screw shaft that forces the polymer through three heating zones that melts the polymer. The extruder is shown in Figure 5.28b. The operation of the extruder is similar to the one diagrammed in the schematic of Figure 5.22. In the case of the TANDEC pilot machine, the extruder provides sufficient pressure to force the molten polymer flow through the screen, through the die assembly and as

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fiber unto the collector. The screen changer is shown at the end of the extruder in Figure 5.28c. From the screen changer the polymer feeds into the back of the 6-in. die assembly, also shown in Figure 5.28c. The screens serve to separate solid contaminants and unmelted chunks from the molten polymer. There are two screens, so that when one becomes filled, it can be hydraulically removed from the polymer flow stream and the other one inserted in place.

The distributor to the die assembly is a parabolic coat hanger type similar to the one used in the spunbond line discussed above. The parabolic shape is evident in Figure 5.29, a photograph of the coat hanger taken during line disassembly for cleaning. Polymer enters from the feed pipe, at the top of the device, and exits through the melt-blown die at the bottom. The coat hanger configuration provides for even polymer distribution across the die.

Video stills and pictures provided by Chris Eash of TANDEC.
Figure 5.29. Coat hanger distributor for the TANDEC® melt-blown line.
Reproduced with permission of Dr. Larry Wadsworth, TANDEC, University of Tennessee, Knoxville, Tennessee USA. Picture provided by Chris Eash of TANDEC.

Figure 5.28d shows the front of the die assembly where the fibers emerge. On both sides of the die, insulated piping can be seen. The insulated piping feeds hot air into two manifolds which are the pipe-like structures seen above and below the die opening. The manifolds regulate the high velocity streams of hot air that converge with the forming fibers as shown in Figures 5.26 and 5.27. Typical hot air temperatures are 215–340°C. The air velocities through the air channels above and below the polymer feed die openings range from 0.5 to 0.8 times the speed of sound.

There are two types of die nosepieces: capillary type and drilled hole type. These are pictured in Figure 5.30. Capillary openings are actually slots that are milled into both sides of the flat mating surfaces that form the die nosepiece. This is shown in the top diagram (a) of Figure 5.30. The bottom diagram (b) illustrates the drilled hole types. The die holes are either mechanically drilled or drilled by electrical discharge machinery (EDM).

During processing, the entire die assembly is heated to 215–340°C in order to produce uniform defect-free webs. Figure 5.28e shows the newly formed fiber emerging from the die on its way to the collector (Figure 5.28f). The fiber emerging from the die is traveling from left to right whereas the collector is pictured from the other side of the machine so that the fiber approaching it in Figure 5.28f is coming from the right. The metal drum collector in Figure 5.28f, is rotating counter clockwise.

The melt-blown process is a major process for producing nonwoven filter media. The major development areas for the process are webs with finer fibers for greater filtration efficiency and webs containing bi-component and multi-component fibers. With respect to the latter, Hills Inc. of West Melbourne, Florida has developed proprietary melt-blowing technology to produce mono-component, bi-component and multi-component fibers with the following types of cross-sections:

- Homopolymer
- Side by side
- Sheath/core
- Pie segments
- Islands in a sea.
A detailed discussion of bi-component and multi-component fibers is presented in Chapter 4, Section 4.3.5.4.2.

5.1.5 Electrospun webs

In 1934, Anton Formhals was the first inventor to patent an electrospinning phenomenon. Electrospinning is a process that produces nanofiber webs by applying a high voltage charge to a polymer solution or melt and using the charge to draw the solution from the tip of a capillary to a grounded collector. Figure 5.31 is a schematic of the process. Voltages range from 5 to 30 kV, sufficient to overcome the surface tension forces of the polymer. The polymer is fed from a pipette or syringe type device containing a metallic tip. The free surface of the charged polymer produces very fine jets of liquid that are rapidly drawn to the grounded collector. The jet extends in a straight line for a certain distance and then bends and follows a looping and spiraling path. The effect causes substantial drawing of the rapidly solidifying fibers as they approach the grounded collector. The collector may be a flat plate as shown in Figure 5.31 or it may be a rotating drum or a moving belt. The highly attenuated fibers may collect directly on the collector or they may collect on a moving substrate passing over the collector to form an interconnected web of small filaments. The fiber diameters for filtration purposes are in the range of 0.25 μm. Since the webs are of very fine thickness (on the order of one micron or less) and since they have limited mechanical properties, the
moving surface on which they are collected is usually a substrate that will provide strength and stability for subsequent processing. Very often the substrate will be a nonwoven chosen specifically for the filtration application. Figure 5.32 is a scanning electron microscopic (SEM) image of a nanofiber web on a cellulose substrate.

There are a number of polymeric materials that used for electrospun nanofiber production. Donaldson Company uses nylon in their Spider Web® and Ultra web® media. Schreuder-Gibson and Gibson(136) in their discussion of electrospun nanofibers for aerosol filtration conducted experiments with polyurethanes and Nylon 6. Formhals(15) conducted his studies with cellulose esters. Choi et al.(137) created electrospun nanofibers from silica using a sol–gel process.

5.2 Wet Lay Process

A wet lay process can be divided into two parts: the wet end and the dry end. The wet end is concerned with mixing fiber and water into an aqueous dispersion or slurry called stock and filtering the dispersion through a moving screen, called a Fourdrinier wire, and thereby forming a wet nonwoven sheet. The dry end uses various forms of mechanical and thermal devices to remove water from the formed sheet and to present a dry sheet at the end of the machine. In simplistic terms, the wet end puts water into the fiber and the dry end takes it out. In reality, there is a lot more going on than just putting water into the fiber and then taking it out.
In the wet end, additives other than fiber may be added to the stock as necessary for processability, product performance, and product quality. The wet end will include devices such as screens and cyclic cleaners to remove impurities and contaminants. Refiners will do work on fibers to help achieve the desired properties of the finished product. The water hydraulic system before and into the former has to be very seriously managed to insure proper dispersion of fiber and formation of a uniform web.

In addition to removing water, the dry end provides for various forms of mechanical, chemical, and thermal treatments necessary for the performance of the web in its filtration application. Mechanical treatments may include wet pressing, corrugating, embossing, calendering, and hydroentanglement. Chemical treatments will include application of resin binders and other additives. Thermal treatment will include the control of cure on thermosetting and crosslinking resins.

5.2.1 Forming of wet lay webs

The wet lay process starts with a furnish, the papermakers term for the recipe of fibers and ingredients that are used to make the products of the wet lay process. The ingredients are added to water in a dispersion vessel called a pulper. Slurry so formed is called stock which is fed to wet lay machine. On the way, the stock may encounter several types of processing steps. These may include refining or fibrillation of the fibers to help them bond better, cyclic cleaning which uses devices that cycle the stock in a centrifugal manner to remove high density (or very low density) contaminants and screens to remove large contaminants. The stock flow and its consistency (bone dry
solids or fiber content) is precisely controlled to assure the targeted grammage. The stock is diluted with additional water just before it is pumped to the headbox of the paper machine.

Just as the card is the heart of the dry laid process, the headbox is the heart of the wet lay process. The headbox is a hydraulic device that maintains a uniform suspension or dispersion of fibers in the slurry and spreads the flow out evenly into a moving screen called a Fourdrinier wire. The Fourdrinier headbox is the traditional papermaker’s headbox. It is diagrammed in Figure 5.33. This type of headbox sends the slurry from a pond through a long, narrow, horizontal opening, called a slice. A horizontal layer of aqueous slurry, 25–100-mm thick, is formed on the moving Fourdrinier (forming) wire. The layer of slurry spreads out over the wire and drains through it. The fibers in the slurry are filtered by the wire and form a wet laid sheet on the wire surface. The headbox former as illustrated in Figure 5.33 is rather old fashioned, however it provides a baseline for comparison to formers that are used for forming long fibered wet lay nonwovens.

![Figure 5.33. Fourdrinier headbox.](image)


The traditional Fourdrinier machine is used to produce some types of paper filter media including high efficiency microglass fiber HEPA and ULPA (high efficiency particulate air and ultra low penetration air) media. However, nonwoven media, that are produced from synthetic fiber and from difficult to disperse furnishes, are produced at higher levels of dilution and on headboxes specially designed for this purpose. Two of
the most common are the Rotoformer® headbox and the Inclined Wire (Deltaformer®) headbox. Both are produced by Glens Falls Interweb, Inc. (GFI) of Glens Falls, New York. They are depicted in Figures 5.34 and 5.35, respectively. Voigt Dorries in Germany also produces an inclined wire machine called the Hydroformer®. The Rotoformer® forms
the sheet on a fabric covered rotating drum, whereas the inclined wire forms the sheet on the incline of the forming fabric as it passes through the pond. Notice both differ from the traditional Fourdrinier headbox of Figure 5.33, in that the web is formed on the forming fabric within the continuum of the pond. The pressure head of water over the forming area can be as high as 100 cm. In the traditional Fourdrinier, formation takes place on the forming fabric after the slice. The gravity pressure head of water on the forming fabric can be no higher than the 25–100 mm width of the slice.

The inclined wire and Rotoformer® machines form the sheet on the incline of the forming fabric (straight incline for the inclined wire and circular incline for the Rotoformer®). Suction boxes underneath the forming fabric enhance the flow of water through the forming area. The inclined wire and Rotoformer® headboxes handle much more water per inch of width, than traditional paper machines. They are better suited for the low consistencies necessary for handling the longer fibers of a nonwoven web. The headboxes operate at much lower consistencies than do traditional paper machines. Traditional paper machines operate at consistencies in the range of 0.3–0.8%. The wet lay nonwoven machines can operate at consistencies below 0.1%, or at whatever is necessary to get good dispersion of the fibers.

Note from Figures 5.34 and 5.35, both the Rotoformer® and inclined wire machines have a pond regulator (sometimes called a boat slice) that acts like a slice. These usually come with adjustable controls for vertical, horizontal, and tilt positions. This device controls formation, fiber orientation, and other web properties. Figure 5.36 diagrams a more up to date version of the Deltaformer® produced by GFI. The pond regulator is replaced with a hydraulic headbox so that the pond is closed and pressurized. Note there is no overflow dam. The overhead wall can be adjusted to regulate the pond in a fashion similar to the pond regulator.

![Diagram of Inclined Wire (Delta Former®) with Hydraulic Headbox](image)

**Figure 5.36. Inclined wire (Delta Former®) with hydraulic headbox.**
Reproduced with permission of Glens Falls Interweb, Inc. Glens Falls, New York, USA.

Figure 5.37 is “Rotoformer® 2000” that has been introduced by GFI. The headboxes of most paper machines as well as nonwoven wet laid machines are fed by a tapered header designed to provide a uniform flow into the headbox. The “Rotoformer® 2000”
replaces the tapered header with a radial distributor (sometimes referred to as an octopus header). This device provides a way to obtain more uniform basis weight profiles in the cross-direction of the web.

The Herty Foundation in Savannah, Georgia has a combined Rotoformer®--inclined wire pilot machine. Figure 5.38 is a photograph of the machine. The sides have been
removed to better show the forming areas. It is so designed that pilot trials can be run on either the lower headbox (the Rotoformer®) or the upper headbox (the inclined wire).

### 5.2.2 Drying of wet lay webs

Once the wet lay sheet is formed a lot happens to it on its way to the windup reel. Most of this is concerned with removing water and drying the sheet. Mechanical devices such as wet presses and suction slots are often used. However, at best these can only get the moisture content down to 50–60%. Most wet laid filter media are not wet pressed, because the wet pressing action densifies the sheet and makes it less bulky.

The rest of the water has to be removed by thermal drying. This can be in the form of steam heated can dryers, hot air dryers, infrared devices, microwave heating, and usually some combination thereof. Steam heated can dryers as illustrated in Figure 5.39 and hot air dryers are the most common means of drying a wet laid nonwoven. For filter media hot air is preferred, because it allows for a bulkier structure. Hot air dryers can operate either by impingement air or by through-air drying. Most often the air dryer is a long, straight, flatbed dryer. The dryer may be sectioned for different levels of drying and for possible curing of the resin in the web. Metso Paper USA, Inc. produces the Honeycomb roll® that is often used for through-air dryers.

![Figure 5.39. Two-tier cylinder drying configuration.](image)

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Dryer felts are woven fabrics that assist in the thermal drying process by pressing the wet web against the surface of the dryer can. They are porous enough to allow for the escape of moisture. They also make it easier for web handling over the dryer cans and allow for easier threading of the machine at start-ups. The pressure on the web between the felt and dryer surface does compress it, resulting in less bulk. For this reason some wet lay filter mills will operate without dryer felts, even though this results in far less efficiency in the thermal drying operation.
5.2.3 Bonding of wet laid nonwovens

Wet laid nonwoven webs can be bonded in both the wet and dry ends of the wet lay machine. Wet end bonding can take place by hydrogen bonding of cellulose pulp fiber webs, by refining the pulp, and/or by adding a bonding agent to the fiber slurry before the web is formed (often referred to as beater addition or beater-ad). The availability of low melting polymer fibers and/or bicomponent fibers is making the thermal bonding option more attractive. The thermal bonding fibers are part of the fiber furnish. Wet end bonding mechanisms whether they are wet strength resins, beater-ad latexes, or thermobonding fibers will require dry end heat to become effective. To illustrate, wet strength resins are thermosetting and have to be heat cured to become effective. Thermal bonding fibers have to have sufficient heat to melt the thermoplastic component.

Dry end bonding of wet lay webs is mostly accomplished by some form of chemical treatment. Most wet lay filter media, even when resin treated in the dry end will have some form of applied wet end bonding mechanism. For example, a medium to be dried and then treated with a latex X will usually contain a wet strength agent to hold the web together as it is wetted out with the aqueous resin.

5.2.3.1 Wet end bonding

(a) Hydrogen bonding: Cellulose pulp fibers in water bind to each other in a chemical mechanism known as hydrogen bonding. It is the fundamental bonding mechanism in the making of paper. Most wet laid nonwovens contain some percentage of cellulose pulp to provide strength and integrity to the web for downstream processing.

(b) Wet end binders: Several types of resins or chemical agents can be added to the fiber slurry or stock to enhance the strength properties of the web. Most often, these are cationic agents attracted to the negatively charged anionic fibers. If the additive is a latex binder, a complex system of retention aids is used to retain the latex particles on the fiber surfaces. Similar chemistry can also be used to retain solid fillers such as clays and activated carbon powder. Cationic wet strength agents are the most frequently used wet end additives. They serve two functions: one is to give the media enough strength to be transported through the wet lay machine and through subsequent aqueous treatments. The other is to make the medium strong enough to stand up to an aqueous filtration application. Sheeted filter media used in plate and frame industrial filtration applications are often referred to as high wet strength filter paper. Coffee filter paper is another example of filter media bonded with a wet strength agent. Common types of cationic wet strength agents are urea formaldehyde and melamine formaldehyde. Polyamide-epichlorohydrin, PAE, is a very popular wet strength agent because it does not emit formaldehyde fumes when the web is dried. Hercules, Inc markets PAE wet strength agents under the trade name of Kymene®.

(c) Binder fibers: can also be added. This includes polyvinyl alcohol type fibers such as Kuralon® and low melting thermobonding fibers. Bicomponent sheath–core fibers with a low melting outer core are often employed for this purpose.

\(^{10}\)Kuralon® is a trade name of Kuraray Co., Ltd., Tokyo, Japan.
5.2.3.2 Resin application to the web

Most wet laid nonwovens used for filter medium applications are resin treated after the web is formed. The resin treatment is intended to provide the desired structural properties so that the web can be converted to the end use filter application and have the integrity to stand up to the hostile challenges of the filtration environment.

Resin can be applied to the web either in-line or off-line. Either way, the most common form of resin applicator is the size press. There are many versions of size presses. Two of the simplest types are depicted in Figure 5.40. The top diagram is a vertical size press, the bottom is a horizontal size press.

In the vertical size press operation, the web passes underneath a bead roll and then through a set or press rolls where the resin is applied. The bottom roll is the applicator roll whose bottom is below the liquid resin level in the resin pan. The applicator roll applies the resin to the base web as it passes through the nip between the applicator roll and the press roll. The press roll applies pressure to force the resin to penetrate and impregnate the web. Resin pick-up by the base web is controlled mostly by the resin solids in the resin bath and less so by the applied nip pressure. It is the intent of this operation to fully saturate the web with resin.

The horizontal size press is depicted at the bottom of Figure 5.40. The rolls of this configuration are along a horizontal line. Sometimes the two outside rolls (metering rolls) are at 45° with the horizontal. There are two applicator rolls, two metering rolls.
and two resin baths. The metering rolls act to fix the film thickness of the resin on the applicator rolls. In the configuration shown in Figure 5.4, the base web is traveling downward through the nip between the two applicator rolls. The applicator rolls pick up resin by rotating through the resin bath. The surface of the metering rolls move contrary to the surface of the applicator rolls, thereby shear off the excess resin on the applicator rolls. The nip between the two applicator rolls is not a pressure nip. It is gapped at some distance that is close enough for both applicator rolls to touch the web and apply resin. The resin is coated on the base web. The ability of the web to become fully impregnated depends on how well the resin can migrate to the web interior. This depends on the capillary properties of the webs fiber structure and the viscosity of the liquid resin mix.

The gap between the metering roll and the applicator roll is adjustable so that the film thickness can be varied. This provides for two levels of control on resin pick-up; solids content of the liquid resin bath and film thickness. The advantage of controlling resin pick-up by film thickness is that it is much quicker than trying to make changes to the solids content liquid resin bath. Controlling by film thickness and applying resin to both sides of the base web allows for liquid resin to be applied at higher solids content than the vertical size press. This reduces energy costs in drying and may allow for higher production rates. It also reduces solvent costs if the resin is being applied from a solvent base.

There are other types of applicators for saturating a wet laid web. These include gravure presses, spray systems, foam bonding, and curtain coaters.

5.2.4 Converting processes for wet lay webs

Wet lay media are subject to a number of converting processes as necessary for its end use filtration performance. These include corrugating, slitting and rewinding, creping, sheet cutting, die cutting, pleating, bag making, and other operations that alter the mechanical structure and geometrical surface of the web. In addition, chemical treatments other than resin are applied to the web. This includes flame retardants, water repellents, surfactants, electrostatic treatments, adsorbents, antimicrobial agents, etc.

5.2.4.1 Corrugating

Corrugation is accomplished by embossing the web between the two corrugating rolls of a corrugating press. The press embosses a sine wave configuration across the web. Figure 5.41 is a photograph of a sample of pleated media with the corrugations very evident. The corrugations are in the machine direction of the sheet. The corrugating rolls are ridged so that there is a sine wave configuration to their surfaces. The rolls are set up so that when they are brought close together the ridges mesh; hill into valley. When a sheet is transported through the nip, the pressure forces the sheet to take on the corrugated cross-section. The photograph of Figure 5.42 shows this as the corrugated medium emerges from the nip of the corrugating rolls.

The corrugating effect is to densify the sheet in its thickness and stretch it in the cross-section. The degree of corrugation is limited by how much the media can be stretched in the cross direction before cracking and tearing. For cellulose media used in engine filtration applications, the stretch is approximately 4% depending on furnish and resin treatment. Densification of the sheet by corrugation causes a loss in permeability. This is somewhat compensated for by the gain in surface area.
For the medium to be corrugatable, it has to be very plastic. Wet lay media is corrugated after the resin has been applied, but before they are fully dried. The volatiles content of the sheet at the corrugating press is 5–20%, whether it be water or organic solvent. The sheet is usually preheated prior to corrugation in order to utilize the thermoplasticity of the resin system. There are cases where the fully dried sheet is corrugated. This can only be done with a low melting thermoplastic resin. The degree of corrugation varies, depending on the resin and the nature of the fibers making up the medium. Basis weight and thickness are important properties that affect the medium’s ability to be corrugated. The corrugation generally ranges from 200 to 400 μm. The maximum achievable on a consistent production basis is 500 μm.

Dense structures such as those used for heavy duty air filter are easier to corrugate than bulky media. Media composed of glass microfibers are very difficult to corrugate because the fibers are so short and the media have very little stretch. Media containing a high percentage of polyester do not corrugate as well as pure cellulose media. The long fibered polyester allows the media to corrugate without cracking, however they do not readily mold to the sine wave mesh of the corrugating rolls.

5.2.4.2 Creping
Some industrial filter medium grades and some vacuum bag grades are creped to increase the surface area for filtration. Generally creped paper is perceived as being tissue creped off of a Yankee dryer – a large cylindrical dryer used for making tissue. Very few wet lay machines (if any) that produce filter media have Yankee dryers. Usually the
creping is done in some form of press rolls (wet press or size press) by pushing the medium against a creping doctor so that the medium bunches up against the blunt edge of the doctor as shown in the possible arrangement of Figure 5.43. Machine speed downstream of the creping doctor and the creping press roll is reduced so as not to pull out the crepe.

5.2.4.3 Rewinding and slitting
At the end of the wet lay process is a reel. The reel winds up the finished paper on cores and into jumbo rolls. The jumbo rolls are then sent to a rewinder where the
rolls are rewound into uniform rolls of a specified diameter. The rewound rolls may be trimmed jumbos and/or split rolls for later processing on a slitter, or finished rolls for the customer. The rewinder can also be used for other purposes such as combining different media into a composite laminate.

Very often, rolls off the rewinder are sent to a slitter to be slit into finished rolls for the customer. A slitter is a form of rewinder that contains rotary cutting blades to slit the jumbo roll into specific roll widths as specified by the customer. A slitter contains a number of rotary cutting blades so that multiple rolls can be cut with each cutting. The blades are set at very carefully measured distances to insure that each roll is cut to the customers’ tolerances. Modern slitters have mechanized computer control to set the cutting blades for accurate slit widths. Slitters can custom cut a roll to widths ranging from 2.5 cm to approximately 250 cm (if the machine is wide enough). The maximum practical width is usually based on the trailer size of the truck that will be transporting the rolls to the customer. Wider rolls are usually ordered by a customer who does his own slitting to allow more flexibility in his production schedule.

Rewinding and slitting are critical parts of the wet lay process because it is where most of the waste occurs. The largest cause of waste is the trim, the extra width of paper in the jumbo roll that contains the deckle edge from the paper machine. Generally a mill will allow for approximately 1.2–2.5 cm of trim on either side of the jumbo. Some wet lay machines are 200 cm or less. For such machines the trim waste can be as high as 3%. This is further complicated by the customers order. Although wet lay machines have flexibility in adjusting the deckle width at the former, they are committed to the width for which they are designed. If the finished rolls do not trim the machine deckle then there may be considerable excess trim. To illustrate, the machine deckle width is 200 cm and the customer orders 60 cm wide finished rolls.
The machine can produce media wide enough for three roll cuts totaling 180 cm. This leaves 20 cm of the 200 cm deckle that has to be trimmed, either at the former, at the slitter, or at some other suitable place in the process. Usually the trim can be recycled however there is a loss in production rate.

There are a number of issues that increases waste because of quality rejections. The most serious of these is slit width variations. The roll as shipped to the customer is too narrow or too wide for the customers operation. Mills can do a good job of measuring and controlling slit width at the slitter; however, they have little control of the environment and its effect on dimensional change when the rolls leave the mill.

5.2.4.4 Stamping and dye cutting
Filter sheets and industrial filter paper produced for industrial filters such as filter presses have to be carefully cut to sizes and shapes that fit the filter. The shapes are die-cut or stamped in converting mills dedicated to this purpose. Die-cutting is like using a cookie cutter. A die-cutting machine uses steel rule die shapes to cut through a wide range of filter materials quickly and easily. A typical converter may have a library of over 200 dies to handle a large variety of customer orders.

5.2.4.5 Bag making
There is a huge variety of filter bag and pocket filter operations, many of which are very proprietary. Among the steps in a bag filter operation are folding, sewing, gluing, trimming, shaping, and packaging. If the bag is to be used for a medical or food processing filtration and separation, then there are also hygienic issues in process control and packaging.

A variation of bag filters is pocket filters. Pocket filters are pleated media with pleat edges sealed so that each pleat fold becomes a pocket.

5.2.4.6 Pleating
It is estimated that over 80% of resin treated filter paper production will go to a customer’s pleating line. Pleating lines have been adapted to pleat dry formed filter media as well as wet laid media, including composite structures and media supported by a support structure such as a metal wire mesh screen. A detailed discussion of the pleating process is presented in Section 5.4.

5.3 Composite Structures

Composite structures were defined in Chapter 1, Section 1.4.8 as the “Two or more different web technologies that are combined to optimize the characteristics of a filter media”\textsuperscript{11}. There are several ways of combining web structures. Unique ideas for new ways are constantly emerging. Following are brief descriptions of some of the processes for producing composite structures.

\textsuperscript{11} R.W. Murphey – personal conversation
5.3.1 SMS process

US Patent 4,041,203 (1977) assigned to Kimberly-Clark Corporation describes a product obtained by combining "an integrated mat of generally discontinuous, thermoplastic polymeric microfibers and a web of substantially continuous and randomly deposited, molecularly oriented filaments of a thermoplastic polymer". It is recognized that the microfiber mat was a melt-blown and the continuously filament web was a spunbond. Bonding of the layers was accomplished by passing them through a set of heated rollers: one of which was smooth and the other containing a plurality of raised points so that the bonding effect was patterned and in discrete points. In one embodiment of this invention the melt-blown web is sandwiched between the two spunbond webs so as to form what is now known as the SMS (spunbond/melt-blown/spunbond) composite. In the example, the inventors (Brock and Meitner (1977)) note that the composite has "especially desirable strength characteristics".

5.3.2 Multi-ply forming

Some forming processes are capable of forming multi-layered media. Carding lines with successive carding machines are certainly capable of doing this. Some wet lay machines are capable of forming dual-ply and triple-ply media. Ahlstrom uses a three-ply machine to produce a three layered filter medium composite identified as their Trinitex® technology.

5.3.3 Laminating

The simplest way to form a composite structure is to combine two or more layers of media in a laminating line. The layers are glued to each other by latex adhesives or hot melt glues. In some cases Van der Waals forces or electrostatic attraction is sufficient to hold the layers together for the intended downstream processing. Sometimes the different layers come off separate unwind stands and are then wound together on a wind-up stand.

5.3.4 Entanglement

Hydroentanglement, needle punching and stitch bonding are other ways of combining the individual layers. Lang and Schmalz (138) described a nonwoven composite structure consisting of two nonwoven webs that were hydroentangled with a scrim material. The scrim material is sandwiched between the two nonwoven webs. The process concept is illustrated in Figure 5.44. The scrim material, usually a woven textile material, provides for improved strength. The product has been developed by Jacob Holm industries GmbH, Germany. It is marketed under the tradename of Norafin®.

5.3.5 Collectors

In some cases, one nonwoven layer serves as the collector for forming another type of nonwoven layer. Nanofiber webs from the electrospun process are usually formed this way.
5.4 The Pleating Process

It has been mentioned in Section 5.2.4.6 that most resin treated paper produced for filter applications will be pleated into one form or another. In addition, many dry formed nonwovens are pleated into some form of cartridge or panel shape. In almost all cases, the medium is in roll form and fed to the pleating process from an unwind stand. Often there is a slitter in line with the unwind stand that will slit the medium into two or more widths. This allows more than one filter to be made at the same time and optimizes the width capacity of the filter line. There is often a dye marking mechanism to indicate where to cut the pleated medium for proper length in the pleat pack. The cutting of pleat packs into specified lengths can either be done by a person with a knife or by a sophisticated, automated, cutting apparatus.

There are many types of pleating machines including “home made” types created by some filter manufacturers. Most are just variations on four fundamental pleating mechanisms: gear pleater, blade pleater, knife pleater, and rotary pleater.

5.4.1 Gear pleaters

The gear pleater diagrammed in Figure 5.45 is perhaps the simplest pleating method available short of hand pleating. A flat sheet of filter media passes between two oppositely rotating matched gear rolls, which fold the sheet into a pleat form and unto a conveyor belt for further processing. The height of the pleat pack is fixed and is determined by the length of gears. Typically, some sort of heat is applied to the flat media ahead of the pleater head for best pleating results. Change in pleat head can only be accomplished with a new set of matched gears at a relatively high cost and downtime.

5.4.2 Blade pleaters

Blade pleaters are often referred to as Chandler pleaters, since they were originally produced by the Chandler Pleating Co. of Ayers, Massachusetts. JCEM GmbH of

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12Much of the material for this section was provided by Charley Wood (deceased) who at the time was an employee of Hollingsworth & Vose Co., Inc. The author is very grateful to the contributions of Mr. Wood.
Fulenbach, Switzerland has since bought out Chandler. The Chandler type of blade pleater operates in a repeating stroke cycle by use of a pusher bar that compresses the medium, a breaker edge that forms the pleat and a stripper bar that holds back the formed pleat. The operation is illustrated in Figure 5.46. The pusher bar clamps down on the flat sheet and pushes the paper forward toward the stripper bar. The breaker edge, in a raised position to form the pleat, drops down to let the pusher bar passes.

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Figure 5.45. Gear pleater.
Drawing provided by Charley Wood, (deceased), West Groton, Massachusetts, USA.

Figure 5.46. Blade pleater operation.
Drawing provided by Charley Wood, (deceased), West Groton, Massachusetts, USA.
The stripper bar starts up and down in front of the newly created pleat and holds the formed pleat pack back. The pusher bar then lifts up and back to start the next stroke cycle. The stripper bar starts back up to assist in the formation of the next pleat. Although slow to operate, the blade pleater is more versatile than the gear pleater. Changes in pleat height are accomplished by changing the cam which determines the length of each stroke. Pleat heights up to 8 cm are possible on the blade pleater.

Blade pleaters are also produced by a2z Filtration Specialties, New Delhi, India. Figure 5.47 is a diagram of the a2z pleater. Figures 5.48 and 5.49 are examples of pleat styles that can be achieved with a2z pleaters. One of the pleat styles in Figure 5.49 is a pleat lock pleat. The pleat lock is an indentation in the pleat fold that locks it in place after it is folded.

Figure 5.47. Blade pleater by a2z Filtration Specialties.
Reproduced with permission of a2z Filtration Specialties Pvt. Ltd., New Delhi, India. Drawing provided by Divijai Singh.

\[\text{Post heat}\]
\[\text{Pleated pack}\]
\[\text{Pre heat}\]
\[\text{Media}\]

\['W'- Pleat\]
\[\text{Step pleat}\]

\['V'- Pleat\]

\[\text{Taper pleat}\]

Figure 5.48. Pleat styles.
Reproduced with permission of a2z Filtration Specialties Pvt. Ltd., New Delhi, India. Drawing provided by Divijai Singh.
5.4.3 Knife pleaters

Knife pleaters differ from blade pleaters in that they operate with a set of top and bottom knives. The knives work in sequence to first compress the sheet to form a pleat and then hold the pleat pack down as the companion knife repeats the sequence. The sequence illustrated in Figure 5.50 shows the top knife (1) pushing the medium against the backstop of the bottom knife to form a top pleat fold. The bottom knife then moves under (2) and in back of the top knife (3) to start a bottom pleat fold (4). The top knife then moves back and over (5) the bottom knife to start a top pleat fold (6) and the sequence repeats itself (7).

Figure 5.49. Pleat styles.
Reproduced with permission of a2z Filtration Specialities Pvt. Ltd., New Delhi, India. Drawing provided by Divijai Singh.

Figure 5.50. Knife pleater operation.
Drawing provided by Charley Wood, (deceased), West Groton, Massachusetts, USA.
Figures 5.51 and 5.52 are photographs of a knife pleater in action. The medium being pleated is a glass microfiber HEPA medium supported by a wire mesh. Figure 5.51 shows the HEPA and the wire mesh feeding to the inlet side of the pleating head. Figure 5.52 pictures the pleated medium emerging from the exit side of the pleating head. Both the wire mesh and the HEPA medium have been consolidated into a single pleated configuration. The knife pleater is most versatile for adjusting pleat height but at the expense of sacrificing production speed.

Traditional mechanical knife pleaters adjust pleat height by the use of cams. Karl Rabofsky GmbH, Berlin, Germany has introduced electronic knife pleaters, whereby electronic controllable servomotors replace the cams. Table 5.1 is a summary of knife pleaters offered by Karl Rabofsky.

5.4.4 Rotary pleaters

The rotary pleater, or more accurately the rotary score pleater is the most frequently used type of pleater, because it allows for high production rates. It typically uses two sets of rolls through which the medium travels. The first set of rolls contains score bars on the top and/or bottom roll to score the sheet using the other roll as an anvil. The illustration of Figure 5.53 shows all the score bars in the top roll. Figure 5.54 is
Figure 5.52. Exit side of a knife pleater showing the wire mesh and a glass microfiber filter medium combined and pleated, emerging from the pleating head.
Reproduced with permission of Kaydon Custom Filtration Corporation, LaGrange, Georgia, USA.

a photograph of a scoring roll in its pleating head assembly. In many applications the score bars are placed in both rolls to alternatively score the sheet top then bottom. Also depicted in Figure 5.53 is a second set of rolls. These are drive rolls that pull the sheet through the pleating operation. Back pressure after the drive rolls causes folding of the paper at the score marks. To a limited extent, pleat height can be adjusted by changing drive gears, which in turn change the relative rotational speed between the score and drive rolls. Larger changes in pleat height are accomplished by changing the number of score bars active in scoring the flat sheet. This is done by either by timing changes on the same set of score rolls or by replacing the score roll assembly with another assembly that has a different number of score bars. Modern rotary pleaters have rubber inserts on the score rolls to act as backing anvils for the score blades. This improves medium flexibility and reduces medium damage from over-scoring.

Figure 5.55 is a rotary pleating line produced by Manufacturing Machine Corp. (MMC) of Pawtucket, Rhode Island USA. Visible on the inlet side of the pleating head is the embossing roll that pressures dimples into the medium. The dimples serve as pleat separators in the pleat package. The MMC pleater also has the capability to apply hot melt along the pleat edges that will seal the folded edges and form pleat
Table 5.1  Rabofsky knife pleating machines comparison chart

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum physical speed</td>
<td>–</td>
<td>–</td>
<td>approx. 130 pl/min</td>
<td>approx. 185 pl/min</td>
<td>approx. 350 pl/min</td>
</tr>
<tr>
<td>Set-up time (min)</td>
<td>15</td>
<td>8</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Pleat height (mm)</td>
<td>5–50</td>
<td>5–50</td>
<td>5–95</td>
<td>5–104</td>
<td>3–150</td>
</tr>
<tr>
<td>Pleat programs</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Files to store</td>
<td>No</td>
<td>No</td>
<td>50 configurations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Automatic recall of set values</td>
<td>No</td>
<td>No</td>
<td>Almost completely</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Software-upgrade Operation</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Network capability</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>LAN capable</td>
<td>LAN capable</td>
</tr>
<tr>
<td>Pressure plate positioning</td>
<td>Manual, per scale</td>
<td>Manual, per scale</td>
<td>Automatic as option</td>
<td>Automatic</td>
<td>Automatic</td>
</tr>
<tr>
<td>Heating system</td>
<td>Quick or standard heating</td>
<td>Quick or standard heating</td>
<td>Quick or standard heating</td>
<td>Quick or standard heating</td>
<td>Quick or standard heating</td>
</tr>
<tr>
<td>Number of drives</td>
<td>1 central drive</td>
<td>1 central drive</td>
<td>3 servo drive</td>
<td>6 servo drives</td>
<td>8 servo drives</td>
</tr>
<tr>
<td>Slide guides</td>
<td>Self-lubrication Option</td>
<td>Self-lubrication Option</td>
<td>Self-lubrication</td>
<td>Self-lubrication</td>
<td>Self-lubrication</td>
</tr>
<tr>
<td>Material guide</td>
<td>Pneumatic cylinders</td>
<td>Pneumatic cylinders</td>
<td>Pneumatic cylinders</td>
<td>Pneumatic cylinders</td>
<td>Pneumatic cylinders</td>
</tr>
<tr>
<td>Pre-heating</td>
<td>Option</td>
<td>Option</td>
<td>Option</td>
<td>Option</td>
<td>Option</td>
</tr>
<tr>
<td>Pleat height adjustment</td>
<td>Manual</td>
<td>Quick adjustment</td>
<td>Automatic</td>
<td>Automatic</td>
<td>Automatic</td>
</tr>
<tr>
<td>Soft-touch</td>
<td>No</td>
<td>No</td>
<td>Option</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Integrated pleat/ pack counter</td>
<td>Option</td>
<td>Option</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Flexibility/efficiency</td>
<td>Normal</td>
<td>Normal</td>
<td>High</td>
<td>Very high</td>
<td>Extremely high</td>
</tr>
<tr>
<td>Special packages</td>
<td>HDI-II</td>
<td>HDI-II</td>
<td>HDI-II</td>
<td>HDI I - III, HIS</td>
<td>HS I as standard</td>
</tr>
<tr>
<td>Remote service</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
<td>Standard</td>
</tr>
</tbody>
</table>

Reproduced with permission of Karl Rabofsky GmbH, Germany.

pockets. Figure 5.56 is an example of pleated medium produced by the MMC machine. Note that the pleat package contains embossed dimples to serve as pleat separators. Also note that the pleat edges are sealed and each pleat fold thus becomes a pocket pleat.
Figure 5.53. Rotary pleating head operation.
Drawing provided by Charley Wood, deceased, West Groton, Massachusetts, USA.

Figure 5.54. Rotary pleating head roll.
Reproduced with permission of Kaydon Custom Filtration Corporation, Lagrange, Georgia, USA.

Figure 5.57 is rotary mini-pleat pleating line by MMC that is designed to pleat ASHRAE and HEPA glass microfiber filter media. It is capable of providing hot melt beads to both sides of the medium. The beads serve as pleat separators for the mini-pleat configuration.
Figure 5.55. Rotary pleater with embossing roll.
Reproduced with permission of Manufacturing Machine Corp., of Pawtucket, Rhode Island, USA.

Figure 5.56. Pleated filter medium with embossed dimples and pocket filter configuration.
Reproduced with permission of Manufacturing Machine Corp., of Pawtucket, Rhode Island, USA.
Figure 5.5. Rotary mini-pleat line for ASHRAE and HEPA glass microfiber media. The line is capable of applying hot melt beads to both sides of the medium – the beads serving as pleat separators.
Reproduced with permission of Manufacturing Machine Corp., of Pawtucket, Rhode Island, USA.
CHAPTER 6

Testing of Nonwoven Filter Media

6.1 Grammage or Basis Weight

Grammage and basis weight are synonymous terms reflecting on the weight per unit area of the media. Grammage usually follows the metric (SI) system. Its units are g/m². Basis weight usually refers to US customary units such as reams of material, lb/1,000 ft², or g/yd². Ream units are used by the American paper industry. The most common form for a filter medium is lb/3,000 ft². This is developed from the weight of a ream containing 500 sheets, 24 × 36 in. (24 × 36 – 500). Filter medium basis weights have also been based on ream sizes of 2,880 ft² (24 × 36 – 480). Sheeted filter media used for industrial filtration such as plate and flame filters are often listed at ream sizes of 1,389 ft² (20 × 20 – 500). In referring to basis weights based on ream sizes, one must make sure the ream size area is understood. The basis weight unit of lb/1,000 ft² is used by the American paperboard industry. The unit of oz/yd² and g/yd² are popular with the American textile industry. These are units often applied to nonwovens produced by dry formed processes. Because of the confusing nature in which basis weights and grammages are reported in the US, the following (Table 6.1) is offered. As much as possible, grammage and the units of g/m² will be used in this handbook.

Grammages of nonwoven filter media can range as high as 900 g/m² for certain types of needle felt media to as low as 10 g/m² for supported melt-blown webs. The electrospun layers of high efficiency composites are in the nano-grammage range.

Test methods for grammage and/or basis weight include ISO 9073–1:1989 and TAPPI T410.

<table>
<thead>
<tr>
<th>US custom unit</th>
<th>Ream size</th>
<th>Conversion to g/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>lb/3,000 ft²</td>
<td>24 × 36 – 500</td>
<td>1.628</td>
</tr>
<tr>
<td>lb/2,880 ft²</td>
<td>24 × 36 – 480</td>
<td>1.695</td>
</tr>
<tr>
<td>lb/1,389 ft²</td>
<td>20 × 20 – 500</td>
<td>3.515</td>
</tr>
<tr>
<td>g/yd²</td>
<td>-</td>
<td>1.196</td>
</tr>
<tr>
<td>oz/yd²</td>
<td>-</td>
<td>33.93</td>
</tr>
</tbody>
</table>
6.2 Volatiles and Moisture Content

Moisture or volatiles content of the web is part of the "as is" basis weight. They affect the economics as well as the properties of the medium. Moisture content of the web will relate to the equilibrium moisture content of its raw materials and the temperature and humidity to which it has been exposed. Equilibrium moisture content is the moisture content in equilibrium with the temperature and relative humidity (RH) of the exposure atmosphere. In Chapter 4, Table 4.2 was presented to include equilibrium moisture contents of several fiber types used in nonwovens and textile materials. The equilibrium conditions are 21°C and 65% RH. Test methods such as TAPPI T550 require a preconditioning period (usually 24 hours) at a specified temperature and RH followed by a conditioning period at 23°C and 50% RH (TAPPI T402). Media containing cellulosic fibers will have a hysteresis effect when conditioned. The equilibrium moisture content will be different for a specimen conditioned from a wetter stage than the same sample conditioned from a dry stage.

Volatiles refer to the total volatiles from the web including moisture and organic volatiles. This is not to be confused with VOC (volatile organic content), the environmental term that refers to the volatile organic content only in the web. Resin-bonded webs often contain both water and organic volatiles, such as formaldehyde, that are released as a result of the curing process. When reporting grammage or basis weight it is important to note whether it is reported on "as is" basis (moisture and/or volatiles included) or on a bone dry basis. For resin treated webs, the volatiles content is often a specified and measured property of the web. It affects other properties including stiffness and dimensional stability. Downstream converting processes such as pleating and bag making are very much affected by moisture and/or volatiles content. For thermosetting webs it is sometimes used as measure and control for degree of cure. Volatiles such as VOC and formaldehyde are strongly regulated by government regulatory agencies (see Section 6.3 for "formaldehyde content").

The simplest method to determine volatiles is to weigh the medium specimen, then heat it in an oven at a specified temperature and time period. The difference in weight before and after heating is the volatiles. A frequently used heating period for determining volatiles content is 150°C for 10 min.

6.3 Formaldehyde Content

Major environmental and workplace safety concerns deal with formaldehyde emissions from filter media. This is usually due to a formaldehyde type resin or crosslinker in the medium's resin formulation. AATCC-112-2003: "Formaldehyde Release from Fabric, Determination of: Sealed Jar Method" is the most common US method for determining formaldehyde. Japanese Ministerial Ordinance #112 is a closely related method used in Asia. In the AATCC method a weighed fabric specimen is suspended over water in a sealed jar. The jar is placed in an oven at a controlled temperature for a specified length of time. The amount of formaldehyde absorbed by the water is then determined colorimetrically. 29 CFR 1910.1048 (US) indicates that if the free formaldehyde content of
a material is greater than 0.1% (1,000 ppm) then it must be labeled for formaldehyde and may have to include the warning "Potential Cancer Hazard".

6.4 Caliper or Thickness

Caliper and thickness are synonymous terms referring to the surface-to-surface distance of the web. The thickness measurement is simple enough. Usually the web is placed under the presser foot of a thickness gauge, either manually operated or automatic, and the thickness is measured when the foot comes to rest on the surface of the media. There are problems. Filter media, by design are bulky structures that are compressible. If the presser foot is exerted with too much force it can sink into the compressible web and give a false low reading. On the other hand, if the presser foot is loaded with too little force, a few loose fibers at the surface can cause a misleading high caliper measurement. Any test method for caliper or thickness must specify the size and shape of the presser foot and the loading applied. Almost any organization that specifies test methods for nonwovens or paper will have a test method for caliper. TAPPI’s method is T411-76. INDA’s is IST 120.1-2. EDANA Test Method 30.5-99 and ISO 9073:1995, Part 2, have provisions for testing nonwovens, bulky nonwovens up to 20 mm, and bulky nonwovens greater than 20 mm.

Since thickness is measured over very small areas of the web, micro-variations in the web can effect the thickness measurement. If the presser foot happens to be placed over a thick spot in the web it will give a different measurement, than if it is placed over a thin spot in the web. Likewise, surface roughness will cause variations in the measurement. Bumpy surfaces will give more variation than smooth surfaces.

Corrugated filter media are widely used in pleated filter cartridges. They require special measurements as depicted in Figure 6.1. Overall caliper is the distance from bottom to top of the sine wave configuration. Thickness is the vertical distance between parallel surfaces of the media. Corrugation height is the distance from the tops of the hills to the bottoms of the valleys of the corrugations.

Note from Figure 6.1 that measurement of two of the corrugation properties fixes the third. An ordinary caliper with a flat presser foot can be used to measure overall caliper, however a wedge shaped presser foot that can fit between corrugations is necessary for the measurement of thickness and corrugation depth. Sometimes an image-projecting device such as an optical comparator or a shadowgraph is used.

![Figure 6.1. The measurement of corrugated filter media.](image-url)
6.5 Air Permeability

Air permeability of a nonwoven filter medium is the measured airflow through an area of filter media at a specified pressure drop. In some test methods it is referred to as the air permeance, a synonym. There are methods that fix the flow and measure the pressure drop. There is also a Gurley method (TAPPI T460 and ISO 5636-5:2003) that measures the air resistance of a medium by measuring the time to pass a specified volume of air through the medium at a specified pressure drop.

The most popular way to measure the air permeability of a filter medium is to fix the pressure drop and measure the airflow. The Frazier Air Permeameter, manufactured by the Frazier Precision Instrument Company, Inc., Hagarstown, Maryland USA, is diagrammed in Figure 6.2. It has been used for years for this type of measurement. The air is sucked through the clamped medium specimen into an enclosed chamber and out through an orifice that measures the flow. A manometer across the medium gives the pressure drop and a manometer across the orifice gives the pressure drop across the orifice for calculation of airflow. The manufacturer provides data tables for converting orifice pressure drop to airflows. Figure 6.3 is a photograph of the Frazier 2000® Air Permeability Instrument. This modern version implements electronic pressure sensing as well as computerized logging and manipulation of the electronic measurements.

Textest AG, Schwerzenbach, Switzerland markets an air permeability tester that has some convenient automated features including direct digital readout of the permeability. It also has an automated clamping system for the specimen. Orifices are easily changed by use of a turn dial instead of having to replace each one by hand.

The airflow measured is based on Darcy’s law discussed in Chapter 2:

\[
\nu_0 = -\frac{k \Delta p}{\mu L} \tag{6.1}
\]

In any measurement the pressure drop, \(\Delta p\), and the viscosity of air \(\mu\) is fixed. The measured airflow \(\nu_0\) then reflects on the permeability constant \(k\) and the thickness \(L\) of the medium. The permeability constant relates to the structure of the media.

Traditionally the air permeability is expressed in units of \(\text{ft}^3/\text{min/ft}^2\) at \(\Delta p = 0.5\) in \(\text{H}_2\text{O}\) and simply reported as CFM. The equivalent in SI units is \(\text{m}^3/\text{s/m}^2\) at \(\Delta p = 12.7\) mm \(\text{H}_2\text{O}\). Often it is reported as \(\text{m}^3/5/\text{m}^2\) at \(\Delta p = 20\) mm \(\text{H}_2\text{O}\). On their website, Frazier Instrument Company\(^{(140)}\) lists the following conversions for the various units of measurement (Table 6.2).

6.6 Density and Bulk

Density and bulk are properties of nonwoven filter media that are related to its filtration properties particularly dirt holding capacity. Density, \(\rho_w\), is the mass per unit volume of the filter medium in g/cm\(^3\) and is calculated from the grammage and thickness as follows:

\[
\rho_w = \frac{G}{t} \tag{6.2}
\]
Table 6.2 Conversion factors for air permeability testing

<table>
<thead>
<tr>
<th>Differential pressure</th>
<th>(inches of water)</th>
<th>(feet of water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>(inches of water)</td>
<td>0.0833 = (feet of water)</td>
</tr>
<tr>
<td>2.</td>
<td>(inches of water)</td>
<td>25.4 = (millimeters of water)</td>
</tr>
<tr>
<td>3.</td>
<td>(inches of water)</td>
<td>2.54 = (centimeters of water)</td>
</tr>
<tr>
<td>4.</td>
<td>(inches of water)</td>
<td>0.254 = (decimeters of water)</td>
</tr>
<tr>
<td>5.</td>
<td>(inches of water)</td>
<td>0.0254 = (meters of water)</td>
</tr>
<tr>
<td>6.</td>
<td>(inches of water)</td>
<td>0.0024582 = (physical atmosphere (atm))</td>
</tr>
<tr>
<td>7.</td>
<td>(inches of water)</td>
<td>0.0025399 = (technical atmosphere)</td>
</tr>
<tr>
<td>8.</td>
<td>(inches of water)</td>
<td>0.003554 = (inches of mercury)</td>
</tr>
<tr>
<td>9.</td>
<td>(inches of water)</td>
<td>1.8683 = (millimeters of mercury (torr))</td>
</tr>
<tr>
<td>10.</td>
<td>(inches of water)</td>
<td>0.036126 = (pounds per square inch (psi))</td>
</tr>
<tr>
<td>11.</td>
<td>(inches of water)</td>
<td>5.2022 = (pounds per square foot (psf))</td>
</tr>
<tr>
<td>12.</td>
<td>(inches of water)</td>
<td>25.399 = (kilograms per square meter)</td>
</tr>
<tr>
<td>13.</td>
<td>(inches of water)</td>
<td>0.0025399 = (kilograms per square centimeter)</td>
</tr>
<tr>
<td>14.</td>
<td>(inches of water)</td>
<td>249.08 = (pascals (Pa) or (newtons per square meter))</td>
</tr>
<tr>
<td>15.</td>
<td>(inches of water)</td>
<td>0.24908 = (kilopascals (kPa))</td>
</tr>
<tr>
<td>16.</td>
<td>(inches of water)</td>
<td>2.4908 = (millibars)</td>
</tr>
<tr>
<td>17.</td>
<td>(inches of water)</td>
<td>0.0024908 = (bars)</td>
</tr>
</tbody>
</table>

Airflow - (cubic feet per square feet of sample per minute) or (feet per minute) or (CFM)

<table>
<thead>
<tr>
<th>Airflow</th>
<th>(cubic meters per square meter of sample per minute)</th>
<th>(meters per minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>(CFM) × 0.3048 = (cubic meters per square meter of sample per minute)</td>
<td>(cubic feet per square feet of sample per minute)</td>
</tr>
<tr>
<td>2.</td>
<td>(CFM) × 0.00508 = (cubic meters per square meter of sample per second)</td>
<td>(feet per minute)</td>
</tr>
<tr>
<td>3.</td>
<td>(CFM) × 30.48 = (cubic centimeters per square centimeter of sample per minute)</td>
<td>(centimeters per minute)</td>
</tr>
<tr>
<td>4.</td>
<td>(CFM) × 0.508 = (cubic centimeters per square centimeter of sample per second)</td>
<td>(millimeters per minute)</td>
</tr>
<tr>
<td>5.</td>
<td>(CFM) × 3.048 = (cubic decimeters per square decimeter of sample per minute)</td>
<td>(decimeters per minute)</td>
</tr>
<tr>
<td>6.</td>
<td>(CFM) × 0.0508 = (cubic decimeters per square decimeter of sample per second)</td>
<td>(decimeters per second)</td>
</tr>
<tr>
<td>7.</td>
<td>(CFM) × 18.288 = (cubic meters per square meter of sample per hour)</td>
<td>(cubic feet per square feet of sample per hour)</td>
</tr>
</tbody>
</table>

where

\[ \rho_w \] is the density of the web in g/cm³.

\[ G \] is the grammage of the web in g/m².

\[ t \] is the thickness of the web in µm.

Bulk \( \beta_w \) is the reciprocal of the density and is expressed as cm³/g of medium:

\[
\beta_w = \frac{1}{\rho_w} = \frac{t}{G} \tag{6.3}
\]

Table 6.3 lists some conversion factors if the grammage or basis weight is expressed in units other than g/m² and/or the thickness is expressed in units other than cm.
6.7 Solidity and Porosity

Solidity, $\chi$ (often referred to as packing density) is the volume of solid material in a unit volume of medium. It can also be expressed as the volume fraction of the solids in the medium. In a nonwoven, the solids will include fiber, resin, additives, and any other ingredient that contributes to the solid volume of the structure. Porosity, $\varepsilon = (1 - \chi)$ is the three-dimensional volume void fraction of the medium. Porosity is not to be confused with air permeability. Permeability as described above is the
flow rate of fluid through the medium at a given pressure drop. Both, the solidity $\chi$ and the porosity $\varepsilon$ are important properties of filter media that are very evident in the theoretical discussions of Chapter 2. They can be “apparently” calculated from basis weight and caliper of the medium and the density of its materials, $\rho_m$, as follows:

$$\chi = \frac{G}{t\rho_m} \quad (6.4)$$

$$\varepsilon = 1 - \chi = 1 - \left( \frac{G}{t\rho_m} \right) \quad (6.5)$$
Table 6.3 Conversion factors for calculating density from various units of grammage and/or basis weight and caliper

<table>
<thead>
<tr>
<th>Grammage Units</th>
<th>Caliper Units</th>
<th>Density Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>g/m²</td>
<td>µm</td>
<td>1</td>
</tr>
<tr>
<td>lb/3,000 ft²</td>
<td>mil</td>
<td>0.06414</td>
</tr>
<tr>
<td>lb/3,000 ft²</td>
<td>in.</td>
<td>0.00006414</td>
</tr>
<tr>
<td>lb/3,000 ft²</td>
<td>µm</td>
<td>1.628</td>
</tr>
<tr>
<td>lb/2,880 ft²</td>
<td>mil</td>
<td>0.0668</td>
</tr>
<tr>
<td>lb/1,389 ft²</td>
<td>mil</td>
<td>0.1385</td>
</tr>
<tr>
<td>g/yd²</td>
<td>mil</td>
<td>0.0471</td>
</tr>
<tr>
<td>g/yd²</td>
<td>in.</td>
<td>0.0000471</td>
</tr>
<tr>
<td>g/yd²</td>
<td>µm</td>
<td>1.196</td>
</tr>
<tr>
<td>oz/yd²</td>
<td>mil</td>
<td>1.333</td>
</tr>
<tr>
<td>oz/yd²</td>
<td>in.</td>
<td>0.001333</td>
</tr>
</tbody>
</table>

Reproduced with permission of the Frazier Precision Instrument Company, Inc. Hagerstown, MD, USA.

where
\( \chi \) and \( \varepsilon \) are the solidities and porosities of the web, respectively in \( \text{cm}^3/\text{cm}^3 \).

\( \rho_w \) is the weight averaged density of the fibers, resins, and other additives making up the web in \( \text{g/cm}^3 \).

Note from Equation (6.4) the solidity or the web is calculated from the density of the web, \( \rho_w \), as determined from Equation (6.2) divided by the density, \( \rho_m \), of its fibers and materials. The reader should exercise caution in using Equations (6.4) and (6.5).

Chapter 2, Section 2.2.3.3 mentions how the complexities of cellular fiber structure, closed pores, and blind pores effect permeable void volume. Sutherland and Purchas\(^{12}\) provided Figure 6.4 to illustrate the various pore complexities.

Chapter 2, Section 2.2.3.3 discussed Lindsay\(^{32}\)'s approach to this problem for water in pulp mats. He refers to the fiber cell structure that is not available to fluid flow as being swollen fiber. He tabulates the definitions of the various porosities in Table 6.4.

In Chapter 2, Section 2.2.3.3, Lindsay defined \( \varepsilon_0 \) in terms of \( \alpha \) and \( c \) (see Chapter 2, Equations (2.25)):

\[
\varepsilon_0 = 1 - \alpha \chi
\]  

(6.6)

\( \alpha \) is the volume of swollen fiber per unit mass of fiber in the medium \( \text{cm}^3/\text{g} \) and \( c \) is the mass concentration of fiber per unit volume of medium in \( \text{g/cm}^3 \).

Rearrangement with the Kozeny Carman Equation (Chapter 2, Equation (2.23)) yields (see Chapter 2, Equation (2.25)):

\[
(kc^2)^{1/3} = \left( \frac{1}{5.558^2} \right)^{1/3} (1 - \alpha c)
\]  

(6.7)

Equation (6.7) is a classic equation used for pulp mats.
Table 6.4  Porosity definitions

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total porosity, ( \varepsilon = 1 - \chi = 1 - (G/\rho_{m}) )</td>
<td>Volume fraction of pore space, or ( 1 - ) volume fraction of solid matrix</td>
</tr>
<tr>
<td>Effective flow porosity, ( \varepsilon_{\text{eff}} )</td>
<td>Volume fraction of pore space open to flow</td>
</tr>
<tr>
<td>Relative flow porosity, ( \varepsilon_{\text{rel}} )</td>
<td>Fraction of total pore space open to flow ( \varepsilon_{\text{rel}} = \varepsilon_{\text{eff}}/\varepsilon )</td>
</tr>
<tr>
<td>Extrafiber porosity, ( \varepsilon_{\text{f}} )</td>
<td>Volume fraction of pore space between swollen fibers, or ( 1 - ) volume fraction of swollen fibers</td>
</tr>
</tbody>
</table>

Reproduced with permission of TAPPI, Atlanta, Georgia, USA.

\( S \) is the flow exposed surface of the fibers per unit mass, commonly called the specific surface area:

\[
S = \alpha S_{(1)}
\]  \hspace{1cm} (6.8)

Lindsey measured \( c \) and \( K \) values on fibrous webs under various degrees of compression. Using this data to plot \((k_0^2)^{1/3}\) vs. \(c\) in Equation (6.7) he was able to determine \(\alpha\) from the slope and \(S\) from the intercept. The relative flow porosity was then calculated:

\[
\varepsilon_{\text{rel}} = \frac{\varepsilon_0}{\varepsilon} = \frac{1 - \alpha}{\varepsilon}
\]  \hspace{1cm} (6.9)

Lindsey’s experiments indicated that values of \(\varepsilon_{\text{rel}}\) range from as low as 45% up to 70% and higher.
6.8 Pore Size and Pore Structure

Pore size, pore structure, along with porosity are related properties that help define a nonwoven filter medium. Porosity relates to the void volume within a filter medium and its capacity to hold dirt. Pore size and pore structure relate to the particle size that can be arrested. Almost all pore size measurements assume cylindrical capillaries through the medium and express the pore size in terms of the diameters of those capillaries. Two primary pore size measurements of a filter medium are: maximum pore size (often referred to as bubble point) and mean flow pore size. The test methods are described in ASTM F316-86\(^{141}\). Although this particular standard is specified for membrane filter media, the technique has been used by nonwoven and paper filter manufacturers for many years.

6.8.1 Bubble point

Figure 6.5 is a schematic of a very simple filter medium holder for determining maximum pore size or bubble point. The medium is clamped in place over a pressurizing chamber. Above the medium is a reservoir, which is filled with a test fluid of known density and surface tension. The pressurizing chamber is connected to a source of pressurized air and to a manometer. The pressure increases when airflow is introduced into the pressurizing chamber. Eventually the air forces its way through the medium and bubbles through the liquid reservoir. The manometer pressure is recorded.
Testing of Nonwoven Filter Media

at the time the first bubble is observed rising through the reservoir. The bubble point or maximum pore size is calculated as follows:

\[ d = (4\sigma \cos \theta / p) \times 10^6 \]  

(6.10)

where
- \( d \) is the maximum pore diameter in \( \mu m \).
- \( \sigma \) is the surface tension, at 20°C, of the reservoir fluid in N/m.
- \( p \) is the pressure when the first bubble was observed in Pa.
- \( \theta \) is the contact angle between the reservoir liquid and the pore wall in degrees.

In the filter holder diagrammed in Figure 6.5, the pressure \( p \) in Equation (6.10) has to be corrected for the height of the reservoir:

\[ p = p_0 - \rho T gh \]  

(6.11)

where
- \( \rho \) is the density of the reservoir fluid, at 20°C, in g/cm³.
- \( h \) is the height of the reservoir in cm.
- \( g \) is the gravitational constant (981 cm/s²).

The height of the reservoir depicted in Figure 6.5 is 0.5 cm (0.2 in.). Donaldson Company, Inc., Minneapolis, Minnesota, USA specifies a device that has a reservoir of 1.5 cm (0.6 in.).

Table 6.5 is tabulation of various liquids that might be used as bubble point reservoir fluids.

<table>
<thead>
<tr>
<th>Test liquid</th>
<th>Density (g/cm³) at 20°C</th>
<th>Surface tension (N/M) at 20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>0.79</td>
<td>0.0225</td>
</tr>
<tr>
<td>Ethanol (95%)</td>
<td>0.805</td>
<td>0.0230</td>
</tr>
<tr>
<td>Isopropanol</td>
<td>0.79</td>
<td>0.0215</td>
</tr>
<tr>
<td>Carbon tetrachloride</td>
<td>1.59</td>
<td>0.0270</td>
</tr>
<tr>
<td>A.C. oil, petroleum distillate</td>
<td>0.78</td>
<td>0.0300</td>
</tr>
<tr>
<td>Porewick a</td>
<td>1.90</td>
<td>0.0160</td>
</tr>
<tr>
<td>Porofil b</td>
<td>1.88</td>
<td>0.0160</td>
</tr>
<tr>
<td>Water</td>
<td>1.00</td>
<td>0.0720</td>
</tr>
</tbody>
</table>

a Test fluid recommended for PMI Capillary Flow Porometers.
b Test fluid recommended for Coulter-I Porometer.

The capillary constant is a tortuosity factor developed in a publication by H. Bechold “The Permeability of Ultrafilters” written in 1968(142). Many companies and organizations that use the bubble point technique do not make this correction.
6.8.2 Mean flow pore size

The mean flow pore size is the pore diameter at a pressure drop at which the flow through a wetted medium is 50% of the flow through the dry medium. It is not the mean pore size because the flow through large diameter pores can be disproportionately larger than the flow through small diameter pores. Figure 6.6 diagrams the apparatus used for measuring mean flow pore size. Two setups are shown: a one holder apparatus and a two holder apparatus. In the one holder setup the dry filter specimen is placed in the holder and air pressure is applied in increasing increments. The flow is measured at each pressure and the flow-pressure relationship is plotted. Figure 6.7 illustrates the graphic procedure for determining mean flow pore size.

*Figure 6.6. ASTM F316-86 apparatus for mean flow pore size and bubble point.*
Reproduced with permission of ASTM International, West Conshohocken, Pennsylvania, USA.
The filter specimen is then removed from the holder and completely wetted with a liquid of known surface tension and density or specific gravity. The liquids listed in Table 6.5 are possibilities. The wetted specimen is then placed in the holder and the flow-pressure plot is repeated on the wetted specimen. The bubble point is determined at the pressure at which air is first seen bubbling through the bubbler displayed in Figure 6.6. The pressure at which the flow rate through the wetted specimen is exactly one half of the flow through the dry specimen is the pressure at which the mean flow pore size is determined. Equation (6.10) is applied to calculate the mean flow pore size. The measurement as described in ASTM F 316-86 and illustrated by Figure 6.7 is a form of extrusion flow porometry. The extrusion flow porometry procedure utilizes air pressure to force a fluid of known surface tension from the pores of the media. The bubble point (or maximum pore size) mean flow pore size and minimum pore size can be determined in accordance with Figure 6.7 and by using equation (6.10). The technique measures the most restricted part of the pore (see Figure 6.8). In addition to the ASTM apparatus described here, there are very sophisticated instruments for measuring the pore structure of filter media. At one time Beckman Coulter, Inc. marketed a Coulter-I Porometer to perform the test, however the instrument is no longer available. It is mentioned here, because some organizations and companies still use the instrument. In addition, the instrument is still referenced in research reports and product data presentations. Recently, Xonics Corporation in Sunrise, Florida USA has introduced an updated version of the Coulter-I Porometer.

Figure 6.7. Determination of mean flow pore size.
Reproduced with permission of Porous Materials Inc. Ithaca, New York, USA (Jena and Gupta 114).

\(^2\) ASTM F 316-86 which applied the capillary constant \( B \) to the bubble point test, Equation (6.10) above also applies this constant to the calculation for mean flow pore size.
Porous Materials, Inc. currently markets several forms of porometers including the Capillary Flow Porometer®. In this instrument a wetting liquid is allowed to spontaneously fill the pores in the sample. Then, a nonreacting gas displaces the liquid from the pores. The gas pressure and flow rates through wet and dry samples are accurately measured. The instrument software automatically plots the flows in accordance with Figure 6.7. The pressure at which flow is first detected is used to determine the bubble point. The point at which the wet curve crosses the half-dry curve is the pressure at which the mean flow pore size is detected. The minimum pore size is determined from the pressure at which the wet curve merges with the dry curve. In addition to providing the maximum, mean flow, and minimum pore sizes, the instrument is also capable of providing the pore diameter range, the pore size distribution, gas permeability, and the distribution function that relates the wet flow to the dry flow as the pore diameter increases.

6.9 Other Techniques for Measuring Pore Size and Structure

In addition to the porometry procedures there are other techniques for measuring pore size and pore structure in filter media. Following is a discussion of those that may apply to nonwoven filter media.

6.9.1 Image analysis

Up to date computer techniques allow for scanning a web and conducting image analysis to determine pore size distribution and properties. Dr. Randall R. Bresee of TANDEC (University of Tennessee Textiles and Nonwovens Development Center)
has been developing this approach for relatively thin webs such as melt-blown and spunbond structures. Figures 6.9(a) and (b) are images from spunbond webs that illustrate this approach. The images show the actual pore structure of the webs. The diamond shaped areas are where the webs were spot bonded with a diamond shaped thermobond. For theoretical treatment, pores are assumed to be cylinders that have perfect circles as cross-section. Realistically, very few pores even approach the shape of a circle. This is very evident from the images of Figure 6.9. Bresee’s technique includes an analysis of pore aspect ratios\textsuperscript{1} presented in Figure 6.10. The mean ratio for Spunbond web 2 is 2.39 and for Spunbond web 4, it is 2.34.

The property table alongside Figure 6.10 includes a row for mean pore orientation. The orientation of a pore is measured relative to the machine direction (MD) of the web. It is determined from the angle of the long axis of the best fit ellipse with the MD. If the long axis is parallel to the MD the pore orientation is 0°. On the other hand, if the axis is perpendicular to the MD (parallel to the cross direction (CD)), then the orientation is 90°. The lower the number for mean pore orientation, the more the pores are orientated in the MD. If the orientation were purely random in all directions, then the mean pore orientation is 45°. Spunbond web 2 of Figure 6.10 has a mean pore orientation of 25.4° whereas Spunbond web 4 has an orientation of 34.4°. Therefore, Spunbond web 2 is more MD orientated.

Figure 6.11 is an analysis that calculates the pore size distribution (based on circular pores). It indicates that: the mean pore diameters are 44.4 \(\mu\)m for Spunbond web 2 and 43.0 \(\mu\)m for Spunbond web 4. It is interesting to note that the pore size distribution appears asymptotic to the zero pore size axis, suggesting that the number of pores approach infinity as the pore size approaches zero.

It should be noted that the image analysis technique is based on light transmittance and therefore can only be used on very thin webs such as spunbond and/or melt-blown media.

6.9.2 Microscopy

According to Ptak and Cady\textsuperscript{144}, “Microscopic measurement is the most direct method of measuring the pore structure.” However it can only be applied to media with straight pores perpendicular to the filter surface. Ptak and Cady determined that perforated sheet metal and woven fabrics were the only filter media for which reliable results could be obtained.

6.9.3 X-ray microtomography

X-ray microtomography is a radiation technique that can reproduce graphic three-dimensional images of small sections of nonwoven and paper structures. Research on

\textsuperscript{1}Pore aspect ratio as measured by Bresee’s technique is based on the pore cross-section. It is determined from the best fit ellipse that can be fitted into the pore cross-section. The pore aspect ratio is determined from the long axis of the ellipse divided by the short axis. If the ellipse happens to be a perfect circle, then the aspect ratio will be 1.0.
Figure 6.9. Images of the pore structure of a thermally spot bonded, spunbonded web.
(a) Spunbond Web 2, (b) Spunbond Web 4.
Reproduced with permission of Dr. Randall R. Bresee TANDEC, University of Tennessee, Knoxville, Tennessee, USA.
this technique is being conducted at the European Synchrotron Radiation Facility in Grenoble, France. The technique (Bloch\textsuperscript{145} and Thibeault et al\textsuperscript{146}) involves directing a very high intensity X-ray beam at various angles through successive layers of a rotating specimen and reconstructing the layers into a three-dimensional image. The layers can also be investigated independently. Bloch indicates that from the image analysis, the following properties can be calculated: porosity, mean chord, mean intercept numbers, specific surface, mean hydraulic diameter, and anisotropy factors. Figures 6.12 (blotting paper) and 6.13 (nonwoven structure) are examples of the structures that can be reproduced.

### 6.9.4 Liquid extrusion porosimetry

Liquid extrusion porosimetry is similar to liquid extrusion porometry in that gas pressure is used to force liquid from the pores of a medium. except in this test the
The medium is supported by a membrane whose pores are much smaller than the pores of the media. The pores of both sample and membrane are filled with a wetting liquid. Sufficient pressure is applied on the sample side so that liquid is forced from the pores of the sample but not from the pores of the membrane. The liquid forced from the sample is extruded through the membrane and its cumulative flow volume is measured. The gas pressure at each point of cumulative volume measured is converted to an equivalent pore diameter by Equation (6.10). These data are used to calculate pore volume, pore volume distribution, and surface area through pores as demonstrated by Figure 6.14.
6.9.5 Liquid intrusion porosimetry

Liquid intrusion porosimetry uses nonwetting liquids to force a gas from the pore structure of a porous medium. This is in contrast with extrusion porometry and extrusion porosimetry techniques that use gas to force liquid from the pore structure. The intrusion technique can provide pore diameter distribution, pore volume, and pore surface area. It determines the pore structure from the volume of liquid used to displace the gas and from the pressure employed. The pressure to force the liquid into the medium combined with the surface tension of the penetrating liquid is used to determine pore size in accordance with Equation (6.10). Mercury intrusion porosimetry and nonmercury intrusion porosimetry are two forms liquid intrusion porosimetry:

(a) *Mercury intrusion porosimetry:* Mercury intrusion is a technique for measuring pore volume and diameter by forcing mercury into the pore structure of a vacuum evacuated nonwoven. The technique can provide pore diameter distribution, pore volume, and pore surface area. Mercury is a nonwetting liquid and its contact angle with the media surface is greater than 90°. As a result, mercury will not readily flow into the pores unless forced to do so by an outside pressure. This pressure is related to pore size. The work to force mercury into the pores is equated to the increase in the free energy of the surface. Pore diameter is determined from the negative form of Equation (6.10):

\[ d = -\frac{4\sigma \cos \theta}{p} \times 10^6 \]  

(6.12)

The surface area is determined from the change in volume \( V \) as pressure is increased:

\[ S = \frac{1}{\left(-\sigma \cos \theta \times 10^6\right)} \int p dV \]  

(6.13)
Pore volume is determined from the volume of mercury forced into the structure.

(b) Nonmercury intrusion porosimetry: Nonmercury intrusion works just like mercury intrusion, except a nonwetting liquid, other than mercury, is used as the intrusion liquid. A nonwetting oil is an example. This technique has the advantage of avoiding a toxic material like mercury. It also greatly reduces the pressure necessary for forcing the fluid into the pores of the web.

### 6.9.6 Gas/vapor adsorption (BET)

BET (Brunauer, Emmet, Teller) theory is based on the attraction of an inert gas to the surface of the substrate being tested. Usually the gas is nitrogen (N$_2$). The testing is conducted at or near the temperature of liquid nitrogen. The amount adsorbed on a pore surface is a function of its vapor pressure as related to its equilibrium vapor pressure. The BET isotherm is as follows:

\[
\frac{p_v}{W(p_0 - p_v)} = \frac{1}{W_m C} + \left(\frac{C - 1}{W_m C}\right) \left(\frac{p_v}{p_0}\right)
\]

where

- $W$ is the amount of adsorbed gas in moles.
- $W_m$ is the amount of gas to form a monolayer in moles.
- $p_v$ is the gas vapor pressure in Pa.
- $p_0$ is the equilibrium vapor pressure in Pa.
- $C$ is a constant related to the adsorption energy of the gas to the solid substrate compared to the liquefaction energy of the gas. If the adsorption energy is high compared to the liquefaction energy, then the gas has a high affinity for the solid substrate, and vice versa if the adsorption energy is low compared to the liquefaction energy, then the gas has a low affinity for the solid substrate.

The specific surface area of the substrate, $S$, is determined by first plotting $p_v/W(p_0 - p_v)$ against $p_v/p_0$. At low vapor pressures ($0.05 < p_v/p_0 < 0.35$) the plot is usually linear. This allows the calculation of $W_m$ from the slope and intercept of the line. Figure 6.15 is an example of a BET plot.

The specific surface area, $S$ in cm$^2$/g, is then computed from $W_m$ as follows:

\[
S = W_m N \alpha / m
\]

where

- $N$ is the Avagadro number $\approx 6.02 \times 10^{23}$ atoms or molecules/mole.
- $\alpha$ is the cross-sectional area of the adsorbed gas molecule (cm$^2$).
- $m$ is the mass of the specimen being tested (g).

The BET technique is generally recognized as being the most accurate technique for measuring surface area of samples with large specific surface areas.
The BET is also used for pore size analysis based on vapor condensation. The principle is that it is easier for vapor to condense in small pores than large pores. The smaller the pore the lower is the vapor pressure at which condensation will occur. The pore size is then related to the ratio of the condensation pressure to the equilibrium vapor pressure, $p_v/p_0$. The phenomenon is described by Kelvin’s Law:

\[
\ln \left( \frac{p_v}{p_0} \right) = \frac{2\bar{V}\sigma \cos \theta}{dRT}
\]

(6.16)

where
- $\bar{V}$ is the molar volume of the condensed vapor, $m^3$/mole.
- $d$ is the pore diameter in m.
- $\sigma$ is the superficial tension, N/m.
- $p_v$ is the vapor pressure at which condensation occurs, Pa.
- $p_0$ is the equilibrium vapor pressure in Pa.
- $\theta$ is the wetting angle $^\circ$. If the condensed liquid perfectly wets the surface, $\cos \theta = 1$.
- $R$ is the universal gas law constant, 8.31 J/mole K.
- $T$ is the absolute temperature, K.

**6.9.7 Summation**

Jena and Gupta\textsuperscript{111} have compared the extrusion, intrusion, and adsorption techniques discussed above in terms of what they can do and what they can’t do. Table 6.6 lists the capabilities of each of the techniques. Table 6.7 compares some of their operational features.
Table 6.6  Capabilities of the extrusion, intrusion, and gas adsorption techniques

<table>
<thead>
<tr>
<th>Property</th>
<th>Extrusion flow porosimetry</th>
<th>Extrusion porosimetry</th>
<th>Intrusion porosimetry (mercury)</th>
<th>Intrusion porosimetry (nonmercury)</th>
<th>Gas adsorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Through pores</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constricted diameter</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Largest constricted diameter</td>
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<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Many diameters of each pore</td>
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<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Flow distribution</td>
<td>Yes</td>
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<td>No</td>
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<tr>
<td>Volume</td>
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<td>No</td>
<td>No</td>
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<tr>
<td>Volume distribution</td>
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<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Surface area</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Through and blind pores</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All diameters of each pore</td>
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<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Volume</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<td>Volume distribution</td>
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<td>No</td>
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<td>Yes</td>
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<tr>
<td>Surface area</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Permeability</td>
<td></td>
<td></td>
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<tr>
<td>Gas permeability</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Liquid permeability</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Effects of application environment</td>
<td></td>
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<tr>
<td>Compressive stress</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Cyclic compression</td>
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<td>No</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Strong chemical environment</td>
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<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
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<td>Elevated temperature</td>
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<td>Yes</td>
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<td>No</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Layered structure</td>
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<td>Orientation</td>
<td>Yes</td>
<td>No</td>
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<td>No</td>
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</tr>
</tbody>
</table>

Reproduced with permission of Porous Materials, Inc. Ithaca, New York, USA (131) Table 7.

Table 6.7  Operational features of the extrusion, intrusion, and gas adsorption techniques

<table>
<thead>
<tr>
<th>Features</th>
<th>Extrusion flow porosimetry</th>
<th>Extrusion porosimetry</th>
<th>Intrusion porosimetry (mercury)</th>
<th>Intrusion porosimetry (nonmercury)</th>
<th>Gas adsorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of toxic material</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>High pressure</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Subzero temperature</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Use of fluid of interest</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Involved/time</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Reproduced with permission of Porous Materials, Inc. Ithaca, New York, USA (131) Table 8.
6.10 Strength Properties

There are many components to the strength properties of nonwoven filter media. Tensile properties include tensile strength, stretch or % elongation, tensile energy absorption (TEA), and tensile stiffness. These are in plane and out of plane properties of the web. Out of plane properties include bending stiffness, burst strength, internal bond strength, and Z-direction compression. In many cases the properties are anisotropic, different in the MD of the web than in the CD. Following are the strength related properties of nonwoven filter media.

6.10.1 Tensile properties

6.10.1.1 Dry tensile properties

Tensile properties are measured by some form of tensile tester. Usually the tester is a constant-rate-of-extension (CRE) tensile testing machine as defined by TAPPI T494 om-96\footnote{TAPPI also specifies T404 “Tensile Breaking Strength and Elongation of Paper and Paperboard (Using a Pendulum Type Tester).” This method is based on instruments that utilize a constant rate of loading. This is an older test method that is now seldom used for nonwoven materials.} or INDA IST No. 110.1-4. There are a number of test methods worldwide. Among them are ASTM D828 and ISO 1924-2:1995. The measurement is usually defined in terms of the specified width of the specimen. In the US, this is most often a 1 in. wide specimen, although sometimes it is 2 in. European standards most often specify a 15 mm wide specimen.

The test involves clamping both ends of the test specimen to mechanically operated clamps separated by a specified distance (refer Figure 6.16). One clamp moves and stretches the specimen till it breaks or ruptures. The moving clamp is connected to a load cell that measures the force exerted on the specimen. The tester is also capable of measuring the stretching distance traveled by the moving clamp. Specified conditions that have to be programmed into the tester are rate of strain and specimen length. Modern day testers contain processors that will calculate tensile strength, stretch and/or elongation, TEA, tensile stiffness, and secant modulus.

The tensile properties are based on the stress–strain or load–elongation curve illustrated in Figure 6.17. Note the curve has two possible horizontal axis; strain and elongation. Strain is the % change in length of the specimen as it is being stretched. Elongation is the change in the length dimension over its original length. The stress–strain is the curve when strain is being used. It is the load–elongation curve if elongation is the x-direction parameter. It is important to note that from Figure 6.17, that the point of maximum tensile strength and the point of rupture are not necessarily the same. In deed, some “rubbery” like nonwoven materials can be stretched and stretched well beyond their point of maximum tensile strength and still not rupture. One should pay strict attention to how certain properties are defined in the test method and note different test methods are not necessarily consistent with each
other in their definitions. For example the discussion below notes the difference in stretch and elongation definitions between TAPPI T404 and TAPPI T494.

The various properties are defined as follows:

(a) **Stress**: The load applied to a nonwoven specimen, ever increasing, as the tension increases. It is measured in force per unit width of specimen. In SI units
Testing of Nonwoven Filter Media

this is often kN/m and sometimes kN/15 mm. In U.S. units, the most common form is lb/in.

(b) **Tensile strength**: The maximum stress or load before rupture of the specimen. Frequent units are kN/m, kN/15 mm, or lb/in. It should be noted from Figure 6.17 that the tensile strength or point of maximum stress and the point of rupture are not necessarily the same points on the stress–strain curve. Many elastic materials, including some nonwovens, can be stretched beyond their maximum stress before rupture occurs.

(c) **Strain**: The increase in length of the specimen as stress is applied. Strain is measured as a percent of the original length before the load was applied:

\[
\text{Strain} = \frac{\Delta L}{L} \times 100
\]  

\[ (6.17) \]

(d) **Stretch**: TAPPI T494 defines stretch “as the maximum tensile strain before rupture”. Like strain, it is measured as percent of original specimen length. It is often referred to as “% elongation”, however this term differs from the definition of elongation in TAPPI 404 (see below) which is based on the point of maximum tensile strength before rupture.

(e) **Elongation**: Elongation is confusing because there appears to be several definitions or understandings of the term. It can be used to express the change in length (\(\Delta L\)) of the specimen, in mm or inches. This is in lieu of strain which represents the change in length as a percentage of original length. However, it is also used as a synonym for strain or percent of original length. Elongation is also expressed as the fraction of original length. TAPPI T404 (see Footnote 5) defines elongation as the tensile strain “at maximum tensile strength before rupture” which is not quite the same as the definition of stretch and % elongation.
as given in TAPPI T494. For purposes of this discussion the length (ΔL) definition of elongation will be used.

(f) **TEA:** This is an indication of the toughness of the medium. It is the integrated area under the load–elongation curve up to the point of rupture. Referring to Figure 6.17, it is the gray area under the load–elongation curve when elongation is used as the horizontal axis. The units are in J/m². The equation for TEA in accordance with TAPPI T-984 is:

\[ TEA = 1 \times 10^6 \frac{A}{LW} \]  

(6.18)

where

- \( TEA \) is the tensile energy absorption in J/m².
- \( A \) is the area under the load–elongation curve in J (Joules).
- \( L \) is the initial test span in mm.
- \( W \) is the specimen width in mm.

(g) **Tensile stiffness:** This is determined from the stress–strain curve. It is an indication of the stiffness or rigidity of the medium. It is the tangent to the elastic portion of the curve up to the elastic limit, i.e. the point where the curve starts to become nonlinear. It is determined from two points on the curve: the first point being at least 5% of the elastic limit and the second being no more than 75% of the elastic limit. The calculation is:

\[ S_1 = \frac{1000(Δf/W)(ΔL/L)}{100} \]  

(6.19)

where

- \( S_1 \) is the tensile stiffness (N/m).
- \( Δf \) is the difference between the two force levels (N).
- \( W \) is the initial width of the initial test specimen, mm.
- \( L \) is the initial test length (mm).
- \( ΔL \) is the change in length corresponding to \( Δf \) (mm).

Note that \( ΔL \) is the elongation at rupture and \( ΔL/L \) is the stretch divided by 100. The tensile stiffness can be converted to Young’s modulus, \( E \), the modulus of elasticity, by dividing by the thickness \( t \) (m):

\[ E = \frac{S_1}{t} \]  

(6.20)

(h) **Secant modulus:** This is the slope of the line drawn from the origin of the stress–strain curve to a point of interest on the curve. In Figure 6.17, the point of interest is the point of maximum stress where the tensile strength is determined. The secant modulus is then defined as the maximum tensile strength divided by the stretch. It is a useful number because it relates to the rigidity of the medium. A high secant modulus indicates a stiff, rigid media, whereas a low secant modulus indicates a soft, stretchy medium. At one time, a major filter manufacturer specified secant modulus as an indicator of pleatability.
(i) **Breaking length**: This is the length of a tensile strip whose weight, if hung from one end, would be sufficient to break the strip. It is related to tensile strength as follows:

\[ BL = 102,000(T/R) = 10.974(T'/R') \]  

where

- \( BL \) is the breaking length in m.
- \( T \) is the tensile strength in kN/m.
- \( R \) is the grammage in g/m\(^2\).
- \( T' \) is the tensile strength in lbf/in.
- \( R' \) is the basis weight\(^5\) in lb/3,000 ft\(^2\).

(j) **Tensile index**: Tensile index (TI) is the tensile strength in N/m divided by grammage in g/m\(^2\):

\[ TI = 1.000(T/R) \]  

(k) **Tensile ratio (MD:CD)**: Almost all nonwoven media are anisotropic, having more fiber orientation in the MD than the CD. The ratio of MD tensile strength to CD tensile strength is often used as a quantitative measure of the anisotropy. Terms often used are MD:CD ratio and fiber orientation ratio. A related term is grain ratio and this is often expressed in terms of the CD:MD ratio.

### 6.10.1.2 Wet tensile strength

Wet tensile strength is measured on the same apparatus as the dry tensile strength and in accordance with TAPPI T494. Prior to testing the sample is soaked in water to measure its strength on a wet basis. Sometimes a surfactant is added to the water for materials that are difficult to wet out. Wet strength is an important property to nonwoven filter media because:

1. It is an indicator of water resistance.
2. It insures processability in wet operations such as saturation in a chemical binder application.
3. It is a necessary property in aqueous filtration operations.
4. It can be used as an indication of cure for media bonded with thermosetting resins.

Tensile strength is not the only test for determining wet strength related properties of nonwoven filter media. Others are wet burst and wet stiffness.

For media bonded with a thermosetting resin, the wet strength property is very much affected by the degree of cure. For example, a specimen treated with a thermosetting resins.

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\(^5\)In accordance with TAPPI T-494 grammage or basis weight is calculated on an air-dry basis, i.e. the moisture content is in equilibrium with the atmospheric conditions to which the specimen has been exposed. For cellulose media the equilibrium moisture content is in the range of 3–9\%.
phenolic resin will have very little wet strength if the specimen is not cured and a much higher strength after curing. The ratio of the uncured wet strength to the cured wet strength is an indicator of how much the specimen has been cured. Of course, if the ratio is 1:1, the specimen is presumed to be fully cured.

6.10.2 Other strength related properties

6.10.2.1 Grab tensile strength ASTM D4632
Grab tensile strength differs from tensile strength test by the way it is held in the CRE apparatus. It can be seen in Figure 6.18 that the clamps are circular and only grip a portion of the width of the specimen, whereas the clamps of the tensile strength test grip (Figure 6.16) the full width of the specimen. The grab tensile is the force to rupture the specimen. It is reported in kN or lb (force). The test also measures the elongation to the point of break as a percent of the original length.

![Image of grab tensile test](image)

Figure 6.18. The grab tensile test in a CRE tester.

6.10.2.2 Burst strength
Because of its simplicity and quickness, burst strength is a commonly used test for measuring the strength of nonwovens. The Mullen Burst tester is one of the more popular instruments for measuring this property. Among the numerous standards for this test are TAPPI T403, ASTM D774, British BS 3137, IST 30.1 (INDA), and ISO 2758. In addition test methods such as ASTM D7386-01 and BS 2576 for textile fabrics can be applied to nonwovens. The test specimen is held between annular clamps and subject to an increasing pressure from a rubber diaphragm pressed against it by a hydraulic pressure. The pressure is increased at a controlled rate till the specimen bursts. The burst strength is the maximum pressure up to the point of burst. Note that, unlike the tensile tests above, the force for the burst test is an out of
plane pressure applied perpendicular to the plane of the specimen. Nevertheless the
failure at burst is mostly an in-plane failure. This because the pressurized
diaphragm, as it pushes against the specimen, stretches and bulges it into a bubble
shaped configuration. When the specimen cannot be stretched any further, it bursts
by failure of its in-plane properties.

The burst strength is expressed as a pressure force. Units are usually in kPa or in
lb/in². (psi). Burst strength may also be reported as:

- Burst index = burst strength, kPa/grammage, g/m²
- Burst ration = burst strength, psi/basis weight, lb/ream
- Burst factor = burst strength, g/cm²/grammage, g/m² (usually oven dry).

6.10.2.3 Tear strength

Tear strength is the force to begin or continue a tear in a fabric under specified condi-
tions. It can be related to filter media, in process and in the field, in their ability to resist
rupture and mechanical failure. There are several types of tear mechanisms. In most
of these, a slit is cut into the specimen and a force applied to the specimen in such a
way that a continuing tear from the slit is propagated. The force may be applied so
that it is in plane or out of plane depending on the test method. Tear strength is ori-
entation dependent, so both MD and CD specimens are tested. Some examples are:

1. Tongue tear (ASTM D2261): The specimen is cut as shown in Figure 6.19. A 3 in.
   (7.6 cm) slit is cut down the middle of a 3 × 8 in. (7.6 × 20.3 cm) specimen. The
   specimen is tested on a CRE tensile test machine. One side of the slit is fastened
   into an upper clamp; the other side turned down and fastened into a lower clamp.
   The tear strength is the force necessary to propagate the tear from the slit.
2. Trapezoid tear (ASTM D4672): The trapezoid tear test uses a trapezoid shaped
test specimen as shown in Figure 6.20. The specimen is clamped in the CRE
tester so that the diagonal sides of the specimen are in the clamp fixture. The
pull is in-plane and normal to the direction of the slit cut at the top of the
specimen. The force to tear is reported as kN or lb (force).
3. Elmendorf tear: The Elmendorf tear test is described by TAPPI T414. Although
   the test is generally designed for testing several plies of a paper medium, it is

![Figure 6.19, Tongue tear test.](image)
Figure 6.20. Trapezoid tear specimens.

Figure 6.21. Elmdorf tear tester.
Reproduced with permission of Hollingsworth & Vose Company Inc. East Walpole, Massachusetts, USA.
often used for single ply tests on nonwoven media including filter media. The
apparatus involves a swinging pendulum. The specimen is slit so that one
side of the slit is attached to a stationary clamp. The other side of the slit is
attached to the moving pendulum. When the pendulum is released it con-
tinues the tear along the slit. The loss in potential energy of the pendulum is the
work done to continue the tear. The force is measured in mN (millinewtons) or
gf (gram force). If more than one ply is used then the force measured is divided
by the number of plies. Some other related methods for Elmendorf tear are
ASTM D689, British BS 4468, Canadian CPPA D.9, and ISO 1974. ASTM D5734
is pertinent to the testing of nonwoven fabrics by the Elmendorf apparatus.
Figure 6.21 is a photograph of the Elmendorf tear tester.

6.10.2.4 Stiffness
Stiffness is an important property for resin-bonded filter medium used in pleated fil-
ter configurations. It measures the resistance to bending of the medium. It is a direc-
tion orientated property so that both MD and CD direction measurements are
usually desired. There are many types of stiffness testers. Two of the most notable
are the Gurley stiffness tester and the Taber stiffness tester.

The Gurley stiffness tester is depicted in Figure 6.22. TAPPI T543 is an applicable
standard. The tester consists of a balanced pendulum or pointer, pivoted at its center
of gravity. The lower end is pointed and moves parallel to a graduated scale mounted
on the base of the instrument. The upper end of the pointer is a triangular vane that
makes contact with the moving specimen. The specimen clamp is attached to an
arm that rotates about the same geometrical center as the pointer. When the speci-
men arm rotates, the specimen comes in contact with the triangular vane and deflects
the pointer until the specimen bends sufficiently to release the pointer. The rota-
tional distance traveled by the pointer is indicated by the graduated scale at base of
the instrument. This distance is an indication of the bending stiffness of the specimen.
The clamped specimen rotates back and forth to 20° from the vertical center. Two
measurements are averaged. The first measurement is as the specimen arm rotates
from left to right and pushes the specimen against the vane in this direction. The
arm is then rotated right to left to push the specimen against the vane from the oppo-
site side for the second measurement. The two-test average is the average of the bend-
ing stiffness from left to right and the bending stiffness from right to left. Weights of
5 g, 25 g, 50 g, and 200 g can attached to the pointer to allow measurements of
specimens with higher stiffness. The weight is chosen to be consistent with the anti-
cipated stiffness of the specimen. The stiffness is reported as Gurley units; one Gurley
unit is equivalent to one milligram of force (mgf). In terms of force units, one milli-
newton mN is equivalent to \(9.807 \times 10^{-3}\) Gurley units. Modern electronic testers
provide digital readouts of the bending stiffness.

The Taber stiffness tester is depicted in Figure 6.23. Applicable standards include
TAPPI T489, ISO 2493, BSI 3748, and SCAN P-29 and APPITA P431. The test has
been around for over 50 years. The test instrument involves a pendulum containing
a clamp for attaching the top of the specimen. The lower edge of the clamp coincides
with the center of the pendulum bearing. Behind the pendulum is a vertical disc that
rotates on the same axis as the pendulum. The disc contains an attachment of two parallel rollers so that the lower edge of the specimen is fitted between these rollers. When the motor driven disc rotates, the rollers push against the specimen and try to bend it in the direction of rotation. The pendulum to which it is clamped rotates with the disc depending on the bending stiffness of the specimen. Since the specimen does bend, the pendulum does not rotate as much as the disc. How much it rotates is a measure of the bending stiffness of the specimen. The reading is taken when the specimen has bent 15° with respect to the rotating disc (7.5° for stiff specimens). This is indicated when the line mark at the top of the pendulum matches up to the 15° or 7.5° line marks on the rotating disc. At this point the line mark at the top of the pendulum is matched up to a scale on a fixed annular disc surrounding the rotating disc. The scale reading is the measurement of the bending stiffness. The stiffness
reported is the average of two readings (left and right deflection). The stiffness is reported as gram centimeters (g-cm).  

6.10.2.5 Internal bond strength

Internal bond strength is like an out of plane tensile strength determined by pulling on the surfaces of a medium so as to try to pull them apart. It is sometimes referred to as the Ply Bond Strength and as the Z-Direction Tensile Strength. Although the tests were developed for paperboard and multiple corrugated boards they have utility for nonwoven filter media. For resin treated media the internal bond strength may be an indicator of resin penetration into the internal structure. If the resin has not penetrated well, then the internal bonding at the center of the medium will be weak and the surfaces will readily delaminate or pull apart. The internal bond test is also used to measure the laminating strength between layers of a composite structure and determine how well they adhere to each other. There are two types of internal bond test tests. In both tests, the substrate is sandwiched between two metal platens. Two sided tape is used to stick each surface to its respective platen. The medium is first compressed by the platens to secure a better adhesive bond. The platens then separate in a direction normal to the surfaces of the substrate so as to force the surfaces to separate. TAPPI T541 and SCAN P80 utilize a compression tester to first vertically compress the taped substrate between the platens and then reverse direction to delaminate the specimen. The force or delaminating pressure required to pull apart the surfaces is reported. The units are lb/in. ² or kPa.

---

The following equation can be used to convert Gurley stiffness units to Taber stiffness units:

\[ S_t = 0.01419 S_g - 0.935 \]

where \( S_t \) is the Taber stiffness and \( S_g \) is the Gurley stiffness.
TAPPI T833 utilizes a pendulum type tester often referred to as a Scott Bond tester. The results of this test are often referred to as the Scott bond. The specimens are taped to a stationary bottom platen on one side and a right-angled metal plate on the top side. The right-angled plate is forced against the specimens for 1–2 s and then the pendulum is released. The right-angled plate is struck by the moving pendulum with a force sufficient to delaminate the specimens. A pointer attached to the pendulum and a corresponding scale indicates the loss in kinetic energy of the pendulum. This is the energy necessary to delaminate the specimens. It is an indicator of the internal bond strength. The delaminating energy is reported in kJ/m$^2$ or in ft-lb/in.$^2$.

6.10.2.6 Fold endurance
Filter media are subject to mechanical variations that may affect their endurance. These include pulsations in the pressure drop of the fluid flowing through the medium and mechanical vibrations in the equipment in which the filter and its medium may be housed. Fold endurance is one way to evaluate a medium’s ability to endure these pulsations and vibrations. The general technique is to attach a strip of medium to two clamps, one of which rotates back and forth at a prescribed frequency. This is shown in the fold endurance tester of Figure 6.24.

6.11 Water Repellency and Water/Moisture Resistance
Water repellency relates to the ability of a medium to resist wetting and penetration by water. The property is determined by the hydrophobicity of the medium, an important property if the medium serves as a moisture barrier in its filtration application. Water repellency and water and/or moisture resistance are different properties. Water resistance relates to the ability of the medium to maintain its properties and structural integrity after exposure to water or moisture. Moisture resistance is generally perceived as the ability of the medium to stand up to environmental variations of humidity in the atmosphere.

6.11.1 Water repellency
There are several ways to measure water repellency. Some are locally improvised. TAPPI T558 describes a method whereas a drop of liquid is carefully placed on the substrate and the contact angle is measured by an automated contact angle tester. Another method is to carefully place a drop of liquid on the substrate and then measure the time to soak into the substrate. A related procedure is to place drops of mixtures of alcohol and water. The higher the alcohol content the more readily the drop will soak into the substrate. Water repellency is then rated by the percent alcohol in and how well it soaks into the medium over a short period of time such as 10 s. AATCC 193-2005 is a test method that relates to this technique. Absorbency is also an indicator of water repellency. In soak tests, a water repellent material will absorb less water than a nonwater repellent material.
Other test methods for water repellency include hydrostatic head methods, spray methods and shower methods:

1. *Hydrostatic head methods*: These are sometimes referred to as water resistance tests, however they are in reality a water repellency test. The measurement is based on the head of water the medium will withstand before penetration occurs. It is a water barrier property. AATCC 127, known as the Suter test, is one of several methods that measure this property. ASME AG-1, Section FC.
Paragraph FC-I-3240(148), requires hydrostatic head testing of HEPA (high efficient particulate air) media to be used in nuclear installations.

2. **Spray methods:** AATCC 22 is an example of a spray test. A small body of water placed about 4 in. (10 cm) over the fabric is sprayed on the fabric through a spreader nozzle. The fabric is at 45° to the direction of spray. The spray duration is 30 s. The fabric is visually rated, on a scale of 0–100, on how well the water beads up; 0 being the worst and 100 being the best (no wetting). The method provides a set of photographs or spray test ratings as standards by which to judge the repellency.

3. **Shower methods:** These also referred to as rain tests, are more severe and demanding than spray methods. The Bundesmann test (ISO 9865) showers water unto the fabric specimen from a height of 4 ft (1.2 m). The duration of the shower is 10 min. The fabrics are clamped to cups and angled 10° to the direction of spray. During the test an X shaped squeegee exercises the fabric from behind to simulate fabric movement during a rainstorm. When the test is completed the beading of water on the fabric is compared to visual standards to obtain a rating of 1–5; 5 being the best. The method can also be used to measure penetration by measuring the amount of water that has penetrated the fabric into the support cup. In addition, water absorption of the fabric can be determined by weighing the fabric before and after the test.

### 6.11.2 Water resistance

Water resistance is a measure of the medium’s ability to maintain properties after being immersed in water or wetted out with water. The primary concerns are medium disintegration, structural failure, and fiber swelling. Filter media used in filtering aqueous fluids need to have sufficient wet strength so as not to disintegrate when exposed to the aqueous environment. A good example is teabag paper which has to survive in a hot water environment and be burst resistant, even when pressed with a teaspoon. Pleated air filters such as engine intake air filters are vulnerable to pleat collapse if they are contaminated with water, say from a rainstorm. Ratio tests of a medium’s wet and dry strength properties are an indicator of its ability to maintain strength properties. The ratio of wet to dry stiffness is a good indicator of pleated medium structural integrity.

Cellulose fibers in particular will swell when exposed to water. This will cause dimensional change in the media. Dimensional change may cause a loss of structural integrity in a filter. ISO 5635:1878 designed for paper and paperboard is a test that measures this change by immersing a specimen in water and measuring its dimensional change.

In a filter medium, fiber swelling may cause pore closure, increased flow resistance, and poorer filtration performance. The author is unaware of any standard test methods that relate fiber swelling to filtration performance. There have been attempts to run flow through tests on wetted filter media in an effort to compare the pressure drop loss to that of dry media. However, the results from such experimentation have been inconsistent.

There are media tests where the medium is tested as an element in a filter housing. Water is injected as a contaminant into the test fluid. Generally, filter failure occurs as a result of the medium’s dimensional change and structure collapse.
6.11.3 Moisture resistance

Moisture resistance is mainly concerned with a medium’s ability to maintain dimensional stability when exposed to high humidity and changes in humidity. Dimensional stability is related to the ability of a medium to maintain dimensions when exposed to some adverse condition such as moisture content, heat, the application of load, and/or passage of time. Hygroexpansivity is the change in dimensions due to changes in humidity. Creep, also known as “cold flow” is the change in dimensions with time of a medium that is under constant load. In a pleated filter, the combination of hygroexpansivity and creep sometimes results in pleat deformation and even pleat collapse. Figure 6.25 illustrates a pleated filter panel element where the pleat folds have been deformed due to hygroexpansivity or creep after the element was manufactured. Note how some of the pleat folds are pinching on each other, effectively reducing the surface area for filtration.

The quality problems associated with dimensional change due to hygroexpansivity are probably the most serious in the nonwovens industry, particularly if the medium contains a moisture absorbing material such as cellulose fiber. Media treated with hygroscopic flame retardants are even more vulnerable to the undesirable effects of hygroexpansivity. For example, slit width variations of finished rolls are most often caused by dimensional change in their width due to exposure to weather and climate variations after the rolls have been manufactured and slit.

The problems of hygroexpansivity and creep are certainly not limited to filter media. It has been long established that paper creeps more when subject to cyclic humidity conditions than at constant humidity. This is probably also true for filter media.
Habeger and Coffin\textsuperscript{(149)} argue that this “accelerated creep” is due to sorption-induced stress concentrations and a nonlinear creep response. They also argue that it is a phenomenon that is still not well understood.

Despite all the concerns of hygroexpansivity there are very few published standards and test methods related to this property and what few there are appear to be related to paper and paperboard. Among these are SCAN-P 28:88, BS 6712-1:1995, ISO 8226-1:1994, and ISO 8226-2:1990. In the SCAN method, length measurement are made at 33\% RH and 66\% RH (starting at 19\% RH). The ISO methods measure dimensional change up to 68\% RH for ISO 8226-1 and 86\% for 8226-2. Figure 6.26 illustrates the hygroexpansivity meter marketed by STFI-Packforsk in Stockholm Sweden that is in accordance with SCAN-P 28:88.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure626.png}
\caption{Schematic of hygroexpansivity meter.}
\end{figure}

\renewcommand{\thefigure}{6.26}

\section*{6.12 Flammability}

Mango\textsuperscript{(150)} reports that there are approximately 14 flame retardant tests, used with some degree of frequency for nonwovens. TAPPI T-461 and NFPA-701 are vertical flame tests of the type most commonly used for nonwoven filter media. The TAPPI T-461 test configuration is depicted in Figure 6.27. NFPA-701 utilizes an apparatus with a very similar configuration. In this test, a flame is applied to the bottom of a specimen, 70 × 210 mm (2.75 × 8.25 in.), and then withdrawn. The following properties are measured:

1. \textit{Char length}: The length of char caused by the flame as determined by poking the char away with a 6 mm rod.
2. \textit{Flaming time}: The time the flame continues to burn or be visible after the igniter flame has been removed.
3. \textit{Glowing time}: The time the specimen continues to glow after the flame has gone out.

ASTM D-2863 is also a vertical flame test that defines an “Oxygen Index” (OI) to measure flammability. A small test specimen is supported vertically in a mixture of oxygen and nitrogen flowing upward through a transparent chimney. The upper end
of the specimen is ignited and the subsequent burning behavior of the specimen is observed to compare the period for which burning continues, or the length of specimen burnt, with specified limits for each burning. By testing a series of specimens in different oxygen concentrations, the minimum oxygen concentration is determined. The OI is that minimum concentration. The higher the OI of a material, the lower is its flammability. Mango\(^{150}\) notes that the ASTM D-2863 is used to measure flammability of polymers and this may differ significantly from the flammability of that polymer in a nonwoven substrate.

There are versions of the vertical flame test where the specimen is tilted at an angle of 45°. Among these are NFPA-702, AATCC-33, and ASTM 1230-61. MVVS-302 (Motor Vehicle Safety Standard, US Department of Transportation) is a horizontal test for interior materials of transportation vehicles. The configuration is illustrated in Figure 6.28.

### 6.13 Filter Media Filtration Testing

A filtration test on a nonwoven filter medium is generally designed to evaluate and rate the medium for some form of filtration efficiency, dirt or dust holding capacity, and/or pressure drop. Tests may be run on a flat sheet media or on standard filters or
filter elements made from the medium. Filtration results on a flat sheet medium do not necessarily parallel the field performance of a filter made from this medium. In addition, standardized filter element testing may not accurately predict field performance. Many variables in filter design, construction, and quality can easily offset the flat sheet performance of a filter medium. In addition, the challenge conditions by which a filter is tested may not effectively represent the environmental conditions a filter will encounter in real life applications. The test dirt or challenge aerosol of a test may not simulate the contaminants in real filter environments. Climate, weather, temperature, humidity, aging, chemical degradation, etc. are all factors that can affect a filter contrary to test performance expectations. Nevertheless, tests and standards are necessary for filter media. It would be practically impossible to test choose a medium for any given filter application unless there were test data to support it.

Following is a discussion of the various factors that are considered in the filtration testing of a medium.

### 6.13.1 Efficiency

There are a number of test methods and methodologies to evaluate filtration efficiency. Following are some of them.

#### 6.13.1.1 Filtration efficiency

Filtration efficiency simply rates a medium by the percentage of contaminant removed by the filter media as expressed in Equation (6.23). The quantity can be by weight or mass, by number of particles, or by volume:

\[
e = 100 \left( \frac{M_u - M_d}{M_u} \right)
\]  

(6.23)

where

e is the filtration efficiency, %.

\( M_u \) is the upstream quantity of the contaminant.

\( M_d \) is the downstream quantity of the contaminant.
Penetration or leakage is the percentage of contaminant that penetrates the medium:

\[ e = \left( 1 - \frac{M_d}{M_u} \right) \times 100 \quad (6.24) \]

In some situations penetration might be the more pertinent perspective. Consider a case where the efficiency has to be improved from 98% to 99%. This appears to be a mere 1% increase in efficiency and would appear to require only a minor modification of the filter medium. On the other hand, the improvement has to reduce penetration from 2% to 1%; a 50% reduction. This would suggest a major redesign of the medium. The author’s experience suggests the latter is the more realistic perspective.

6.13.1.2 Single pass efficiency

In a single pass efficiency (SPE) test the particle contaminant in the fluid passes through the filter once. Any particles that penetrate are trapped by an “absolute” filter downstream of the test filter. After the test is completed, the absolute filter is weight analyzed to determine the penetration and the efficiency from Equation (6.23). Usually the test contaminant is controlled to a specified particle size or particle size range. An example of a SPE test is SAE HS806 for engine lube oil filters. The HS806 test also allows for cumulative efficiency testing (Section 6.13.1.3), multi-pass efficiency (Section 6.13.1.4), and dirt holding capacity (Section 6.13.3).

6.13.1.3 Cumulative efficiency

Cumulative efficiency is determined by making efficiency measurements at various intervals during a filter life test. In SAE HS806, the test dust contaminant is continuously added to the oil, which is continuously recirculated through the test filter. The oil is sampled at selected intervals during the test and analyzed for dust contaminant content. This is compared to the cumulative quantity of dust fed to system at the time of sampling. The efficiency so determined is the cumulative efficiency up to that point in the test. Note that unlike the SPE test, any contaminant that penetrates or leaks through the filter comes around for another chance to be filtered. The test is a multi-pass test, however the term “multi-pass testing” usually refers to testing where particle analyzers and counters are used to determine efficiency by particle size (see Section 6.13.1.5).

6.13.1.4 Micron rating

Micron rating is intended to be an indicator of the particle size of the particles that might be filtered by the medium. It is generally applied to liquid filters and their media. Supposedly a 5-micron filter would be capable of filtering particles 5 microns and larger in diameter. This type of filter rating is weak because it does not indicate the degree of efficiency for the rating, and allows for wide variance in filter performance of different filters having the same micron rating. Nominal and absolute micron ratings were adapted by some manufacturers. According to the Filter Manufacturers Council, nominal ratings were supposed to be based on 50% filtration efficiency for the particle size characterized and absolute ratings were based on 98.7%. Even this rating system is nebulous because test conditions are not well defined.
6.13.1.5 Multi-pass efficiency

The multi-pass procedure uses particle counter-analyzers to determine filtration by particle size. It is used to test actual filter elements and flat sheet media. Efficiencies are measured at selected intervals during the test and for a range of selected particle sizes. The efficiencies are cumulative and reported as “β (beta) ratios” as defined in Section 6.13.1.6. ISO 16889-99 developed for hydraulic fluid filters is one method based on the multi-pass procedure. It is discussed in more detail in Chapter 7, Section 7.3.2. Other standards based on multi-pass testing include ISO 4572-81, a predecessor to ISO 16889-99 for hydraulic fluid testing and SAE J1858 and ISO 4548-12 for engine lube oil filters. Filters for several types of materials in addition to hydraulic fluids, e.g. engine fuels, may be tested in accordance with the ISO 16889-99 or ISO 4572-81 procedures.

6.13.1.6 Beta rating

The β-ratio is the ratio of upstream particles to downstream particles. The more efficient is the filter, the higher is the β-ratio:

\[ \beta = \frac{N_{d,U}}{N_{d,D}} \]  \hspace{1cm} (6.25)

where

\[ N_{d,U} \] is the upstream particle count for particles of diameter \( d \) or greater.
\[ N_{d,D} \] is the downstream particle count for particles of diameter \( d \) or greater.

The β-ratio is related to filtration efficiency \( e \) as follows:

\[ \beta = \frac{1}{1 - (e/100)} \]  \hspace{1cm} (6.26)

In multi-pass testing, a subscript is attached to \( \beta \) to indicate the particle size for which the rating is being reported. A more detailed explanation of the β-ratio is provided in Chapter 7, Section 7.3.2.

6.13.1.7 Fractional efficiency

Fractional efficiency is a term generally applied to filtration efficiencies based on particle size or particle size groups. The β-ratio discussed above is a form of fractional efficiency, however the term is more often applied to air filtration standards. For example ASHRAE 52.2-1999 assigns MERV ratings (minimum efficiency reporting values) to fractional efficiency groups of particle sizes (see Section 6.13.1.8).

6.13.1.8 MERV rating

MERV ratings are minimum efficiency reporting values that are particular to ASHRAE 52.2-1999\(^{(152)}\). They are determined by subjecting a filter to fractional efficiency tests in accordance with test procedures defined by ASHRAE 52.2-1999. The procedures and methodology are discussed in Chapter 8, Section 8.2.2.2. A MERV rating is assigned based on its performance in the tests. MERV ratings range from MERV 1 for very coarse filters to as high as MERV 16 for very high efficiency filters. It should be noted that the lowest MERV ratings (MERV 1–MERV 4) are not determined from fractional efficiency
testing in accordance with ASHRAE 52.2, but from ASHRAE arrestance testing as prescribed by ASHRAE 52.1-1992\textsuperscript{153}.

6.13.1.9 Arrestance
Arrestance is a mass or weight efficiency as determined by Equation (6.23). ASHRAE 52.1 requires that it be called the “ASHRAE arrestance”. The ASHRAE procedure determines “average ASHRAE arrestance” of a filter based on measurements made at prescribed intervals during the life of the test. The ASHRAE 52.1 procedure is discussed in more detail in Chapter 8, Section 8.2.2.3.

CEN (Comité Européen Normalisation) Standard EN779\textsuperscript{154-1} utilizes an arrestance procedure for its G-rated filter classes (see Section 6.13.1.11). This is further discussed in Chapter 8, Section 8.2.2.1.

6.13.1.10 ASHRAE dust-spot efficiency
The ASHRAE dust-spot efficiency test is part of the ASHRAE 52.1-1992\textsuperscript{153} test procedure. It measures filtration efficiency of atmospheric dust by comparing the discoloration of two target filter sheets: one upstream of the test filter and one downstream. Since some of atmospheric dust will be filtered by the test filter, the downstream target filter will discolor at a different rate than the upstream target filter. By comparing the difference in discoloration, an efficiency number called the “ASHRAE atmospheric dust-spot efficiency” is determined.

6.13.1.11 CEN ratings
CEN Standard EN779\textsuperscript{154-1} is the European counterpart to ASHRAE 52.2. The standard rates filters according to their efficiencies by class, the higher the class number the more efficient is the filter. The coarse filters are rated G1 through G4 and are tested by an arrestance test as mentioned in Section 6.13.1.9. Classes F5 through F9 are tested by 0.4 $\mu$m liquid aerosol particles. The efficiency is based on the number percent of particles removed. Note that this differs from the arrestance which is based on the weight percent of particles removed.

6.13.1.12 HEPA and ULPA ratings
European standards for rating the efficiencies of HEPA and ULPA (ultra low penetration air) filters and media are prescribed by EN 1822\textsuperscript{154-2}. They are based on the filtration efficiency of the most penetrating particle size (MPPS). For filter testing, the medium is flat sheet tested (in accordance with EN 1822-3) to determine the MPPS. The filter is then tested for that particle size and at the flow rate at which the MPPS was determined. The challenge contaminant is either a monodisperse aerosol or a polydisperse aerosol. The ratings are an extension of EN 779. Ratings are H10–H14 for HEPA filters and U15–U17 for ULPA filters.

The US counterpart to EN 1822 are the recommended practices (RPs) of the Institute of Environmental Science and Technology (IEST). IEST-RP-CC001.4 is the RP that classifies 11 different filter types from Type A to Type K. The classifications are not necessarily in the order of efficiency. The efficiency includes a leak test and a penetration test. The penetration test is based on the efficiency of a medium against a 0.3 $\mu$m liquid aerosol, usually dioctylphthalate (DOP). Polyalpha olefin (PAO) has been approved as an alternative to DOP.
6.13.1.13 MPPS
The concept of MPPS has been discussed in Chapter 2, Section 2.1.2. It is the particle size that has the highest penetration through the media. Usually it is in the range of 0.1–0.4 μm. In the EN 1822 procedure, the efficiency is determined by number count. If the aerosol is quasi-monodispersed, the aerosol generated has had a particle size near MPPS. If the aerosol is polydispersed its fractional efficiency counting is done to determine MPPS.

6.13.1.14 Aerosol efficiency penetrometers
There are several types of filter testers that are used to test HEPA and ULPA filter media. The original Q127 penetrometer in accordance with MIL-STD-282 utilized 0.3 μm DOP smoke. British Standard BS 3928 has based its efficiency on 0.6 μm sodium chloride (NaCl) particles which, unlike DOP and PAO, is a solid aerosol. Although the Q127 penentrometer is still in use, more modern versions have been developed. Air Techniques International (ATI), the original developer of the Q127, now produces the Model TDA-100P automatic filter tester. Manual or full automatic operation is available. The unit uses either DOP or PAO as challenge aerosols. TSI Incorporated in St. Paul Minnesota USA has developed several automated filter testers and associated equipment capable of testing flat sheets, face-mask filters and other forms of air filters. The Model 8127 tests filters by oil aerosol only whereas the Model 8130 has the capability to test by either oil aerosol or salt aerosol. There is also a CertiTest® Model 3160 tester that also generates salt and oil aerosols, but over a range of particle sizes, so as to allow fractional efficiency and MPPS determination. Figure 6.29 is a flow diagram schematic of the Models 8127 and 8130 filter testers. Note they both use photometers to measure particle counts by light scattering. The Model 3160 uses condensation particle counters (CPCs). Figure 6.30, a photograph of the Model 3160 identifies some of its key components.

6.13.1.15 Filtration efficiency, bacterial filtration efficiency, and viral filtration efficiency
Particle filtration efficiency (PFE), bacteria filtration efficiency (BFE) and viral filtration efficiency (VFE) are tests are set up to evaluate surgical face mask and other medical filtration materials (see Chapter 8, Section 8.42).

7Vijayakumar points out that the DOP particle size of 0.3 μm, as determined by a photometer, is a mass median diameter. The count mean diameter (CMD), based on the average particle size of the number distribution is quite a bit smaller and is closer to the MPPS for HEPA filters. CMD is defined as the average particle size of the mass distribution.

8A test method will not only specify the particle size of the test contaminant, but also its concentration. The concentration for aerosols is either expressed in ppmv (parts per million by volume) or in mg/m³ (milligrams per cubic meter). The conversion is

\[\text{mg/m}^3 = \text{ppmv}/(12.187)(\text{MW})/(273.15 + T)\]

where

- MW is the molecular weight of the aerosol.
- T is the ambient temperature in °C.
Figure 6.29. Schematic of TSI Models 8127 and 8130 filter testers.
Reproduced with permission of TSI Incorporated, St. Paul, Minnesota, USA.

Figure 6.30. TSI CertiTest® Model 3160 automatic filter tester
Reproduced with Permission of TSI Incorporated, St. Paul, Minnesota, USA.

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Reproduced from "CertiTest® Model 3160 Automated Filter Tester – “Operation and Service Manual”. P/N 19 30041 Figure 2-1, Page 2-3, Revision – May 2003.
The PFE test in accordance with ASTM F2299-03 uses aerosolized latex particles, usually 0.1 micron, as the challenge aerosol. Control counts are performed without a test sample in the system, then the sample is tested. Efficiency is determined by comparing the counts through the sample to the control counts.

ASTM F2101-01 is a standard using an aerosol of *Staphylococcus aureus* (*S. aureus*) to evaluate the BFE of face-mask materials. Other types of bacterial organisms may be used, however they may give different results because of differences in shape and size. *S. aureus* has an approximate diameter of 0.8 microns. The organisms are generated into an aerosol with a nebulizer. As in the PFE test, the control is determined from counts without the test specimen in the system.

The VFE test procedure is adapted from the Military Standard MIL-M-36954C and ASTM F2101. The challenge aerosol is Bacteriophage OX174. The bacteriophage is one of the smallest of viral organisms. It has a diameter of range of 0.025–0.027 microns. The testing is very similar to the BFE test, except the smaller organism is used. The VFE procedure has become of recent interest because of the developing concerns of avian bird flu.

### 6.13.2 Pressure drop

Most filtration test methods require a pressure drop at a given flow rate. The pressure drop relates to the size of the pump or blower necessary to force fluid through the filter or filter medium. It also relates to the breathability of gas-mask and face-mask materials.

The pressure drop is measured by some form of differential pressure device with probes upstream and downstream of the media. In some cases this is no more than a simple u-tube manometer. Modern test stands have more sophisticated devices with electronic processors and digital readout capability. Usually the filter is pressure drop rated before it has been loaded with test contaminant. In some cases, the rating is established after a specified load has been applied to the filter.

### 6.13.3 Filter life testing

Filter life or dirt holding capacity is determined in two possible ways:

1. The test is run to a specified pressure drop and the time to that pressure drop is reported.
2. The amount of test dust trapped by the filter is measured and the filter is rated by its dirt holding capacity. Often the dirt holding capacity is prorated to area of filter media in the filter and reported as g/m² of medium or in some other form of mass:area ratio. This is important when comparing different media.

The time to pressure drop is often demonstrated by a plot. When using this criteria, one must be careful that the flow rate and rate of contaminant feed is controlled very carefully. The dirt holding capacity is probably a more informative test. The test results may not reflect on the media, but rather on the filter construction. For example, in pleated filters, the pleat count and pleat spacing may have more of an effect than the medium effect.
7.1 Introduction to Liquid Filter Applications

Liquid filtration applications are concerned with the filtration of either aqueous or hydrocarbon fluids. A large use of liquid filter media made from nonwovens and filter paper is in engine filtration applications. Engine filtration to include both air and liquid filtration is treated as a separate subject in Chapter 9.

The types of nonwovens used in nonautomotive liquid filter applications include needlefelts, paper sheets, filter papers, resin bonded paper, dry laid webs, and spunbond products. In liquid filtration there are also important applications for nonwoven supported membrane filters.

Large scale liquid filtration is accomplished mostly by cake filtration. Many forms of filter equipment use a filter fabric to support the cake. Often, the fabric is a woven filter cloth: however there are applications where the fabric is a needlefelt nonwoven. In recent years there has been an emergence of Spunlace (hydroentangled) felts and fabrics for industrial filter applications. Nonwoven and paper filter media are popular in filter presses.

Replaceable filter elements are used in many filter applications. Two of the most common types are liquid bag filters and cartridge filters. Liquid bag filters are often made of woven fabric filter media: however there are some applications where a nonwoven or a nonwoven composite material is utilized. A well-known form of a bag filter is the teabag composed of wet lay Manila hemp (abaca) fibers.

The biggest use of nonwovens in liquid filtration is as cartridge filters. Cartridge filters are used as polishing filters in industrial applications, for applications where high purity is demanded or where ultra high efficiency is expected. Examples are the health care and industries. Cartridge filters are also used in consumer filter applications such as home water filters and swimming pool filters. Pleated resin treated filter paper is the filter medium for many cartridge filter applications. Filtration of hydrocarbon fuels and engine lubricating oils are the biggest use of resin treated paper in liquid filter applications. This will be discussed in Chapter 9.

Following are applications of nonwoven filters in liquid filtration:

Filtration of aqueous fluids

1. Water treatment plants
2. Water desalinization
3. Water discharge treatment plants
4. Industrial process streams
5. Industrial chemicals
   (a) Paints
   (b) Latices
   (c) Electroplating solutions
   (d) Printing inks
6. Drinking water filtration
7. Beverage filtration
   (a) Coffee filter
   (b) Nonalcoholic beverages
   (c) Wine filtration
   (d) Beer filtration
8. Filtration of aqueous foods
   (a) Sugars
   (b) Food processing plants
9. Medical filtration applications
   (a) Blood filters
   (b) Vent filters
   (c) Contamination barriers
10. Pharmaceutical applications
11. Swimming pool filters
12. Aquarium filters

Filtration of hydrocarbon fluids

1. Industrial hydrocarbon processing
   (a) Petrochemicals
   (b) Resins (solvent base)
   (c) Lacquers
2. Aviation and diesel fuel filtration
3. Hydraulic fluids
4. Machine tool coolant and cutting oil filtration
5. Edible oil filtration
   (a) Fast food restaurants
   (b) Food processing

7.2 Nonwoven Filter Media for Liquid Filter Applications

7.2.1 Needlefelt products

Although needlefelt filter media are more often used in air filter applications, there are a number of liquid applications. They are a popular choice for bag filters and pocket filters. They are also used in vacuum belt filters. Because of the broad range of fibers that can be chosen for needle felts production, the media can be designed for filtration efficiency, for temperature, and for desired chemical exposure. The following indicates
the choice of needle felt fibers and what temperature and chemical exposures they can be used for:

1. **Cotton** – for alkalis and organic solvents up to 95°C.
2. **Rayon** – for aliphatic and aromatic solvents up to 150°C in a closed system and up to 120°C in an open system.
3. **Polyamide (nylon)** – for alkalis and solvents (except for alcohols) up to 150°C.
4. **Polypropylene** – for acids and alkaline solutions, and aliphatic solvents up to 110°C.
5. **Polyester** – for acids, oxidizing agents, and most organic solvents up to 150°C.
6. **Polyaramid (Kevlar®)** – for acids and alkalis up to 220°C.
7. **Polyphenylene sulphide (PPS)** – for acids, alkalis, and organic solvents up to 200°C.
8. **Polytetrafluoroethylene (PTFE)** – for acids, alkalis, and organic solvents up to 260°C.
9. **Polyimide (P84)** – for acids up to 260°C.

For example, Table 7.1 is a list of needlefelt properties identified for liquid filtration. Note that because of possible cross-lapping effects, the MD (length) direction tensile strength of some media may be less than the CD (cross) direction tensile strength.

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Weight (g/m²)</th>
<th>Air permeability (m³/m²/min @ ΔP = 20 mm H₂O)</th>
<th>Thickness (mm)</th>
<th>Tensile strength (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester</td>
<td>640</td>
<td>1.6</td>
<td>1.35</td>
<td>30 MD, 55 CD</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>9.5</td>
<td>1.0</td>
<td>90 MD, 55 CD</td>
</tr>
<tr>
<td>Polyamide</td>
<td>8 30</td>
<td>4.4</td>
<td>2.6</td>
<td>55 MD, 75 CD</td>
</tr>
<tr>
<td></td>
<td>8 10</td>
<td>2.0</td>
<td>2.7</td>
<td>55 MD, 75 CD</td>
</tr>
<tr>
<td></td>
<td>8 30</td>
<td>1.3</td>
<td>2.2</td>
<td>60 MD, 80 CD</td>
</tr>
<tr>
<td></td>
<td>8 10</td>
<td>1.5</td>
<td>2.4</td>
<td>60 MD, 80 CD</td>
</tr>
<tr>
<td></td>
<td>1050</td>
<td>3.5</td>
<td>3.3</td>
<td>65 MD, 90 CD</td>
</tr>
<tr>
<td></td>
<td>1075</td>
<td>2.2</td>
<td>3.0</td>
<td>65 MD, 90 CD</td>
</tr>
<tr>
<td></td>
<td>1050</td>
<td>2.5</td>
<td>3.4</td>
<td>65 MD, 90 CD</td>
</tr>
<tr>
<td></td>
<td>1050</td>
<td>1.5</td>
<td>2.8</td>
<td>60 MD, 85 CD</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>400</td>
<td>8.9</td>
<td>1.5</td>
<td>60 MD, 50 CD</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>9.8</td>
<td>2.4</td>
<td>60 MD, 35 CD</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>6.0</td>
<td>1.75</td>
<td>60 MD, 35 CD</td>
</tr>
<tr>
<td></td>
<td>6 10</td>
<td>0.8</td>
<td>1.6</td>
<td>30 MD, 50 CD</td>
</tr>
<tr>
<td></td>
<td>640</td>
<td>20.0</td>
<td>3.8</td>
<td>50 MD, 75 CD</td>
</tr>
</tbody>
</table>

### 7.2.2 Melt-blown media

Melt-blown nonwoven media are used in a number of liquid filter food and drink applications. This includes coffee bags, milk filter, and edible oil filtration. They are used in high efficiency reverse osmosis and ultrafiltration filters. Melt-blown media is most often used in composite form, often combined with spunbond media in SMS (spunbond/melt-blown/spunbond) type structures.
7.2.3 Spunbond media

Spunbonded media are used in almost every possibility of liquid filtration applications. An important one is in roll filters used in machine shops for removing metal shavings from coolant fluids and cutting oils. In Chapter 3, Section 3.3, it was noted that Reemay Advantage® and Reemay Freedom® marketed by BBA Filtration are media marked for swimming pool applications.

SoloFlo® is a flash spun spunbond developed by Dupont composed of HDPE. It is designed for microfiltration of aqueous fluids. This includes drinking water as well as industrial streams such as waste water treatment and plating solutions. The development and properties of the SoloFlo type medium is well discussed by Warren, etc.,(156) Mayer and Warren(157) reported on AFCTD (AC Fine Test Dust) challenge trials on an Oberlin pressure filter. The results were comparable to competitive media such as melt-blown polypropylene, PTFE membrane laminates, microporous membranes, and Dupont style T-980 (a flash spun material related to Tyvek®).

7.2.4 Electrospun media

Electrospun filter media have developed very well for air filtration applications, however they have exhibited less utility in liquid filtration applications. One reason may be that the electrostatic charge, inherent in electrospun media, is drowned out in liquid filtration. The nanofibers webs of the electrospun process consists of very fine fibers and would be expected to provide for high filtration efficiency, however, it may be at the expense of filter life and dirt holding capacity.

7.2.5 Filter papers

Wakeman and Tarleton(24) sub-classify filter papers as follows:

(a) Industrial papers
(b) Laboratory papers
(c) Filter sheets.

7.2.5.1 Industrial filter papers

Industrial filter papers are filter media intended for general liquid filter applications. They are often die cut or stamp punched to the desired shape for the intended application. Very often this is a filter press. They are also sold in roll form for roll filters and downstream converting. Typical applications are beverage filtration, pharmaceuticals, light oils, syrups, and vegetable oil filtration in food processing and restaurants. Roll forms of the media are used in roll filters for removing metal filings from machine shop coolant and cutting oils.

Some grades are identified as “wet strength” papers because they contain a wet strength such as melamine formaldehyde or polyamide epichlorohydrin to provide durability and structure support in aqueous filtration operations. They are sometimes creped to provide increased surface area for filtration. Creping also imparts more stretch
and flexibility when such properties are desired. Most industrial filter papers are made from wood pulp fibers, however for fine filtration operations; they are made with glass microfibers. In such cases a resin binder, such as polyvinyl alcohol, polyvinyl acetate, and acrylic polymers may be employed to add strength to the sheet. Industrial filter papers can be impregnated with adsorbent or absorbent powders such as activated carbon, diatomaceous earth, and perlite clay.

Ahlstrom is a major producer of industrial filter papers at their mill in Mount Holly, Pennsylvania. Table 7.2 is a summary of their industrial filter papers used in the fast food industry for filtering edible oils.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Composition</th>
<th>Surface</th>
<th>Basis weight(^a) (lb/1 389 ft(^2))</th>
<th>Thickness (mils)</th>
<th>Rapidity(^b) (ml/min)</th>
<th>Micro retention(^c) (µm)</th>
<th>Wet strength(^d) in H(_2)O</th>
</tr>
</thead>
<tbody>
<tr>
<td>933</td>
<td>Cellulose</td>
<td>Creped</td>
<td>70 (246)</td>
<td>40.0</td>
<td>435</td>
<td>27</td>
<td>120</td>
</tr>
<tr>
<td>963</td>
<td>Cellulose</td>
<td>Creped</td>
<td>54 (190)</td>
<td>28.5</td>
<td>440</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>967</td>
<td>Cellulose</td>
<td>Creped</td>
<td>70 (246)</td>
<td>40.0</td>
<td>475</td>
<td>33</td>
<td>100</td>
</tr>
<tr>
<td>968</td>
<td>Cellulose</td>
<td>Creped</td>
<td>50 (176)</td>
<td>27.5</td>
<td>600</td>
<td>40</td>
<td>75</td>
</tr>
<tr>
<td>1,278</td>
<td>Cellulose</td>
<td>Unfinished</td>
<td>35 (123)</td>
<td>19.5</td>
<td>–</td>
<td>45</td>
<td>250</td>
</tr>
<tr>
<td>1,384</td>
<td>Cellulose</td>
<td>Creped</td>
<td>44 (155)</td>
<td>23.0</td>
<td>450</td>
<td>31</td>
<td>110</td>
</tr>
<tr>
<td>8301</td>
<td>Cellulose/</td>
<td>Smooth</td>
<td>14 (49)</td>
<td>12.4</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>synthetic blend</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Basis weight based on a ream size of 500 sheets, 20 in × 20 in = 1,389 ft\(^2\).
\(^b\) Flow of water through the media at a continuous column height of 100 cm.
\(^c\) Particle size at 98% retention per Coulter Counter\(^e\).
\(^d\) Burst strength: pressure in inches of water to rupture a 2 inch diameter sample.

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### 7.2.5.2 Laboratory papers

Laboratory papers are recognized as the circular filter sheets used in laboratories around the world. They are also marketed in fluted, cone, and bag form, depending on the application. There are two categories of laboratory papers: qualitative and quantitative. According to Sutherland and Purchas\(^{12}\), "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 purity and composition of the filter paper are of crucial importance." Qualitative filter papers are characterized by their flow rates and relative efficiencies. Quantitative filter papers are also characterized by relative flow and efficiency and also by chemical composition. It is of critical importance that quantitative papers be of low ash content. For very high efficiency filtration, laboratory papers composed of glass microfibers are used.

A very well known producer of laboratory filter papers is Whatman International Ltd. in England. They produce both cellulose and glass microfiber filter paper. Table 7.3 is a tabulation of their cellulose filter papers. Table 7.4 is a similar tabulation of their glass microfiber filter papers.
<table>
<thead>
<tr>
<th>Grade</th>
<th>Particle retention*</th>
<th>Airflow rate (s/100 ml/in.²)</th>
<th>Ash (%)</th>
<th>Typical thickness (μm)</th>
<th>Basis weight (g/m²)</th>
<th>West burst (psi)</th>
<th>Dry burst (psi)</th>
<th>Tensile M/D dry (N/15 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qualitative</td>
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<td></td>
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</tr>
<tr>
<td>1</td>
<td>11</td>
<td>10.5</td>
<td>0.06</td>
<td>180</td>
<td>88</td>
<td>0.3</td>
<td>16</td>
<td>39.1</td>
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<tr>
<td>2</td>
<td>8</td>
<td>21</td>
<td>0.06</td>
<td>190</td>
<td>103</td>
<td>0.7</td>
<td>16</td>
<td>44.6</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>26</td>
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<td>390</td>
<td>187</td>
<td>0.5</td>
<td>28</td>
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</tr>
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<td>20-25</td>
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<td>0.06</td>
<td>205</td>
<td>96</td>
<td>0.7</td>
<td>10</td>
<td>28.4</td>
</tr>
<tr>
<td>5</td>
<td>2.5</td>
<td>94</td>
<td>0.06</td>
<td>200</td>
<td>98</td>
<td>0.4</td>
<td>21</td>
<td>55.6</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>35</td>
<td>0.2</td>
<td>180</td>
<td>105</td>
<td>0.3</td>
<td>15</td>
<td>39.1</td>
</tr>
<tr>
<td>General purpose and wet strengthened qualitative</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>91</td>
<td>10</td>
<td>6.2</td>
<td>N/A</td>
<td>205</td>
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<td>2</td>
<td>18</td>
<td>28</td>
</tr>
<tr>
<td>93</td>
<td>10</td>
<td>7</td>
<td>N/A</td>
<td>145</td>
<td>67</td>
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<td>12</td>
<td>38</td>
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<tr>
<td>113</td>
<td>30</td>
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<td>420</td>
<td>131</td>
<td>8</td>
<td>24</td>
<td>38.6</td>
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<tr>
<td>114</td>
<td>23</td>
<td>5.3</td>
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<td>77</td>
<td>8.9</td>
<td>15</td>
<td>42.1</td>
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<tr>
<td>Ashless quantitative</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>8</td>
<td>19.3</td>
<td>0.007</td>
<td>210</td>
<td>92</td>
<td>0.5</td>
<td>16</td>
<td>46.7</td>
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<tr>
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<td>0.007</td>
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<td>8.9</td>
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<td>96</td>
<td>0.6</td>
<td>12</td>
<td>38.2</td>
</tr>
<tr>
<td>44</td>
<td>3</td>
<td>57</td>
<td>0.007</td>
<td>176</td>
<td>77</td>
<td>0.4</td>
<td>44</td>
<td>39.4</td>
</tr>
<tr>
<td>Hardened low ash quantitative</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>2.7</td>
<td>96</td>
<td>0.005</td>
<td>115</td>
<td>97</td>
<td>9.1</td>
<td>33</td>
<td>84</td>
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<tr>
<td>52</td>
<td>7</td>
<td>11.4</td>
<td>0.005</td>
<td>175</td>
<td>101</td>
<td>8.3</td>
<td>24</td>
<td>71.5</td>
</tr>
<tr>
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<td>20-25</td>
<td>4.2</td>
<td>0.005</td>
<td>185</td>
<td>92</td>
<td>9.4</td>
<td>18</td>
<td>57.6</td>
</tr>
<tr>
<td>Hardened ashless quantitative</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>540</td>
<td>8</td>
<td>13.2</td>
<td>0.006</td>
<td>160</td>
<td>88</td>
<td>9</td>
<td>20</td>
<td>63</td>
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<tr>
<td>541</td>
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<td>3.8</td>
<td>0.006</td>
<td>155</td>
<td>82</td>
<td>5.3</td>
<td>14</td>
<td>43.4</td>
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<tr>
<td>542</td>
<td>2.7</td>
<td>69</td>
<td>0.006</td>
<td>150</td>
<td>93</td>
<td>9.2</td>
<td>28</td>
<td>82.6</td>
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</table>

Ash determined by ignition of the cellulose filter at 900°C in air.
*Particle retention rating at 98% efficiency.

**Trace elements – Typical**

<table>
<thead>
<tr>
<th>Grade</th>
<th>1</th>
<th>42</th>
<th>542</th>
<th>Grade</th>
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<th>42</th>
<th>542</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>&lt;0.5</td>
<td>2</td>
<td>1</td>
<td>Iron</td>
<td>5</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Antimony</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
<td>Lead</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Arsenic</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
<td>Magnesium</td>
<td>7</td>
<td>1.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Barium</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>Manganese</td>
<td>0.06</td>
<td>0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Boton</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>Mercury</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Bromine</td>
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<td>1</td>
<td>1</td>
<td>Nitrogen</td>
<td>23</td>
<td>12</td>
<td>260</td>
</tr>
<tr>
<td>Calcium</td>
<td>185</td>
<td>13</td>
<td>8</td>
<td>Potassium</td>
<td>3</td>
<td>1.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Chlorine</td>
<td>130</td>
<td>80</td>
<td>55</td>
<td>Silicon</td>
<td>20</td>
<td>&lt;2</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.3</td>
<td>0.3</td>
<td>0.7</td>
<td>Sodium</td>
<td>160</td>
<td>33</td>
<td>8</td>
</tr>
<tr>
<td>Copper</td>
<td>1.2</td>
<td>0.3</td>
<td>0.2</td>
<td>Sulfur</td>
<td>15</td>
<td>&lt;5</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Fluorine</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>Zinc</td>
<td>2.4</td>
<td>0.6</td>
<td>0.3</td>
</tr>
</tbody>
</table>

*All results expressed as μg/g.

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Table 7.4  Typical properties of Whatman® glass microfiber filter papers

<table>
<thead>
<tr>
<th>Grade</th>
<th>Particle retention* (s/100 ml/1 in.)</th>
<th>Airflow rate (g/m²)</th>
<th>Basis weight (µm)</th>
<th>Typical thickness (µm)</th>
<th>West burst (psi)</th>
<th>Tensile MD dry (N/15 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF/A</td>
<td>1.6</td>
<td>4.3</td>
<td>53</td>
<td>260</td>
<td>0.3</td>
<td>5.5</td>
</tr>
<tr>
<td>GF/B</td>
<td>1</td>
<td>12</td>
<td>143</td>
<td>675</td>
<td>0.5</td>
<td>6.4</td>
</tr>
<tr>
<td>GF/C</td>
<td>1.2</td>
<td>6.7</td>
<td>53</td>
<td>280</td>
<td>0.3</td>
<td>6.6</td>
</tr>
<tr>
<td>GF/D</td>
<td>2.7</td>
<td>2.2</td>
<td>121</td>
<td>675</td>
<td>0.3</td>
<td>6.4</td>
</tr>
<tr>
<td>GF/F</td>
<td>0.7</td>
<td>19</td>
<td>75</td>
<td>420</td>
<td>0.3</td>
<td>8.9</td>
</tr>
<tr>
<td>934-AH</td>
<td>1.5</td>
<td>3.7</td>
<td>64</td>
<td>435</td>
<td>0.5</td>
<td>4.1</td>
</tr>
<tr>
<td>QM-A</td>
<td>2.2</td>
<td>6.4</td>
<td>87</td>
<td>775</td>
<td>1.5</td>
<td>7.3</td>
</tr>
<tr>
<td>CMF 150</td>
<td>1.2</td>
<td>3.1</td>
<td>139</td>
<td>730</td>
<td>1.4</td>
<td>4.2</td>
</tr>
<tr>
<td>EPM 2000</td>
<td>2</td>
<td>4.7</td>
<td>85</td>
<td>450</td>
<td>1.8</td>
<td>6.3</td>
</tr>
</tbody>
</table>

* Particle retention rating at 98% efficiency.

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7.2.5.3  Filter sheets

Filter sheets are filter pads made on a wet lay machine that are thick enough to be used for depth filtration purposes. They range from 3 to 4-mm thick and are composed of cellulose fibers and a variety of filter aids such as diatomaceous earth or perlite clay. At one time they were composed of asbestos; however, the use of asbestos has been long discontinued because of its hazardous nature. Because of their thickness, filter sheets are referred to as depth filter sheets. They are mostly used in plate and frame type filter presses. Circular disc forms of filter sheets are used in lenticular filters.

Figure 7.1 is a diagram of a typical plate and frame filter press. A filter fabric is inserted between each plate and frame. Inlet flow is into the frames, through the fabric, and through the foraminous fabric support structure of the plate. The filtrate is discharged from the plate. The cake builds up on the filter fabric until the filter cycle is terminated. When the press is opened, the cake is then discharged to some sort of collection device such as a conveyor or collection bin. Filter fabrics can be woven
cloth, nonwoven fabrics such as needlefelt or spunbond, and industrial filter papers. Filter sheets are used when the effect of depth filtration is desired.

Lenticular filters are composed of parallel discs, each disc shaped like a double convex lens. Filter media covering both sides of the convex disc allow for inward filtration through both faces. Figure 7.2 is a photograph of the Zeta Plus® filters and cartridges marketed by Cuno-3M. It utilizes Zeta Plus® filter medium, a rigid depth filter sheet that has been chemically bonded with a positive electrolytic charge to enhance its ability to attract particulate matter from a liquid stream.

7.2.6 Resin treated filter paper

Resin treated filter paper, well described in Chapter 3, Section 3.5.2, is the medium of choice in most pleated filters. Liquid filter applications include lube oil filters, fuel filters, fuel filter separators, swimming pool filters, home water filters, and hydraulic filters.

7.2.7 Composite structures

In liquid filtration, composite structures are often used to provide gradient density filtration. They are also for prefilters to membrane filtration and reverse osmosis. Needlefelts for liquid filter applications are usually scrim reinforced to provide adequate strength.

1Zeta Plus is a trademark of 3M Company used under licence.
Ecologix Environmental Systems, L.L.C in Roswell, Georgia USA markets a line of liquid filter bags under the trade name of Ultrafit®. These are welded liquid filter bags containing a layer of melt-blown polypropylene microfibers. They also contain laminated multiple layers of graduated nonwoven material: the polypropylene microfibers being secured by ultrasonic means.

Another application for composite structures is taste and odor adsorbing media in drinking water filters. These contain an activated carbon layer (see Chapter 3, Section 3.9).

Composite media find broad application in engine filtration applications. This includes the filtration of lube oil, diesel fuels, and aviation fuels.

7.3 Filters that Use Nonwoven Filter Media

7.3.1 Roll filters

7.3.1.1 Description of roll filters

Roll filters are used in applications where the objective is to remove a waste material from a liquid stream. Examples are filters for sludge removal from waste water discharges and removal of metal particles in the coolant oils of machine shop operations. Roll filters are filters that unwind a roll of media and pass it through a filter chamber where it does the filtering. They generally operate on an indexing system that advances the filtering section of the medium when it starts to build up with filter cake and the flow rate becomes slow. Roll filters come in a variety of shapes and mechanisms. Two types are deep bed filters and pressure filtration systems filters.

Figure 7.3 is a picture of the Deep Bed Filters marketed by Industrial Filters Company (IFC) in Fairfield, New Jersey, USA. Note that the photograph which came from IFC promotional literature is backgrounded by a picture of a nonwoven medium used in this machine. The medium unwinds unto a conveyor belt which carries the media through the deep bed filtration area. The movement of the medium is controlled by automatically indexed based on slowdown of the fluid flow rate. Solids removal is by gravity filtration. The medium and cake are discharged together into the sludge box. This type of filter is primarily used for filtration of cooling oil from grinding operations and machine shop operations. It is also used in other places such as food processing operations. Figure 7.4 is a schematic of its use in waste sludge dewatering operations. Table 7.5 is a listing of the nonwoven filter grades recommended by IFC for their filters.

One manufacturer of pressure filtration systems is Oberlin Filter Company in Waukesha, Wisconsin USA. Figure 7.5 is a schematic of the Oberlin system used for coolant filtration. The roll filter medium unwinds into a filter compartment which closes around the medium and becomes pressurized by air and dirty coolant pumped into the compartment. The coolant is filtered through the medium until the cake build-up is such that the flow rate becomes too low or the pressure drop becomes too high. At this time the medium is blasted with air to remove excess fluid. The chamber then opens and fresh medium is advanced into the chamber for the next filtration cycle. The cake on the dirty medium, advancing out of the chamber, is doctored off the medium and into a tote box.
Figure 7.3. Industrial Filters Corporation (IFC) deep bed filter.
Reproduced with permission of Industrial Filters Company, Fairfield, New Jersey, USA.

Figure 7.4. IFC deep bed filter for sludge dewatering.
Reproduced with permission of Industrial Filters Company, Fairfield, New Jersey, USA.
7.3.1.2 Media for roll filters

Spunbonded polypropylene is probably the most widely used media for coolant filtration. This is one of the important applications for the Typar® and Tekton® spunbonded polypropylenes produced by Fiberweb™. Table 7.6 is a summary of their typical properties. Note that in one grade, TSISLF the LF stands for ultra low fuzz. This grade is designed for quick release of filter cake.

Roman[156] identifies polyester blends and pattern bonded nylon (PBN) as two frequently used media for roll filters used in cutting oil filtration. Polyester has the advantage of not extracting oil. Media made from polypropylene and nylon fibers do have this tendency and are more prone to blinding and premature indexing.

Tyvek®, a solution spun polyethylene is generally too tight and too dense to be used as a filter medium, however a variation to this is a series of filter grades, marketed by DuPont, known as SoloFlo®. The SoloFlo® media have already been discussed in...
Figure 7.5. Oberlin pressure filter.
Reproduced with permission of Oberlin Filter Company, Waukesha, Wisconsin, USA.

Table 7.6 Typar®/Tekton® polypropylene filtration media

<table>
<thead>
<tr>
<th>Style number</th>
<th>Basis weight (gsm)</th>
<th>Thickness (mm)</th>
<th>Grab tensile N MD × XD</th>
<th>Trap tear N MD × XD</th>
<th>Mullen burst (kPa)</th>
<th>Frazier air perm l/m²/s@124 Pa</th>
<th>Textest air perm (l/m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low denier</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>3091L</td>
<td>31</td>
<td>0.20</td>
<td>90 × 68</td>
<td>27 × 23</td>
<td>144</td>
<td>2,745</td>
<td>3,302</td>
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<td>3121L</td>
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<td>0.23</td>
<td>144 × 126</td>
<td>54 × 41</td>
<td>193</td>
<td>1,930</td>
<td>-</td>
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<td>3161L</td>
<td>54</td>
<td>0.25</td>
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<td>54 × 45</td>
<td>241</td>
<td>1,270</td>
<td>1,219</td>
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<td>3409L</td>
<td>136</td>
<td>0.38</td>
<td>540 × 360</td>
<td>158 × 90</td>
<td>729</td>
<td>147</td>
<td>-</td>
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<td>3609L</td>
<td>203</td>
<td>0.51</td>
<td>765 × 495</td>
<td>270 × 158</td>
<td>1217</td>
<td>80</td>
<td>66</td>
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<td><strong>Standard</strong></td>
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<td></td>
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<td></td>
</tr>
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<td>3121 (N)</td>
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<td>2,103</td>
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<td>680</td>
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</tr>
<tr>
<td>3601 (G)</td>
<td>203</td>
<td>0.53</td>
<td>1,215 × 1,283</td>
<td>482 × 554</td>
<td>N/A</td>
<td>195</td>
<td>-</td>
</tr>
<tr>
<td>3801 (N)</td>
<td>271</td>
<td>0.64</td>
<td>1,575 × 1,530</td>
<td>450 × 392</td>
<td>N/A</td>
<td>60</td>
<td>-</td>
</tr>
<tr>
<td>T-515 (LF)</td>
<td>203</td>
<td>0.51</td>
<td>1,035 × 1,035</td>
<td>198 × 239</td>
<td>711</td>
<td>147</td>
<td>152</td>
</tr>
</tbody>
</table>

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Section 7.2.3. Mayer\(^{(159)}\) has reported on these media in combination with Oberlin automated pressure filters to remove heavy metals from wastewater streams.

Kimberly-Clark markets Powerloft\(^{®}\), a bi-component polyolefin (polypropylene/polyethylene) medium primarily used for roll filter applications. It is a gradient density, spunbonded medium produced by a proprietary process. Typical properties are listed in Table 7.7.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Grammage (basis weight)</th>
<th>Permeability</th>
<th>Color</th>
<th>Caliper</th>
<th>CD tensile strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>oz/yd(^2) g/m(^2)</td>
<td>cfm/ft(^3)</td>
<td>m(^1)/m(^2)-min</td>
<td>@12.7 mm H(_2)O</td>
<td>in.</td>
</tr>
<tr>
<td>1.5 osy high loft</td>
<td>1.5</td>
<td>51</td>
<td>710</td>
<td>216</td>
<td>White/ blue</td>
</tr>
<tr>
<td>2.0 osy medium/high loft</td>
<td>2.0</td>
<td>68</td>
<td>520</td>
<td>159</td>
<td>White/ blue</td>
</tr>
<tr>
<td>2.5 osy medium loft</td>
<td>2.5</td>
<td>85</td>
<td>415</td>
<td>126</td>
<td>White/ blue</td>
</tr>
<tr>
<td>3.0 osy medium/high loft</td>
<td>3.0</td>
<td>102</td>
<td>400</td>
<td>122</td>
<td>White/ blue</td>
</tr>
<tr>
<td>4.0 osy medium loft</td>
<td>4.0</td>
<td>136</td>
<td>325</td>
<td>99</td>
<td>White/ blue</td>
</tr>
</tbody>
</table>

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### 7.3.2 Nonwovens for replaceable filter elements

#### 7.3.2.1 Explanation of replaceable filter elements

The largest use of nonwoven filter media is in replaceable filter elements. Sutherland and Purchas\(^{(12)}\) identify three types of replaceable filter elements:

1. Panel or cassette filters mostly used for air filtration.
2. Bag or pocket filters.
3. Cylindrically shaped cartridge filters.

The author defines “filter element” as that part of the filter that fits inside the housing and contains the media that does the actual filtering. For example, when filter mats are used for furnace filters and air ventilation systems, the filter medium itself is the replaceable filter element. In most liquid filtration systems, the medium is configured into some form of filter element. Bag filters and cartridge filters are most common. Most cartridge filters contain pleated media. The pleated medium as it comes out of the pleating machine is referred to as a “pleat-pack”. Pleat-packs are not filter elements until they are stabilized with a support structure, such as plastisol seals, end caps, support frames, pleat separators, pleat lock devices, etc.

It should be noted that cartridge filters are not always cylindrically shaped. Generally, they consist of a housing and a filter element. To illustrate, Figure 7.6 is a photograph of a diesel fuel filter. The pleated medium component on the left is the element and the

\(^1\)Reproduced from product data on Kimberly-Clark website: http://www.kcfiltration.com/kcfiltration.swf
entire assembly on the right, which includes the outside housing and the inside element, is the cartridge.

It is noted above that panel or cassette filters are used mostly for air filtration. This form of cartridge filter will be discussed in Chapter 8. The discussion in this chapter will be concerned with bag filters, and cartridge filters used for liquid filtration.

7.3.2.2 Cartridge filters

Cartridge filters are that part of a filtration system that are removable from the main body of the system for disposal and replacement, or for cleansing and reuse. In some applications, they can be cleansed in place by procedures such as reverse flow and reused without being removed. There are filter cartridges that are reclaimed for reuse. The cartridge or element is shipped to the manufacturer who strips it down and installs a fresh filter medium.

Cartridge filters or filter elements that are removed for cleansing or reclaim are specialized. Those removed for cleansing are “service-cleanable” cartridges or elements. These types of cartridges or elements are used in the manufacture and processing of polymers. Examples of “reclaimable” elements are filters used in high pressure hydraulic systems that require very expensive filter elements. In this situation, it would be economically justifiable to reclaim both the element and the housing.

7.3.2.2.1 Cartridge filters construction and assembly

Just about every type of nonwoven filter medium is used in filter cartridges. Most cartridge filters are cylindrically shaped. Some liquid filter cartridges have noncylindrical
shapes. Figure 7.6 above is an example of a noncylindrically shaped cartridge. Note that the housing is not a cylinder and the pleated filter element is oval shaped. Engine filtration (lube oil and fuel), one of the biggest users of liquid filter cartridges, will be discussed in Chapter 9. However, it is difficult to have a discussion of the types of filter cartridges without including engine filters. Therefore, the general construction, shape, and nature of liquid engine cartridge filters will be included in this discussion of cartridge filters.

There is a wide variety of cartridge filters and a wide variety of filter media used in these cartridges. Included are woven fabric media, sintered metal media, membranes, wound yarn and/or filament, mesh screen materials, and other novel media. This discussion will focus on cartridges containing nonwoven media.

7.3.2.2.2 Pleated filter elements

The most common form of cartridges are those containing elements of pleated filter media. The pleating process is discussed in Chapter 5, Section 5.4. Figure 7.7 is a picture of a pleated element construction using a felt medium. Note from the cut-away that the pleated felt medium is supported by a rigid pleated support mesh to prevent pleat collapse and pleat pinching. The outside and inside of the pleated filter cylinder is supported by concentric perforated cylinders. The inside cylinder is the core of the filter element. At the top of the element is an end cap that embeds and seals the pleated medium edges with the edges of the inner and outer cylinders. This is necessary to prevent leakage and by-passing of the filter medium. Note that the construction of Figure 7.7 is referred to as a filter element because it will be installed in some form of housing to become a cartridge.

Figure 7.7. Pleated filter element.
Another form of element is illustrated in Figure 7.8. This is a general purpose filter element containing multi-layers of pleated filter media. Versions of this cartridge incorporate various types of filter media including membranes of polypropylene, nylon, and PTFE sandwiched between protective layers of spunbonded media.

Figure 7.9a shows the cutaway components of a typical spin-on automotive engine oil filter. Figure 7.9b shows the filter in assembled form. The assembly is a cartridge filter containing both the filter element and the housing.

Although most pleat configurations are in a zig zag shape, there are new technologies that are particularly interesting. For example, Pall Corporation, East Hills, New York, USA has patented the Ultipleat® filter technology (US Patents 5,543,047 and 5,690,765), a filter construction using crescent shaped pleats. The curved pleat configuration results in a more stress resistant filter media. Figure 7.10 illustrates the pleat configuration and the fluid flow patterns. Figure 7.11 is an illustration of the pleat shape in the Pall Ultipleat® filter construction. Figure 7.12 demonstrates the improvement in filter life when compared to conventional pleats.

7.3.2.2.3 Dirt holding capacity in cartridge filters
The disposable cartridge or element is one that is sufficiently inexpensive, so that any attempt to clean and reuse the cartridge would not be economically justified. Depth filter cartridges usually cannot be readily cleansed because the dirt is so well entrapped in the medium that cleansing would provide little benefit in restoring the cartridge for reuse. Eventually, even cleanable cartridges will have to be replaced. It is evident that dirt-holding capacity is an important requirement on filter cartridges.

Ways to increase dirt holding capacity are:

(a) **Increase the surface area of the medium:** Pleating is the most popular way of increasing the surface area of a medium. By folding the medium back and forth, more of it can be fitted within the confines of a filter housing. Corrugation and, to a lesser degree, creping enhances the surface area of a filter medium.

(b) **Use a prefilter:** The concept here is that the prefilter would filter out the rocks and bolts and the final filter would take out the fine stuff that passes through the prefilter. Several arrangements are used for doing this. One is to use two filters or two banks of filters depending on the system. The first filter or filter bank would be the prefilter(s) and the second filter or bank of filters would be the final filter(s). There are filter designs where the prefilter medium and the final filter medium are contained within the same filter housing. There are also ways of designing prefiltration and final filtration effects into a single medium as discussed below.

(c) **Gradient density filter media:** Gradient density media have a change in density as the flow passes from the upstream surface to the downstream surface. The change in density allows for a form of depth filtration so that larger particles are removed at the low density upstream surface and finer particles are removed in higher density interior of the medium.

There are several ways of achieving gradient density effects in filter media. Wet lay filter paper is inherently a gradient density structure because as it forms, the side against the wire or forming fabric (the wire side) is denser than the side
Figure 7.8. All-polypropylene multilayer general purpose filter element.
Figure 7.9a. Engine oil filter components.
Reproduced with permission of Hollingsworth & Vose Co., Inc., East Walpole, Massachusetts, USA.

Figure 7.9b. Cutaway of engine oil filter assembly.
Reproduced with permission of Hollingsworth & Vose Co., Inc., East Walpole, Massachusetts, USA.
away from the forming fabric (the felt side). Multilayer forming of a fabric, where each layer has a successively lower density or successively larger pore structure, is also a way of forming gradient density media. This can be done with multi-card machines in the dry laid process and with multi-ply headboxes in the wet lay process. Kaukopaasi and Shah reported on a study of resin treated multi-layer wet lay media made out of wood pulp. Their report suggested that...
Lower onstream flow resistance with Ultipleat filter technology

Figure 7.12. Pall Ultipleat® vs. conventional pleat – effect on filter life.
Reproduced with permission of Pall Corporation, East Hills, New York, USA.

Figure 7.13. Cross-section of a gradient density filter medium.
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multi-layering could as much as double dirt holding capacity while at the same time increase filtration efficiency.

Dual layer structures can be designed to be gradient density media by combining a high porosity layer on the upstream side with a high filtration efficiency layer on the downstream side; in effect a prefilter and final filter within the same medium. Figure 7.13 is a cross-section photograph of a gradient density filter medium which is used in liquid filter bag applications.

(d) *Use bulkier and thicker media:* The bulkiness of a filter medium is related to its dirt holding capacity. Bulkiness can be increased by increasing the grammage of the
filter medium or by increasing its pore structure or pore volume. Pore volume can be increased by using coarser fibers, crimped fibers, and higher modulus (stiffer) fibers.

There are caveats in these approaches. A bulkier medium may have a snugger fit in the filter cartridge. If it is a pleated medium cartridge, the additional bulk may force the pleats to pinch and restrict flow resulting in a loss in dirt holding capacity rather than the desired increase. One may correct for this by reducing the number of pleats in the cartridge, however this reduces the surface area available for filtration and then what is gained by increased bulk is lost by reduced surface area. Increasing bulk by increasing pore volume of the filter medium may increase dirt holding capacity however, filtration efficiency may be compromised.

(e) Use positively charged media: An example of this is the Zeta Plus® filters and cartridges marketed by Cuno-3M that are mentioned above. Zeta Plus® is a family of patented filtration media composed of filter aids embedded in a cellulose fiber matrix. Molecules carrying a positive (cationic) charge are chemically bonded to the matrix components to form an interconnected, rigid filter sheet with positively charged electrokinetic capture sites. Since most contaminants found in fluid streams are negatively charged (anionic), they will be inherently attracted to the positive sites on the medium. The result is improved efficiency and dirt holding capacity. The Zeta Plus® media are used in a variety of industrial liquid filter applications, including pharmaceutical and bio-processing separations.

7.3.2.3 Wound filter elements
Wound filter elements are sometimes used in liquid coalescing separations such as separating water from fuel streams. They are analogous to paper rolls, in that the medium is wound around a mandrel. Kaydon Custom Filtration Corporation, LaGrange, Georgia USA produces two such filters illustrated in Figure 7.4. The filter on the left contains a reddish filter cylinder made from filter paper heavily impregnated with a phenolic resin. The paper was wound around a mandrel and then heated to fuse, bond, and cure the layers to each other. The result is a filter cylinder that appears to be a solid mass of resin impregnated fibers.

The filter on the left, also a liquid coalescing filter contains layers of wound glass fiber mat. This is the yellow layer contained between the inner core and outer cylinder housing.

7.3.2.4 Candle filters
Candle filters are a form of cylindrical filter cartridge that are mounted vertically. Very often there will be a multitude of these candles in an enclosure. They are generally used in air filtration applications. The two most common applications are as ceramic, glass, or metal filters for hot gas filtration (up to 1,000°C) and for air defogging operations (oil and/or moisture).

7.3.2.5 Bag filters
Bag filters are used for a number of liquid filter applications including bulk chemicals; food industry applications such as vegetable oil, coolants, cleaning fluids, paints,
Figure 7.14. Wound filter elements— the filter on left contains a wound filter element produced from heavily impregnated resin treated filter paper, the filter on the right contains a medium from wound layers of glass fiber mat.
Reproduced with permission of Kaydon Custom Filtration Corporation, LaGrange, Georgia, USA.

varnishes, waxes, and plastisols. Bag filters may be as simple as a filter medium bag attached to the end of a pipe. It will probably be more secure if it is attached by means of an adapter as shown in Figure 7.15. For higher-pressure and larger volume applications, the bag is inserted into a housing and supported by a mesh basket as displayed in Figure 7.16.

Many filter bags are composed of woven materials, however nonwoven materials have made an entry into this market. Nonwoven material types used in bag filters include needle felts, various forms of carded nonwovens, melt-blows, spunbonded webs, and composite structures. An example is Coform (Cox\(^{(161)}\)) produced by Kimberly Clark Corporation. Coform is a proprietary nonwoven process that combines debonded kraft pulp with meltblown polypropylene to form a unique filtration medium. Blending fibers of different sizes and shapes creates a unique pore structure that provides high efficiency while retaining good fluid flow mechanics and high particulate capacity. This unique process employs polypropylene meltblown as a binder so that there are no chemicals which could contaminate the fluid stream. Many of the medium’s properties, such as fiber blend, weight and pore density through the structure can be controlled in the manufacturing process. The Coform web is most often formed on a polypropylene spunbond carrier sheet. Properties of two Coform products are listed in Table 7.8 (Cox\(^{(161)}\)).
Adaptor head system

Figure 7.15. Filter bag adapter.

Figure 7.16. Filter bag housing.
Table 7.8 Coform liquid filtration media

<table>
<thead>
<tr>
<th>Properties</th>
<th>Coform filtration media 3.25 ozy</th>
<th>Coform filtration media 5.8 ozy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>White</td>
<td>White</td>
</tr>
<tr>
<td>Basis weight, oz/yd²</td>
<td>3.2</td>
<td>5.8</td>
</tr>
<tr>
<td>Grammage, g/m²</td>
<td>110</td>
<td>197</td>
</tr>
<tr>
<td>Air permeability cfm/ft² @ ΔP = 0.5 &quot;H₂O</td>
<td>139.2</td>
<td>54.8</td>
</tr>
<tr>
<td>m³/s/m² @ ΔP = 12.7 mmH₂O</td>
<td>0.71</td>
<td>0.28</td>
</tr>
<tr>
<td>Caliper</td>
<td>0.060</td>
<td>0.110</td>
</tr>
<tr>
<td>construction</td>
<td>1.5</td>
<td>2.8</td>
</tr>
<tr>
<td>60% debonded kraft</td>
<td>60% debonded kraft</td>
<td></td>
</tr>
<tr>
<td>pulp / 40%</td>
<td>pulp / 40%</td>
<td></td>
</tr>
<tr>
<td>polypropylene</td>
<td>polypropylene</td>
<td></td>
</tr>
<tr>
<td>meltblown</td>
<td>meltblown</td>
<td></td>
</tr>
<tr>
<td>Carrier Sheet</td>
<td>1.25 ozy black</td>
<td>1.25 ozy black</td>
</tr>
<tr>
<td>1.25 ozy black polypropylene</td>
<td>polypropylene</td>
<td></td>
</tr>
<tr>
<td>spunbond</td>
<td>spunbond</td>
<td></td>
</tr>
</tbody>
</table>

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7.4 Testing of Liquid Filters

The rating of filters and filter media for filtration performance is at best a difficult and treacherous procedure. The two important factors in a filter test are efficiency assessment, dirt holding capacity and pressure drop. The measurement of all of these factors can be very problematic.

7.4.1 Efficiency assessment

The simplest measure of efficiency is by gravimetric means. One determines the mass of contaminant upstream of the filter and downstream of the filter. The efficiency is:

\[ e = 100 \left( \frac{M_u - M_d}{M_u} \right) \]  

\( e \) is the filtration efficiency, %;
\( M_u \) is the upstream mass of the contaminant;
\( M_d \) is the downstream mass of the contaminant.

The problem with the mass approach is that it gives no concept of particle size. The sensitivity of our times demands that the filter user be able to assess not only the
overall efficiency of the filter, but also the particle size on which this efficiency is based on. More modern filtration testing techniques deal with this requirement by providing instruments to do particle size analysis.

Particle size analyzers and particle count analyzers determine the size and count of particles in a sample. Following are some of the techniques for particle size analyzers:

(a) *Light extinction:* A common system for automated particle counting (APC). The fluid is transported through a small transparent tube located between a light source on one side of the tube and an optical sensor on the other side. The sensor emits a specified electrical signal. The tube is narrow enough so that any particle in the fluid passing through the light source – sensor line will block some of the light to the sensor, the amount of light blockage depending on the size of the particle. The “shadow” so created on the sensor causes a change in the emitted electric signal which can be related to the size of the particle. The number of changes will be a count of the particles.

(b) *Dynamic light scattering:* Also known as photon correlation spectroscopy (PCS), this technique determines hydrodynamic particle sizes by measuring the speed at which particles diffuse in the base liquid. The suspended particles are subjected to laser beams. The sum of the dispersed beams is measured. The method gives the mean particle diameter and the range of the particle size distribution.

(c) *Electrosensing-zone technique:* Originally developed for sizing blood cells, this technique provides a number-based distribution. Particles are suspended in a weak electrolyte and drawn through a small aperture. The width of the aperture, sized for the particle sample in question, can range from 0.4 to 1.200 μm. An “electrosensing” zone is created when current flows between two electrodes located on either side of the aperture. Particles passing through the aperture produce a current that is proportional to their particle size. This allows the electrosensing zone to count each particle.

(d) *Laser diffraction:* Also called low angle light scattering (LLAS), laser diffraction uses a light-scattering phenomenon coupled with mathematical algorithms to calculate the volume-based particle-size distribution. They are reported as volume-based distribution of spherical particles. The particle size range is from 0.05 to 2,000 μm.

(e) *Microscopy:* Allows for direct measurement of the particles in question. Manual particle size counting is tedious and subject to large variation because of small sample size. Often the analysis is done from an analytical membrane through which the fluid has been filtered and the particles retained on the membrane. The membrane contains a grid to simplify the particle counting and sizing. Modern computerized techniques allow for image analyzers to greatly speed-up and simplify the count procedure. An advancement of the microscope technology is the use of scanning electron microscopes (SEM). A problem with microscopic techniques in filter test stand studies is that a sampling bottle or container is used to take the sample. Unless the bottle or container is ultra-cleaned, residual dust inside can greatly contaminate the analysis.

(f) *Sedimentation:* Applies Stoke’s law to determine particle size based on the particle settling rates. Centrifugation may be used to assist the settling rate. This
method requires that the contaminant be denser than the fluid in which it is suspended. It also requires close temperature control for viscosity control of the fluid. The method is popular as a quality tool in some industries such as paint and ceramics, however it is not very well suited for filtration analysis.

(g) **Sieving:** Useful for analyzing suspensions or slurries with large particle sizes such as pulp fiber length analysis. It does not lend itself to filtration analysis.

### 7.4.2 Multi-pass test stand

The multi-pass test stand is the one most standardized for testing non-aqueous liquid filters and liquid filter media. Originally standardized by ISO 4572-81, the standard has since been upgraded to ISO 16889-99. This test is primarily specified for the filtration of hydraulic fluids. It is also used in engine filter evaluations for lube oil filters and fuel filters. The test measures the particle count of a carefully calibrated liquid contaminant upstream and downstream of the filter. It is a fractional efficiency test because it measures the filtration efficiency of the contaminant at various particle sizes. For filtration efficiency, it uses a factor called the Beta ($\beta$) ratio. This has been previously discussed in Chapter 6, Section 6.13.1.6.

The $\beta$-ratio is the ratio of upstream particles to downstream particles. The more efficient is the filter, the higher is the $\beta$-ratio.

\[
\beta = \frac{N_{d,u}}{N_{d,D}} \tag{7.2}
\]

$N_{d,u}$ is the upstream particle count for particles of diameter $d$ or greater; $N_{d,D}$ is the downstream particle count for particles of diameter $d$ or greater.

The $\beta$-ratio is related to filtration efficiency $e$ by the formula:

\[
e = \frac{1}{1 - (e/100)} \tag{7.3}
\]

$e$ is the filtration efficiency, %.

The $\beta$-ratio is reported with a subscript indicating the particle size for which the ratio is being reported. The test is cumulative. The $\beta$-ratio being reported is for all particles equal or greater than the particle size indicated by the subscript. The subscript will also include (c) to indicate the testing was done by the ISO 16889-99 procedure with a National Institute of Standards and Technology (NIST) certified and traceable test suspension. This is important, because there are still organizations that still use the old ISO 4572-81 method. To illustrate, $\beta_{10(0c)} = 25$ indicates that the ratio for 10 $\mu$m particles or greater was 25 (equivalent to 96% filtration efficiency) and that the NIST certified test suspension was used.

Table 7.9 relates $\beta$-ratio to filtration efficiency based on upstream particle count of 10,000 particles.

Figure 7.17 is a diagram of a typical multi-pass test stand. Figure 7.18 is a photograph of a test stand. The specified concentration of contaminant is injected into the
### Table 7.9  Comparison of β-ratio and filtration efficiencies

<table>
<thead>
<tr>
<th>If the upstream particle count</th>
<th>And the downstream particle count</th>
<th>Filtration efficiency (%)</th>
<th>β-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000</td>
<td>5,000</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>10,000</td>
<td>1,000</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>10,000</td>
<td>500</td>
<td>95</td>
<td>20</td>
</tr>
<tr>
<td>10,000</td>
<td>100</td>
<td>99</td>
<td>100</td>
</tr>
<tr>
<td>10,000</td>
<td>10</td>
<td>99.9</td>
<td>1,000</td>
</tr>
<tr>
<td>10,000</td>
<td>1</td>
<td>99.99</td>
<td>10,000</td>
</tr>
</tbody>
</table>

![Figure 7.17. Multi-pass filter test schematic.](image)

Injection reservoir upstream of the test filter at a known rate. Automated particle counters measure the particles by size and by count per volume of fluid both upstream and downstream of the filter being tested. The fluid downstream of the test filter and is recycled and continuously injected with contaminant throughout the life of the test. In accordance with ISO 16889-99, the following three contaminant levels are allowable: Condition 1: 3 mg/l; Condition 2: 10 mg/l; and Condition 3: 15 mg/l (Bensch16,23). The test is continued until a prescribed pressure drop is reached, at which point the test is terminated. The particle counts are recorded at 10 equal intervals during the test. For example, if the test is to be run for 100 min, particle size analysis will be conducted every 10 min. If the test is to last 1 h, then the analysis will be every 6 min. Since the particle counting is continuous and the test stand is computerized, the computer is programmed to back calculate the particle
counts at the 10 equal time intervals. Dirt capacity is also reported as the amount of test injected to cause the filter to reach its terminal differential pressure.

### 7.4.3 Test dust complication

One of the complications in upgrading from ISO 4572-81 to ISO 16889-99 was that the original test dust, AC Fine Test Dust (ACFTD) prescribed for 4572-81 was no longer being produced by what was then AC Rochester Division of General Motors. This was one of the reasons for upgrading. The new test dust is designated as ISO Medium Test Dust (ISO MTD). ISO MTD is similar to ACFTD in that it is silica based and from the same Arizona source as ACFTD, however it is processed differently and has a different particle size distribution. ISO MTD is supplied by Powder Technology Incorporated. ACFTD was ball milled and then classified into a convenient particle size distribution. There were two forms: ACFTD and AC Coarse Test Dust (ACCTD). The particle size distributions were done with microscopic particle counting. The new ISO dust instead of being ball milled is jet milled.

Figure 7.19 provided by Lifshutz compares the old with the new. The curves crisscross at 10 μm. Below 10 μm, the new size is larger than the old. Above 10 μm, the new size is smaller than the old. One result of this is that the definition of particle size will be changed under the new NIST calibration procedure. For example, 2 μm under the old procedure now becomes 4.6 μm(c) – the (c) referring to the NIST calibration. On the high side 15 μm becomes 13.6 μm(c). The ISO 16889-99 procedure also changed the definition of particle diameter and this may be at least part of the reason for the different particle sizes. Although particles are not perfect spheres, their size is based on the
assumption that they are. In the old definition, the particle diameter was based on the longest chord through the particle. Under the new definition the diameter is based on the sphere that has the same surface area as the particle. This is illustrated in Figure 7.20 provided by Lifshutz. 

There are four forms of the ISO test dust as listed by Bensch in Table 7.10.

7.4.4 Test comparison

Pall Corporation, East Hills, New York, USA ran a series of tests comparing the new ISO 16889-99 procedure to the previous ISO 4572 procedure. The results were reported by Bensch and presented as Figures 7.21–7.25. Five filters were tested and β-ratios were compared for different particle size ranges. The results are consistent with the particle size "criss-cross" demonstrated in Figure 7.19. For small particle sizes in the 1–3 μm range higher β-ratios were obtained with ISO 4572 (Figure 7.21). On the other hand, higher ratios were obtained by ISO 16889 for particles in the 6 μm and higher range (Figure 7.25). The criss-cross appears to be at 5–6 μm (Figures 7.22–7.24).

The testing by Pall Corporation also compared dirt holding capacities. Bensch indicates that although the two test may give different results for the same filter, there is no consistent pattern. The results may depend on the specific filter tested.

7.4.5 Cleanliness levels

The goal of a filter is to raise the purity of a fluid so that it can be used for its intended application. In fluid power systems and lubricating oil systems, particulate contamination causes abrasive wear and deterioration on the parts they are in contact with. Cleanliness levels for hydraulic fluids have been established to identify the quality of
Figure 7.20. Definition of particle size.
Reproduced with permission of INDA, Cary, North Carolina, USA (163).

Table 7.10 ISO test dusts

<table>
<thead>
<tr>
<th>ISO designation</th>
<th>Common name</th>
<th>Other names</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 12103 – A1</td>
<td>ISO ultrafine test dust (ISO UFTD)</td>
<td>PTI* 0–10 µm test dust</td>
</tr>
<tr>
<td>ISO 12103 – A2</td>
<td>ISO fine test dust (ISO FTD)</td>
<td>PTI* fine test dust SAE fine test dust</td>
</tr>
<tr>
<td>ISO 12103 – A3</td>
<td>ISO medium test dust (ISO MTD)</td>
<td>PTI* 5–80 µm test dust SAE 5–80 µm test dust</td>
</tr>
<tr>
<td>ISO 12103 – A4</td>
<td>ISO coarse test dust (ISO CTD)</td>
<td>PTI* coarse test dust SAE coarse test dust</td>
</tr>
</tbody>
</table>

*PTI – Powder Technology, Inc.

Reproduced with permission of Pall Corporation, East Hills, New York, USA.

Figure 7.21. Filtration ratios for Pall KZ Media.
Reproduced with permission of Pall Corporation, East Hills, New York, USA.
Figure 7.22. Filtration ratios for Pall KP Media.
Reproduced with permission of Pall Corporation, East Hills, New York, USA.

Figure 7.23. Filtration ratios for Pall KN Media.
Reproduced with permission of Pall Corporation, East Hills, New York, USA.

Figure 7.24. Filtration ratios for Pall KS Media.
Reproduced with permission of Pall Corporation, East Hills, New York, USA.
an oil or hydraulic fluid. Schroeder Industries LLC, Leetsdale, Pennsylvania USA has published a very thorough and detailed report on contamination management\(^{(164)}\). In it they identify the following standards for cleanliness levels: ISO 4405, ISO 4406-1999, NAS 1638, and SAE AS 4059. They are summarized in Table 7.11.

### Table 7.11 Cleanliness standards

<table>
<thead>
<tr>
<th>Standard</th>
<th>ISO 4405 Application</th>
<th>ISO 4406:1999 Parameters (mg/l of fluid)</th>
<th>NAS 1638</th>
<th>SAE AS 4059</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 4405</td>
<td>Highly contaminated media, e.g. washing media, machining fluids</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parameters</td>
<td>Number of particles</td>
<td>&gt;4 μm (c)</td>
<td>5–15 μm</td>
<td>&gt;4 μm(c)</td>
</tr>
<tr>
<td></td>
<td>&gt;6 μm (c)</td>
<td>5–25 μm</td>
<td>&gt;6 μm(c)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;14 μm (c)</td>
<td>25–50 μm</td>
<td>&gt;14 μm(c)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;100 μm</td>
<td>&gt;50–100 μm</td>
<td>&gt;21 μm(c)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;70 μm</td>
<td></td>
<td>&gt;38 μm(c)</td>
<td></td>
</tr>
</tbody>
</table>

#### Analysis methods

1. **Manual evaluation:**
   - The fluid undergoing analysis is filtered through a prepared membrane and the cleanliness class (contamination rating) estimated or counted by hand using a microscope.
2. **Automated particle counting:**
   - The fluid undergoing analysis is conducted through a particle counter, which tallies the particle fractions.

#### Remarks

1. **Manual evaluation:**
   - Very time-consuming, not very exact.
2. **Automated particle counting:**
   - Result available almost immediately.

---

Reproduced with permission of Schroeder Industries LLC, Leetsdale, Pennsylvania, USA.
### Table 7.12 SAE AS 4059 cleanliness coding system

<table>
<thead>
<tr>
<th>Maximum particle concentration (particles/100 ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size ISO 4402 calibration or visual counting</td>
</tr>
<tr>
<td>&gt;1 µm</td>
</tr>
<tr>
<td>Size ISO 11171 calibration or electron microscope**</td>
</tr>
<tr>
<td>&gt;4 µm(c)</td>
</tr>
<tr>
<td>Size coding</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>000</td>
</tr>
<tr>
<td>00</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
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<tr>
<td>7</td>
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<tr>
<td>8</td>
</tr>
<tr>
<td>9</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>12</td>
</tr>
</tbody>
</table>

Table shows the cleanliness classes in relation to the particle concentration determined.

*Particle sizes measured according to the longest dimension.

**Particle sizes determined according to the diameter of the projected area-equivalent circle.

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ISO 4405 is a gravimetric standard for relatively heavily contaminated fluids. The others rate cleanliness classes by particle size and count. NAS 1638 (National Aerospace Standard – US) has been largely superseded by SAE AS 4059. In fact, the most current version of NAS 1638 states “Inactive for new designs after May 30, 2001, see AS 4059C”. Table 7.12 tabulates the cleanliness classes of AS 4059. Note particle sizes are based on either of two different methods: ISO 4402 or ISO 11171, which do not give the same numbers. Regardless of which method is used, the particles are divided into 6 size ranges: A < B < C < D < E < F. There are 15 coding classes ranging from 000, the cleanest, to 12, the dirtiest.

There are three reporting options:

1. **Specifying at single sizes:** For example if the particle size of interest is >15 µm or >14 µm(c), and no more than 3,460 particles per 100/ml larger than this are specified, then the class code would be AS4059 6C.

2. **Specifying for specific sizes:** To illustrate, if the particle sizes of interest are >5 µm, >15 µm, and >25 µm (>6 µm(c), >14 µm(c), and >21 µm(c)) and the maximum number of particles greater than these sizes are 2430, 217, and 20, respectively, then the rating is AS4059 3B/2C/1D. Note that not all particle sizes have to be specified.
3. **Specifying the highest cleanliness class measured:** For example, if all six particle size ranged are of interest and the rating is **AS4059 6A through F**, then the maximum number of particles exceeding any size cannot be greater than the limits for that size as listed in the line of Size Code 6.

ISO 4406-1999 is similar in principle to SAE AS 4059, however it has different numbers. There are 20 cleanliness classes (8–28) and three particle size ranges (>4 μm(c), >6 μm(c), and >14 μm(c)). Unlike AS 4059 which allows particle counting by either the longest chord or by the diameter of the area equivalent circle, ISO 4406 calls out the equivalent circle technique.
CHAPTER 8

Air Filter Applications

8.1 Industrial Air Filtration

8.1.1 Dust collection systems

Dust collection systems are a big user of nonwoven filter media. The filter housings often referred to as bag houses are very large and usually consist of a large number of filter elements. The filter elements are usually fabric bags or fabric envelopes. Cartridge filter elements are also used in these systems. For very high temperature (up to 1000°C) applications, candle filters composed of ceramic fiber may be used.

The fabrics for the bag or envelope filter elements are either woven fabrics or non-woven felts. It is estimated that the market split between these two filter media types is 50:50. Dickenson, argues that the filters operate by sieving the particles from dust-laden air and building a filter cake on the media. The filter cake actually does most of the filtering. The fabric serves as a support structure. Figures 8.1 and 8.2 are

Figure 8.1. MBT normal operation.
Reproduced with permission from Donaldson Company, Inc. © Donaldson Company, Inc. All rights reserved.
diagrams of two types of modular baghouses: MBT and MBW. The MBT module is one where the bags are replaced from the top. The MBW module provides a walk-in space for replacing the bags.

Economics requires that the filter elements be able to be reconditioned or cleaned. The most common methods for doing this are mechanical shaking, low-pressure reverse air, and high pressure-reverse jet (pulse jet). Figure 8.3 depicts a pulse-jet filter. Figure 8.4 diagrams the normal filtering mode and the reverse jet cleaning operation of a reverse jet cleaner.

Table 8.1 lists the characteristics of fabric-type collectors. Note that nonwovens are predominantly used in the “Continuous operation any loading” type of systems. The advantage of using felts rather than woven fabrics, in bag and envelope filters is that felts are more efficient as determined by efficiency ratings. Because felts are more difficult to clean, they are more commonly used in pulse-jet type of filters. Often a surface treatment is applied to give it better cake release properties. This includes calendering, glazing, and singeing as discussed in Chapter 3, Section 3.2.1.

The efficiency of a fabric filter medium can be improved by applying a membrane to the surface of the fabric. Often these are applied to needlefelt fabrics. W.L. Gore and Associates has pioneered this approach with their GORE-TEX® ePTFE membranes laminated to a number of baghouse fabrics. Table 8.2 lists some of the needlefelled laminates. A variety of fibers is available for optimizing the choice of heat and chemical resistance. Table 8.3 lists temperature, physical resistance, and chemical resistance of a number of fibrous materials used in baghouse filter fabrics.

AFFCO (American Felt and Filter Company) in New Windsor, New York USA, markets a filter medium product called “The Heat Shield™” (166). “The Heat Shield™” is a Nomex® needlefelt reinforced with a woven basalt scrim. It is being promoted for high temperature baghouse operations such as might be found in a hot mix asphalt plant. AFFCO claims when a Nomex® felt was placed in a 1000°F (523°C) for 60 min it was “destroyed beyond recognition”. On the other hand when the felt was reinforced with
Air Filter Applications

Distribution soundproof baffles of casing of cleaning gases and systems.

Integral piston valve

Access doors to cleaning system

Access doors to filtering sleeves easily removable by mobile lifting trolley

Figure 8.3. Pulse-jet filter


the basalt scrim there was “Zero shrinkage”. Tables 8.4 and 8.5 are a data sheet and specifications, respectively, of the “The Heat Shield™” products. Note that in addition to Nomex®, the basalt reinforcing scrim can be used with other fibers such as PPS, P-84®, and Tellon®.

Figure 8.4. Normal and reverse jet cleaning operation.\textsuperscript{2}

Table 8.1 Characteristics of fabric type collectors\textsuperscript{3}

<table>
<thead>
<tr>
<th>Fabric reconditioning requirement</th>
<th>Interruptible operation – light to moderate loading</th>
<th>Interruptible operation – heavy loading</th>
<th>Continuous operation – any loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of reconditioning</td>
<td>Shaker</td>
<td>Shaker (low pressure)</td>
<td>Reverse pulse (high pressure) pulse jet or fan pulse</td>
</tr>
<tr>
<td>Collector configuration</td>
<td>Single compartment</td>
<td>Multiple compartments with inlet or outlet dampers for each</td>
<td>Single compartment</td>
</tr>
<tr>
<td>Fabric configuration</td>
<td>Tube or envelope</td>
<td>Tube or envelope</td>
<td>Tube or Pleated cartridge</td>
</tr>
<tr>
<td>Type of fabric</td>
<td>Woven</td>
<td>Woven</td>
<td>Nonwoven felt Nonwoven Paper mat</td>
</tr>
<tr>
<td>Air flow</td>
<td>Highly variable</td>
<td>Slightly variable</td>
<td>Virtually constant Virtually constant</td>
</tr>
<tr>
<td>Normal rating (filtration velocity, ft/min)</td>
<td>1–6 ft/min</td>
<td>1–3 ft/min</td>
<td>5–12 ft/min &lt;1–2.5 ft/min</td>
</tr>
</tbody>
</table>


Donaldson Company, Inc. of Minneapolis, Minnesota, USA has introduced Dura-Life™, a line of hydroentangled felts for baghouse operations. Donaldson Company reports twice the filter life (Fulko) compared to needle punch felts. Their data show that the hydroentangled material with finer fibers gives a more uniform material with smaller pore size. This results in better surface loading and less depth loading, which in turn gives “better pulse cleaning = lower pressure drop = longer life”.

8.1.2 Fume and vapor emissions

Federal regulation, good safety practice, worker protection, and protection of the environment demand that fumes and vapors from industrial operations be removed and separated from the exhaust air stream. Fumes and vapors can emerge from welding operations, paint spraying, machine tools (oil mists), chemical laboratories, etc.
Table 8.3 Properties of fiber materials used in filter bags

<table>
<thead>
<tr>
<th>Generic name</th>
<th>Maximum temperature °C (°F)</th>
<th>Physical resistance</th>
<th>Chemical resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Continuous</td>
<td>Intermittent</td>
<td>Dry heat</td>
</tr>
<tr>
<td>Cotton</td>
<td>80 (180)</td>
<td>-</td>
<td>G</td>
</tr>
<tr>
<td>Polyester</td>
<td>135 (275)</td>
<td>-</td>
<td>G</td>
</tr>
<tr>
<td>Acrylic</td>
<td>235 (275)</td>
<td>140 (285)</td>
<td>G</td>
</tr>
<tr>
<td>Modacrylic</td>
<td>70 (160)</td>
<td>-</td>
<td>F</td>
</tr>
<tr>
<td>Nylon (polyamide)</td>
<td>115 (240)</td>
<td>-</td>
<td>G</td>
</tr>
<tr>
<td>Nomex*</td>
<td>205 (400)</td>
<td>230 (450)</td>
<td>E</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>95 (200)</td>
<td>120 (250)</td>
<td>G</td>
</tr>
<tr>
<td>PTFE (fluorocarbon)</td>
<td>260 (500)</td>
<td>290 (550)</td>
<td>E</td>
</tr>
<tr>
<td>Fluorocarbon</td>
<td>230 (150)</td>
<td>-</td>
<td>E</td>
</tr>
<tr>
<td>Vinyon</td>
<td>175 (350)</td>
<td>-</td>
<td>F</td>
</tr>
<tr>
<td>Glass</td>
<td>290 (550)</td>
<td>315 (600)</td>
<td>E</td>
</tr>
<tr>
<td>Wool</td>
<td>100 (215)</td>
<td>120 (250)</td>
<td>F</td>
</tr>
</tbody>
</table>

* *Du Pont de Nemours International S.A. trademark.
Key: E—Excellent; F—Fair; G—Good; P—Poor.

Dickenson[165] identifies two types of industrial fumes, “dry smoke” and “wet smoke”. Dry smoke usually consists of solid particles in air such as that emitted by welding operations or certain types of machining operations. Wet smoke is aerosols such as oil mists. Aerosols are liquid droplets dispersed in air having a particle size range of 0.5–10 μm. The fumes of both dry and wet smoke are removed from the workplace by air extraction devices such as hoods, canopied hoods, ventilated booths, ventilated enclosures, and slotted air extraction devices (also known as fish tails).

Once removed from the workplace, the fume particles have to be separated from the exhaust air stream. Separation devices include electrostatic and/or electrodynamic...
Table 8.4  The Heat Shield™ data sheet

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Style 74/6HTBA.14</td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td>aramid with basalt scrim</td>
</tr>
<tr>
<td>Finish</td>
<td>calendered, singed one side</td>
</tr>
<tr>
<td>Weight</td>
<td>14 oz/sq yd</td>
</tr>
<tr>
<td>Permeability</td>
<td>25 - 35 cfm</td>
</tr>
<tr>
<td>Mullen Burst</td>
<td>550 - 650 psi</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.06 - 0.07 in</td>
</tr>
<tr>
<td>MD Tensile Strength</td>
<td>120 - 150 lb</td>
</tr>
<tr>
<td>CD Tensile Strength</td>
<td>200 - 250 lb</td>
</tr>
<tr>
<td>MD Elongation</td>
<td>10 - 20%</td>
</tr>
<tr>
<td>CD Elongation</td>
<td>10 - 20%</td>
</tr>
</tbody>
</table>

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Table 8.5  Specifications for "The Heat Shield™" filter media

<table>
<thead>
<tr>
<th>Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials of construction</td>
<td>PPS P-84, Kynol, Teflon, Basofil, Polyacrylonitriles, Nomex</td>
</tr>
<tr>
<td>Surface finishes</td>
<td>Calendering, glazing (eggshell), or singeing</td>
</tr>
<tr>
<td>Coatings</td>
<td>PTFE, acrylic, or silicone</td>
</tr>
<tr>
<td>Blends and composites</td>
<td>Dual density, fire resistant, static retardant (stainless steel or epitropic)</td>
</tr>
<tr>
<td>Operating limitations</td>
<td>Do not exceed recommended temperature limitations of materials. Use only in chemically compatible environment</td>
</tr>
<tr>
<td>Standard basis weights</td>
<td>8, 10, 12, 14, 15, 18, and 18 oz/sq yd</td>
</tr>
</tbody>
</table>

Printed with permission of AITCO, New Windsor, New York, USA.

means, centrifugal impaction units, and paper and bag type filters. Nonwoven media are certainly used in the paper and bag type filters. They are also sometimes used as the media for prefilter filters to the other types of separation devices.

AAF International has introduced portable weld fume filters. These are self-contained units that capture welding smoke and fumes at the source. They consist of long duct arms that can be positioned over the localized work site and extract smoke and fumes. This is illustrated in the schematic of Figure 8.5. The unit diagrammed is the Optifo® WFE 150P. There is also an Optifo® WFE 300P that contains two arms. The arms can be rotated 360° and extended approximately 100 in. Two filters located in the main cabinet are high efficiency cartridge filters rated at 99.9% filtering efficiency. Activated carbon filters are also available.
In addition to workplace, protection gas cleaning devices are necessary to reduce or eliminate vapors and dust emissions from incinerators, power stations, cogeneration plants, and production facilities of the paper, cement, metallurgical, and other industries. This is to be in compliance with the environmental regulations of many countries. The systems include scrubbing systems, carbon adsorption, catalytic oxidizers, ceramic filters, and oxidizer systems. Some facilities use biofiltration, a technique to remove odorous and other obnoxious components from a gas stream by passing the stream through a medium that has been inoculated with microorganisms that break down the offending components.

The fumes are often hot (up to 900°C) and corrosive. Fabric bag filters are often included as a prefilter to the cleaning system usually. According to Dickenson\(^{165}\), “the development of heat and corrosion resistant fabric media, particularly modern treated needlefelts, has been one of the most significant advances in the dust extraction and treatment of hot gases.” Needlefelts composed of polyamides, polypropylene, PTFE, aramides, glass, and mineral fibers have successfully been used in a wide range of hot gas filtration applications. Table 8.6 lists the properties of various filter fabrics.
### Table 8.6  Properties of various filter fabrics

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Short period excursions [°F]/[°C]</td>
<td>250°F/120°C</td>
<td>220°F/105°C</td>
<td>295°F/145°C</td>
<td>250°F/120°C</td>
<td>285°F/140°C</td>
<td>430°F/220°C</td>
<td>375°F/190°C</td>
<td>555°F/290°C</td>
<td>500°F/260°C</td>
<td>Amorphous</td>
</tr>
</tbody>
</table>

Resistance against alkali:  
1 = Excellent;  
2 = Good;  
3 = Very good;  
4 = Fair;  
5 = Poor.  

8.2 Heat Ventilation and Air Conditioning Systems

HVAC (Heat ventilation and air conditioning) systems control air quality in residences and the work place. They also provide for clean air in sensitive work areas where dust or microbial contamination may be a problem. Examples are manufacturing of sensitive electronic components, pharmaceutical manufacture, and hospital operating rooms. Clean rooms using HEPA (High efficient particulate air) and ULPA (Ultra low penetration air) filters are often designated for dust sensitive work areas. Residential ventilation filters usually do not require such high degrees of filtration efficiency. Likewise, routine workplace areas such as office locations usually do not justify such levels of filtration efficiency. However, there is consideration and concern for people with serious allergies and health problems that may need protection from the finer and smaller contaminants in the air environment. In recent times, an increasing concern about protection against CBR (chemical, biological, and radiation) agents has arisen.

8.2.1 Filters for air cleaning systems

8.2.1.1 Panel filters

Square or rectangular panel filters are the most frequently used for air cleaning systems in the residences and in the work place. This does not include air freshener type filters that are becoming increasingly popular in homes and residences.

Panel filters can be as simple as mats of high loft medium that a residence owner can cut from a roll of the medium and fit into his filter location. The mats are also available in precut filter sizes. Usually the mats are composed of fiberglass or polyester. They are often reinforced with a support scrim. Some mat filters are composed of natural fibers. Airguard, Louisville, Kentucky advertises their Permalast® Filters as being composed of “latex coated natural fibers (hog’s hair)”. AAF International, Louisville, Kentucky markets a “Cut-N-Fit™” mat made from a blend of hogs hair and coconut fibers.

There are also more complicated mini-pleat panel filters that are most often used for high efficiency air filter applications (see Section 8.3.1).

Kinzer and Moreno(17), identified six main categories of in-duct air cleaning devices for residential air handling systems. They are:

(a) Fiberglass filters – These are glass mat filters composed of 15–60 μm glass fibers with a high porosity. These are the most common filters used in residential furnace and air conditioning systems. They are low cost. Their purpose is to protect the system from debris that might damage components of the air systems such as fans, motors, cooling coils, and heat exchangers. These filters are 3/4–1 in. (1.9–2.5 cm) thick and available in standard and special sizes up to 20 × 30 in. (50 × 75 cm). Manufacturers recommend that these filters be changed once a month during seasons of normal use.

(b) Pleated filters – Pleated filters are composed of nonwoven mats made from synthetic and/or natural fibers. Like the fiberglass filters they are highly permeable.
The fibers most frequently used are cotton and polyester. The fibrous mat is the filter medium. It is usually supported by a wire frame in the form of V-shaped pleats. These filters are also 3/4–1 in. thick and come in a variety of sizes. The pleating increases the exposed surface area of the medium and extends filter life. The manufacturers recommend that these filters be replaced every 2–3 months during seasons of normal use.

(c) **Washable/reusable filters** – These are panel filters that can be cleaned and reused. They are also highly permeable. The filter medium is usually a combination of synthetic reticulated foam between layers of woven polyester or polypropylene mats. Another version consists of a layer of a nonwoven polyester sandwiched between layers of woven polyester or polypropylene mats. The layers are usually contained between metal or plastic grids. They are also very permeable. The thickness is 3/4–1 in. Some filters have adjustable frames so that they can be cut to fit a variety of heating and cooling systems. Understandably, these filters are considerably more expensive than the fiberglass and pleated filters described above.

(d) **Electret filters** – These filters use a filtering medium consisting of a mat of electrostatically charged fibers. In addition to simple mechanical particle capture, these filters can also trap particles by electrostatic attraction. The filtration efficiency is substantially improved compared to comparable uncharged filters and at no increase in resistance to air flow. The filters are 3/4–1 in. thick and come in a variety of sizes. They are disposable and priced higher than fiberglass and pleated filters but less than washable/reusable filters. Their recommended replacement life is 3 months during seasons of normal use.

(e) **Deep pleated filters** – These filters are up to 5 in. (13 cm) thick and usually require special support structure in the duct work. The medium is similar to that used in pleated filters discussed above. These filters are relatively expensive and pricing is in the range of washable/reusable filters. In some designs the frames are reusable and only the medium needs be replaced. Other designs have the filters made of rigid cardboard frames and the whole unit is disposable. The large surface area due to deep pleating greatly extends the filter life. Manufacturer's recommend replacement is once or twice a year.

(f) **Electronic air cleaners** – Electronic air cleaners do not use a filter medium to collect particles. Rather, they use a high voltage ionization field to charge the particles with a negative or positive charge. The charged particles are then deposited on collector plates. These filters can be quite efficient as indicated below, however they are quite expensive. The collector plates need to be cleaned periodically. The cleaners require regular maintenance every 1 to 2 months.

Kinzer and Moreno tested 27 filters in a fractional efficiency procedure based on ASHRAE 52.2P, a drafted standard that later became ASHRAE 52.2-1999. The 27 filters were divided into the six categories discussed above. One of the results they presented was a comparison of the filtration efficiencies for 0.3–1.0 μm particles presented in Figure 8.6. Their data indicated that best performance comes from the electrostatic (electret) and electronic filters.
Figure 8.6. Minimum and maximum efficiency over the 0.3–1.0 μm particle size range for each of the six residential in-duct air cleaning device categories.

Reproduced with permission of the American Filtration and Separation Society, Richfield, Minnesota, USA (170).

Duran (171) identifies the following types of media used in indoor air filtration applications:

(a) Fiberglass
(b) High loft polyester (PET)
(c) Cotton/Polyester
(d) Needlefelt
(e) Fibrillated film
(f) Meltblown
(g) Bi-component spunbond.

8.2.1.2 Pocket filters
Pocket filters are filters containing a series of multiple bag-like pockets offering extended surface areas and increased dust holding capacity. Examples of pocket filters offered by Flanders-Precisionaire, St. Petersburg, Florida are illustrated in Figures 8.7, 8.8, and 8.9. These filters are 24 in. in height and available in 12 and 24 in. widths. Depths range from 12 to 36 in. and the number of pockets range from 3 to 12 in. Table 8.7 summarizes some of the design data for these filters.

8.2.2 HVAC standards
In Europe, the primary standard for air filters are Eurovent 4/5 and EN 779. EN 779 is controlled by CEN (Comité de Européen Normalisation), or in English, European Committee for Standardization. In the United States, development of standards for ventilation filtration are being jointly sponsored by the United States Environmental Protection Agency and ASHRAE.

8.2.2.1 CEN EN 779:2002 E and Eurovent 4/5
European Standards for HVAC filters are Eurovent 4/5-1992 and EN 779(154.1). Other related standards are BS 6540 and DIN 24 185. EN 779 was revised in 2002. The
Figure 8.7. Pocket filter - Precision Pak* by Flanders–Precisionaire. Reproduced with permission of Flanders–Precisionaire. St. Petersburg, Florida, USA.

Figure 8.8. Pocket filter - Precision Pak XDH* by Flanders–Precisionaire. Reproduced with permission of Flanders–Precisionaire. St. Petersburg, Florida, USA.
Table 8.7 Summary of pocket filters by Flanders–Precisionaire

<table>
<thead>
<tr>
<th>Filter</th>
<th>Medium</th>
<th>Medium backer</th>
<th>Flow rating</th>
<th>Efficiency ratings per ASHRAE</th>
<th>MERV ratings per ASHRAE</th>
<th>UL 900 class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision Pak®</td>
<td>Lofted fiberglass or microfine synthetic</td>
<td>Nonwoven polyester</td>
<td>Up to 625 fpm</td>
<td>55% 65% 85% 95%</td>
<td>10–15</td>
<td>Class 2</td>
</tr>
<tr>
<td>Precision Pak XDH®</td>
<td>Dual phase polyolefin 100% synthetic, thermobonded, electrostatically enhanced</td>
<td>Nonwoven polyester</td>
<td>Up to 625 fpm</td>
<td>65% 85% 95%</td>
<td>11–14</td>
<td>Class 2</td>
</tr>
<tr>
<td>Swiss Aire®</td>
<td>Nearly rigid, high strength 100% synthetic, progressive density</td>
<td>–</td>
<td>2,000 cfm</td>
<td>50% 60% 90%</td>
<td>8–15</td>
<td>Class 1</td>
</tr>
</tbody>
</table>

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application for an ISO standard status was in progress at the time of writing this book. The ranking system ties to EN 1822-1:1988, the standard for HEPA and ULPA filters discussed in Section 8.3.2.4.1. EN 779 rates nine classes of filters divided into two groups: G1–G4 for “coarse” filters and F5–F9 for “fine” filters. These are listed in Table 8.8. Equivalent Eurovent 4/5 ratings are also included. Higher ratings for HEPA and ULPA filters are provided for in EN 1822, 2154.21. The G classes of filters are tested to a pressure drop of 250 Pa and are challenged with an ASHRAE synthetic arrestance dust composed of Arizona road dust, carbon black, and cotton linters. The rating is based on the average arrestance, \( A_m \), of the test dust. Arrestance is the weight fraction percentage of the test dust retained by the filter. The F classes of filters are tested to a pressure drop of 450 Pa. The rating is based on the average efficiency, \( E_m \), of the test aerosol at 0.4 \( \mu \)m. Note that the efficiency is not the same as arrestance. The efficiency is based on the number fraction of 0.4 \( \mu \)m particles retained on the filter. The test aerosol is diethylhexylsebacate (liquid DEHS) or equivalent. It has a particle size range of 0.2–10 \( \mu \)m. A tested filter is rated and classified by its arrestance or efficiency in accordance with Table 8.8.

### Table 8.8 Classification of air filters according to EN 779

<table>
<thead>
<tr>
<th>Class</th>
<th>Equivalent Eurovent 4/5 class</th>
<th>Final pressure drop (Pa)</th>
<th>Average arrestance ( A_m ) of synthetic dust (%)</th>
<th>Average efficiency ( E_m ) of 0.4 ( \mu )m particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>EI1</td>
<td>250</td>
<td>( 50 \leq A_m &lt; 65 )</td>
<td>–</td>
</tr>
<tr>
<td>G2</td>
<td>EI2</td>
<td>250</td>
<td>( 65 \leq A_m &lt; 80 )</td>
<td>–</td>
</tr>
<tr>
<td>G3</td>
<td>EI3</td>
<td>250</td>
<td>( 80 \leq A_m &lt; 90 )</td>
<td>–</td>
</tr>
<tr>
<td>G4</td>
<td>EI4</td>
<td>250</td>
<td>( 90 \leq A_m )</td>
<td>–</td>
</tr>
<tr>
<td>F5</td>
<td>EI5</td>
<td>450</td>
<td>–</td>
<td>( 40 \leq E_m &lt; 60 )</td>
</tr>
<tr>
<td>F6</td>
<td>EI6</td>
<td>450</td>
<td>–</td>
<td>( 60 \leq E_m &lt; 80 )</td>
</tr>
<tr>
<td>F7</td>
<td>EI7</td>
<td>450</td>
<td>–</td>
<td>( 80 \leq E_m &lt; 90 )</td>
</tr>
<tr>
<td>F8</td>
<td>EI8</td>
<td>450</td>
<td>–</td>
<td>( 90 \leq E_m &lt; 95 )</td>
</tr>
<tr>
<td>F9</td>
<td>EI9</td>
<td>450</td>
<td>–</td>
<td>( 95 \leq E_m )</td>
</tr>
</tbody>
</table>

Note: The characteristics of atmospheric dust vary widely in comparison with those of synthetic loading dust used in the tests. Because of this test results do not provide a basis for predicting either operating performance or life. Loss of media charge or shedding of particles or fibers can also adversely affect, revised 2002 standard.

### 8.2.2.2 ASHRAE 52.2-1999

ASHRAE takes a different approach than Eurovent. ASHRAE 52.2-1999 defines a minimum efficiency reporting value (MERV). This is determined by subjecting a filter to a fractional efficiency test in accordance with test procedures defined by ASHRAE 52.2-1999. A MERV rating is assigned based on its performance in the tests. A fractional efficiency test is a filtration test where by the filter media is evaluated over a range of particle sizes. ASHRAE 52.2-1999 lists 12 particle size ranges in Table 8.9. The 12 particle size ranges are organized into three groups as shown in the last column of Table 8.9: \( E_1 \) (0.3–1.0 \( \mu \)m), \( E_2 \) (1.0–3.0 \( \mu \)m), and \( E_3 \) (3.0–10.0 \( \mu \)m). The test duct for the ASHRAE 52.2-1999 procedure is shown in Figure 8.10. In the test procedure a filter is challenged with a laboratory generated aerosol of potassium.
### Table 8.9  Particle Size Ranges and Groupings of ASHRAE 52.2-1999

<table>
<thead>
<tr>
<th>Range</th>
<th>Lower limit (µm)</th>
<th>Upper limit (µm)</th>
<th>GMPS a (µm)</th>
<th>Average minimum PSE b Designator group</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.03</td>
<td>0.04</td>
<td>0.35</td>
<td>E1</td>
</tr>
<tr>
<td>2</td>
<td>0.40</td>
<td>0.55</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.55</td>
<td>0.70</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.70</td>
<td>1.00</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.00</td>
<td>1.30</td>
<td>1.14</td>
<td>E2</td>
</tr>
<tr>
<td>6</td>
<td>1.30</td>
<td>1.60</td>
<td>1.44</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.60</td>
<td>2.20</td>
<td>1.88</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2.20</td>
<td>3.00</td>
<td>2.57</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>3.00</td>
<td>4.00</td>
<td>3.46</td>
<td>E3</td>
</tr>
<tr>
<td>10</td>
<td>4.00</td>
<td>5.50</td>
<td>4.69</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>5.50</td>
<td>7.00</td>
<td>6.20</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>7.00</td>
<td>10.00</td>
<td>8.37</td>
<td></td>
</tr>
</tbody>
</table>

- **GMPS** = Geometric mean particle size.
- **PSE** = Particle size removal efficiency.

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---

**Figure 8.10. Schematic of ASHRAE 52.2 test duct.**

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chloride (KCl). Particle size counters measure upstream and downstream counts for each of the 12 particle size ranges. Fractional efficiency of each particle size range is thereby determined. The first test is the initial efficiency test. The filter is then loaded with a synthetic test dust and the test repeated. The test continues with additional increment loadings of the synthetic dust. After each loading, the filter is again challenged with the KCl aerosol and the efficiency determined for each particle size range. Of the several loadings, there will be one for each particle size range gives the lowest efficiency. This is the minimum efficiency for that particle size range.

The minimum efficiencies for each of the particle size ranges in a group ($E_1$, $E_2$, and $E_3$) are averaged. The average minimum efficiency for each group is reported as $E_1$, $E_2$, and $E_3$ accordingly. The MERV rating is then assigned from the criteria of Table 8.10.

At this point, the author will be very surprised if the reader is not totally confused. An example is in order. The example will be the one used by Arnold in his explanation of ASHRAE 52.2-1999. Table 8.11, from Arnold’s paper, is a test report of a filter test conducted in accordance with ASHRAE 52.2-1999. Reported are the

| Composite average particle size efficiency (% in size range [µm]) | Minimum final resistance
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Range 1 (0.30–1.0)</td>
<td>Range 2 (1.0–3.0)</td>
</tr>
<tr>
<td>1</td>
<td>n/a</td>
</tr>
<tr>
<td>2</td>
<td>n/a</td>
</tr>
<tr>
<td>3</td>
<td>n/a</td>
</tr>
<tr>
<td>4</td>
<td>n/a</td>
</tr>
<tr>
<td>5</td>
<td>n/a</td>
</tr>
<tr>
<td>6</td>
<td>n/a</td>
</tr>
<tr>
<td>7</td>
<td>n/a</td>
</tr>
<tr>
<td>8</td>
<td>n/a</td>
</tr>
<tr>
<td>9</td>
<td>n/a</td>
</tr>
<tr>
<td>10</td>
<td>n/a</td>
</tr>
<tr>
<td>11</td>
<td>n/a</td>
</tr>
<tr>
<td>12</td>
<td>n/a</td>
</tr>
<tr>
<td>13</td>
<td>$E_1 &lt; 75$</td>
</tr>
<tr>
<td>14</td>
<td>$75 &lt; E_1 &lt; 85$</td>
</tr>
<tr>
<td>15</td>
<td>$85 &lt; E_1 &lt; 95$</td>
</tr>
<tr>
<td>16</td>
<td>$95 &lt; E_1$</td>
</tr>
</tbody>
</table>

Note: The minimum final resistance shall be at least twice the initial resistance, or as specified above, whichever is greater. Refer to 10.7.1.1.4.

The minimum final resistance specified is for test purposes to determine minimum efficiency, not as a recommendation for actual use. For example, air cleaners used in residences may be changed or cleaned at a lower final resistance than that required by this standard. Also see Appendix A 3.1.

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Table 8.11 Test data report for ASHRAE 52.2-1999 test

<table>
<thead>
<tr>
<th>Size range (μm)</th>
<th>Fractional efficiency (%)</th>
<th>Composite minimum efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3–0.4</td>
<td>25.4</td>
<td></td>
</tr>
<tr>
<td>0.4–0.55</td>
<td>29.9</td>
<td></td>
</tr>
<tr>
<td>0.55–0.7</td>
<td>38.6</td>
<td></td>
</tr>
<tr>
<td>0.7–1.0</td>
<td>48.1</td>
<td></td>
</tr>
<tr>
<td>1.0–1.3</td>
<td>56.2</td>
<td></td>
</tr>
<tr>
<td>1.3–1.6</td>
<td>61.0</td>
<td></td>
</tr>
<tr>
<td>1.6–2.2</td>
<td>68.6</td>
<td></td>
</tr>
<tr>
<td>2.2–3.0</td>
<td>79.5</td>
<td></td>
</tr>
<tr>
<td>3.0–4.0</td>
<td>84.4</td>
<td></td>
</tr>
<tr>
<td>4.0–5.5</td>
<td>86.2</td>
<td></td>
</tr>
<tr>
<td>5.5–7.0</td>
<td>87.8</td>
<td></td>
</tr>
<tr>
<td>7.0–10.0</td>
<td>88.7</td>
<td></td>
</tr>
</tbody>
</table>

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initial fractional efficiencies and the fractional efficiencies after each of five incremental loadings of the synthetic test dust. The minimum efficiencies of the four particle size ranges in Group $E_1$ are 25.4%, 29.8%, 38.6%, and 48.1%, respectively. The average of these four minimum values is 33.5%. The average minimum of the four groups in $E_2$ (56.2%, 61.0%, 68.6%, and 79.5%, respectively) is 66.3%. The average of the four groups in $E_3$ (84.0%, 86.2%, 87.8%, and 88.7%, respectively) is 86.8%.

Using the above determined values ($E_1 = 33.5\%, E_2 = 66.3\%, \text{ and } E_3 = 86.8\%$) refer to Table 8.10 to determine the MERV rating. Under the 0.3–1.0 μm column, $E_1$ at 33.5% fits the criteria of $E_1 < 75$ therefore its MERV rating is 13 or lower based on this column. However, in the 1–3 μm column, $E_2$ at 66.3% satisfies the criteria (65 ≤ $E_2 < 80$) for a MERV rating of 11. In the 3–10 μm column, $E_3$ at 86.8% is also consistent with the MERV rating of 11 (85 ≤ $E_3$). The highest rating whose criteria is satisfied in all three columns is the one assigned to the filter. For the filter of this example, the rating is 11 and the filter is identified as an MERV 11 filter. When an MERV rating is reported the flow rate is also reported. In this test, the flow rate reported in Table 8.11 is 492 ft/min (2.50 m/s) therefore the filter is reported as a MERV 11 @ 492 ft/min or MERV 11 @ 2.50 m/s. Also note that the test requires a minimum resistance after the final incremental loading of the synthetic test dust. If the MERV rating is MERV 4 or lower, the filter also has to be tested in accordance with ASHRAE 52.1-1992.

8.2.2.3 ASHRAE 52.1-1992

ASHRAE 52.1-1992 was designed to provide a relatively rapid test procedure for rating ventilation filters. It is a predecessor to ASHRAE 52.2-1999. There are two parts to the test. In the first part, it measures filtration efficiency of atmospheric dust by comparing the discoloration of two target filter sheets: one upstream of the test filter
and one downstream. Since some of the atmospheric dust will be filtered by the test filter, the downstream target filter will discolor at a different rate than the upstream target filter. By comparing the difference in discoloration, an efficiency number called the "ASHRAE atmospheric dust spot efficiency" is determined. There is also a second part of the test where ASHRAE arrestance and dust holding capacity are determined. The second part of the test challenges the test filter with a prescribed "ASHRAE synthetic test dust" and utilizes an absolute filter to catch all the test dust that penetrates the test filter. It is important to note that the ASHRAE atmospheric dust spot efficiency and the ASHRAE arrestance are not the same thing.

Figure 8.11 is a schematic of the test duct. It contains a dust feeder, dust spot samplers, and manometers to measure pressure drop across the filters. In addition to the test filter, the test duct also has a location for installing an absolute filter downstream of the test filter. The absolute filter is used for the dust holding capacity and arrestance part of the test.

The dust spot samplers are "flow-limiting critical flow venturi nozzles" designed so that the sampling rates upstream and downstream of the test filter are identical. The target filters are HEPA media sheets composed of glass microfibers. Optical methods are used to measure the opacity (reduction in light transmittance) of each target filter. There are two protocols for the sampling flow: intermittent and constant.

In intermittent sampling, the downstream probe is sampling continuously whereas the upstream probe samples intermittently as programmed. The intermittent programming is designed so that the discoloration of the upstream target filter will be roughly the same as the downstream target filter. The dust spot efficiency is determined from the following equation:

\[
E = 100 \times \left| 1 - \frac{S_u}{S_d} \left( \frac{Y_d}{Y_u} \right) \right|
\]  

(8.1)
E is the ASHRAE atmospheric dust spot efficiency (%);
S_u is the total "on" time for the upstream sampler during the test;
S_d is the total "on" time for the downstream sampler during the test;
Y_d is the opacity of the stream target;
Y_u is the opacity of the stream target.

In constant flow sampling, both samplers are run for the same period of time. The opacities are converted to an opacity index by using an equation or a graph provided in the standard. The dust spot efficiency then becomes:

\[ E = 100 \times [1 - (Z_d/Z_u)] \]  

(8.2)

Z_d is the opacity index of the downstream target;
Z_u is the opacity index of the upstream target.

In the arrestance part of the test the ASHRAE arrestance is calculated as follows:

\[ A = 100\times[1 \times (W_d/W_u)] \]  

(8.3)

W_d is the weight of synthetic test dust fed to the test filter;
W_u is the weight of synthetic test dust captured on the final filter.

The test is run in increments. It starts with a dust spot test run on the clean filter. The absolute filter is then put in place and the dust feeder loaded with a predetermined amount of the synthetic test dust. The test dust is then fed to the filter and the arrestance is determined. The dust spot test is then repeated. Another predetermined amount of the synthetic test dust is fed to the filter for another arrestance test. The increments are repeated until the pressure drop across the test filter exceeds the rated final pressure drop or the arrestance falls to 85% of its maximum value (75% for self-renewable filters).

8.2.2.4 Comparison and application guidelines for ASHRAE 52.1 and ASHRAE 52.2
ASHRAE 52.2(152) (Table E-1) offers a comparison of the two test methods and application guidelines. This is reproduced in Table 8.12.

8.2.2.5 Standard for portable air cleaners
The Association of Home Appliance Manufacturer (AHAM) has developed an American National Standards (ANSI)-approved standard for portable air cleaners (ANSI/AHAM Standard AC-1 1988). This standard may be useful in evaluating the effectiveness of portable air cleaning devices. Under this standard, room air cleaner effectiveness is rated by a clean air delivery rate (CADR) for each of three particle types: tobacco smoke, dust, and pollen. The ratings are based on room size and efficiency: the higher the efficiency and the larger the room the higher the CADR. The CADR also takes into consideration the draftiness of the room and the contaminant source. For example, the CADR for pollen will be higher in a drafty room because the source of pollen is from outside.
<table>
<thead>
<tr>
<th>Standard 52.2 Minimum efficiency reporting value (MERV)</th>
<th>Approximate standard 52.1 results</th>
<th>Application guidelines</th>
<th>Typical applications and limitations</th>
<th>Typical air filter/cleaner type</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>n/a</td>
<td>≤0.3μm Particle size</td>
<td>Cleanrooms</td>
<td><strong>HEPA/ULPA Filters</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Virus (unattached)</td>
<td>Radioactive materials</td>
<td>≥99.999% efficiency on</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Carbon dust</td>
<td>Pharmaceutical manufacturing</td>
<td>0.10–0.20μm particles, IEST</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sea salt</td>
<td>Carcinogenic materials</td>
<td>Type F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All combustion smoke</td>
<td>Orthopedic surgery</td>
<td>≥99.999% efficiency on</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Radon progeny</td>
<td></td>
<td>0.30μm particles, IEST Type D</td>
</tr>
<tr>
<td>19</td>
<td>n/a</td>
<td>0.3–1.0μm Particle size</td>
<td>Hospital inpatient care</td>
<td>≥99.97% efficiency on</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All bacteria</td>
<td>General surgery</td>
<td>0.30μm particles, IEST Type C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Most tobacco smoke</td>
<td>Smoking lounges</td>
<td>≥99.97% efficiency on</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Droplet nuclei (sneeze)</td>
<td>Superior commercial buildings</td>
<td>0.30μm particles, IEST Type A</td>
</tr>
<tr>
<td>18</td>
<td>n/a</td>
<td>1.0–3.0μm Particle size</td>
<td>Superior residential</td>
<td><strong>Bag filters</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Legionella</td>
<td>Better commercial buildings</td>
<td>Nonsupported (flexible)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Humidifier dust</td>
<td>Hospital laboratories</td>
<td>microfine fiberglass or</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lead dust</td>
<td></td>
<td>synthetic media: 300–900 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Milled flour</td>
<td></td>
<td>(12–36 in.) deep, 6–12 pockets</td>
</tr>
<tr>
<td>17</td>
<td>n/a</td>
<td>Auto emissions</td>
<td></td>
<td><strong>Box filters</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nebulizer drops</td>
<td></td>
<td>Rigid style cartridge filters</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Welding fumes</td>
<td></td>
<td>150–300 mm (6–12 in.) deep</td>
</tr>
<tr>
<td>16</td>
<td>n/a</td>
<td>70–75%</td>
<td></td>
<td>may use lofted (air laid) or</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;95%</td>
<td></td>
<td>paper (wet laid) media</td>
</tr>
<tr>
<td>15</td>
<td>&gt;95%</td>
<td>60–65%</td>
<td></td>
<td><strong>Bag filters</strong></td>
</tr>
<tr>
<td></td>
<td>n/a</td>
<td>&gt;95%</td>
<td></td>
<td>Nonsupported (flexible)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50–55%</td>
<td></td>
<td>microfine fiberglass or</td>
</tr>
<tr>
<td>14</td>
<td>&gt;98%</td>
<td>40–45%</td>
<td></td>
<td>synthetic media: 300–900 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(12–36 in.) deep, 6–12 pockets</td>
</tr>
<tr>
<td>13</td>
<td>&gt;98%</td>
<td></td>
<td></td>
<td><strong>Box filters</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rigid style cartridge filters</td>
</tr>
</tbody>
</table>

(Continued)
<table>
<thead>
<tr>
<th>Standard 52.2 Minimum efficiency reporting value (MERV)</th>
<th>Approximate standard 52.1 results</th>
<th>Application guidelines</th>
<th>Typical applications and limitations</th>
<th>Typical air filter/cleaner type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Duct spot efficiency</td>
<td>Arrestance</td>
<td>Typical controlled contaminant</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>30–35%</td>
<td>&gt;90%</td>
<td>3.0–10.0 μm Particle size</td>
<td>Commercial buildings</td>
</tr>
<tr>
<td>7</td>
<td>25–30%</td>
<td>&gt;90%</td>
<td>Mold, Spores, Hair spray</td>
<td>Better residential</td>
</tr>
<tr>
<td>6</td>
<td>&lt;20%</td>
<td>85–90%</td>
<td>Fabric protector, Dusting aids</td>
<td>Industrial workplaces</td>
</tr>
<tr>
<td>5</td>
<td>&lt;20%</td>
<td>80–85%</td>
<td>Cement dust, Pudding mix, Snuff, Powdered milk</td>
<td>Paint booth inlet air</td>
</tr>
<tr>
<td>4</td>
<td>&lt;20%</td>
<td>75–80%</td>
<td>&gt;10.0 μm Particle size Pollen</td>
<td>Minimum filtration</td>
</tr>
<tr>
<td>3</td>
<td>&lt;20%</td>
<td>70–75%</td>
<td>Spanish moss, Dust mites</td>
<td>Residential</td>
</tr>
<tr>
<td>2</td>
<td>&lt;20%</td>
<td>65–70%</td>
<td>Sanding dust, Spray paint dust</td>
<td>Window air conditioners</td>
</tr>
<tr>
<td>1</td>
<td>&lt;20%</td>
<td>&lt;65%</td>
<td>Textile fibers, Carpet fibers</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** An MERV for other than HEPA/ULPA filters also includes a test airflow rate, but it is not shown here because it has no significance for the purposes of this table.

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8.2.2.6 Fire and flame resistant standards

Standards for fire or flame resistance of air filters are established by UL 900 by Underwriters Laboratories, Northbrook, Illinois USA (UL 900). The standard classifies two types of air filters as follows:

1. **Class 1 Air Filters** – Those that, when clean, do not contribute fuel when attacked by flame and emit only negligible amounts of smoke.

2. **Class 2 Air Filters** – Those that, when clean, burn moderately when attacked by flame or emit moderate amounts of smoke or both.

The test involves a wind tunnel in which the filter is installed. A flame is applied to the filter media and the area as measured below the smoke density time curve is determined. If the area is $< 16.1 \text{ cm}^2$ ($2.5 \text{ in}^2$), the filter may qualify for a Class 1 Air Filter rating. If it is $< 58 \text{ cm}^2$ ($9 \text{ in}^2$), it may qualify for a Class 2 Filter Rating.

In addition, the filters are judged by how well they sustain flame. A Class 1 Air Filter rating requires that when subjected to the UL Spot Flame Test, the upstream face shall not continue to flame after removal of the test flame. The Class 2 Air Filter rating requires that the filter shall not produce flame or extended sparks (25 or more) which are sustained beyond the end of the test duct when subjected to the flame-exposure test.

ASME AG-1, Section FC-145 (to be discussed in Section 8.3.2.4.2) has provisions for HEPA filter resistance to heated air (Paragraph FC-5150) and resistance to the spot flame test (Paragraph FC-5160). The exposure to heated air is conducted in a test chamber at a rated flow of heated air at $370^\circ\text{C} \pm 25^\circ\text{C}$ ($700^\circ\text{F} \pm 50^\circ\text{F}$) for no less than 5 min. After exposure the filter is tested for aerosol penetrations (not to exceed 3%). In the flame test, a Bunsen burner flame is directed at several points on the upstream face of the filter and applied for 5 min. The requirement is that there be no sustained flaming on the downstream face of the unit after removal of the flame. The code states that an Underwriters Laboratories label (UL 586) is acceptable evidence of compliance with paragraphs FC 5150 and FC 5160.

8.3 High Efficiency Air Filtration

8.3.1 A brief history of high efficiency air filtration

The early developments of high efficiency air filters began with military gas mask canisters designed to protect military personnel from the toxic smokes of chemical and biological warfare. They were designed to remove aerosol particles in the sub-micron range. The earliest forms of the media were developed by Germany and contained asbestos fiber mixed with esparto pulp. During World War II, the United States Army Chemical Warfare Service (CWS) in conjunction with the United States Naval Research Laboratory (NRL) reproduced the German medium and had it manufactured by Hollingsworth & Vose Company in East Walpole, Massachusetts USA. The gas mask medium produced for the US Army was identified as CWS type 6.

The National Defense Research Council (NDRC) solicited the assistance of university and industrial scientists to develop better smoke filters. The theoretical work of Langmuir has already been discussed in Chapter 2, Section 2.2.3.2. His associates,
LaMer and Sinclair\(^{(173)}\), developed a filter test based on dioctyl phthalate (DOP) smoke particles. The fundamentals of this test are still in practice today. The test stand they developed is now known as the Q127 penetrometer. Many of the test stands for this test have been since modernized and are capable of testing with smoke particles other than DOP.

After World War II the development of filters to protect against chemical warfare expanded to large volume filters to protect operational headquarters where wearing of a gas mask was impractical. The developments of nuclear processes and materials at this time created a natural tie-in because of the necessity of controlling radioactive particles in air. The acronym, HEPA (High Efficiency Particulate Air), was coined by Humphrey Gilbert from a 1961 Atomic Energy Commission report "High-Efficiency Particulate Air Filter Units, Inspection, Handling, Installation"\(^{(174)}\). HEPA media were defined by MIL STD 282 as being 99.97% efficient against 0.3 \(\mu\)m DOP smoke.

In the 1950s, the US Government sponsored development of new materials to replace the CWS medium. The concern was that the esparto and asbestos then used in the medium was imported from foreign countries and left the government vulnerable to shortages in these materials. This concern was fortunate, not because of the availability of the materials, but because afterwards the health concerns of asbestos demanded that this fiber not be used. The replacement developed by Arthur D. Little, Inc., Boston, Massachusetts USA was a filter containing a filter medium composed of glass microfibers. Media composed of glass microfibers are still the mainstream for the high efficiency air filters of today.

In the mid-1950s media composed of Fiberfax\(^{\circ}\) fibers were produced by Hollingsworth & Vose Company, East Walpole, Massachusetts USA, Hurlbut Paper Company, South Lee, Massachusetts, USA (no longer in operation), and Flanders Filters (now Flanders-Precisionaire), St. Petersburg, Florida USA. Fiberfax\(^{\circ}\) was a ceramic fiber produced by Carborundum Corporation (now a division of St. Gobain, France). The media had excellent heat resistance in excess of 1000°C, however the fibers could not be produced with the fine diameters required for the high efficiency filtration requirements. This led to the development of glass microfibers with diameters as low as 0.2 \(\mu\)m. Two pioneer developers of glass microfibers were Johns Mansville Corp., now located in Denver, Colorado USA and Owens Corning Fiberglas Corp.

Arthur D. Little started the first high efficiency filter manufacturing company, Cambridge Filter Company (now located in Gilbert, Arizona USA), in the early 1950s. By 1957, three firms were in the business. Early quality difficulties led to a QA inspection program and the establishment of a Government-Industry Filter Committee. Military standards were established. These included MIL-F-51068, Filter, Particulates, High-Efficiency, Fire Resistant\(^{(175)}\) and MIL-F-51079, Filter Medium, Fire Resistant, High Efficiency\(^{(176)}\). MIL-F-51068 was concerned with filters and MIL-F-51079 was concerned with the media. These standards were in active until 1994 when they were incorporated into ASME AG-1, Section FC\(^{(148)}\) which is administered by the Committee on Nuclear Air and Gas Treatment (CONAGT). For many years, the military standards were the world-wide guide for HEPA filters and HEPA media. This was despite the fact that HEPA filters were finding more and more use in non-nuclear and non-military applications.

In the 1960s HEPA filters were finding clean room applications in the electronics industry, in the pharmaceutical industries, and in hospital operating rooms. More
recently HEPA filters have become popular for protecting people against allergens, disease, and harmful microbes in the workplace, in residences, in office buildings, and even in automobiles. Modern day vacuum cleaners often contain HEPA filters to collect the fine particles of annoying dust that leak through the filter bag. The events of 9–11 has led to increased emphasis on HEPA and ULPA filtration to protect military and civilian personnel against biological and chemical threats.

In some applications the demand for filtration efficiency was even more restrictive than the 99.97% efficiency (0.3 μm DOP smoke) required of HEPA filters. Higher efficiency filters were first produced in 1961 and had an efficiency of 99.999%. These filters latter became known as ULPA (Ultra low penetration air) filters.

The original HEPA filter design was a square or rectangular panel filter utilizing the media in a deep pleated form. In Great Britain and Europe new filter designs were developed. This included round HEPA Filters and the mini-pleat design.

New standards needed to be developed. One result, EN 1822-1(154,2) developed by the CEN is discussed in Section 8.3.2.4.1.

In addition IEST (The Institute of Environmental Science and Technology) has established recommended practices (RPs) for the testing of HEPA and ULPA filters (see Section 8.3.2.4.3).

### 8.3.2 HEPA filters

#### 8.3.2.1 Traditional panel filters
The traditional design of a HEPA filter is as depicted in Figure 8.12. The media is a pleated glass microfiber media using corrugated metal separators to keep the pleats...
apart and not pinching. Leakage by-pass around the medium is prevented by gasket seals and by adhesive bond between the filter pack and the integral casing.

8.3.2.2 Separator-less HEPA filters
Other filter styles have since emerged. One modification is separator-less filter panels. The medium is molded on the wet lay machine to form intervals of corrugations. Between each interval the medium is flat so that it can be folded and pleated. The corrugations act as spacers and provide for a honeycomb of passage ways to maximize filter surface area. An example of this effect is shown in Figure 3.5 of Chapter 3. The corrugated separators are eliminated. The advantage is that the pleat folds can be brought closer together, resulting in increased surface area as compared to the traditional filters with separators.

8.3.2.3 Mini-pleat filters
The panel filters, with or without separators, are based on a 6–12 in. pleat design. Mini-pleat filters utilize pleat folds that are 7/8–1 1/4 in. (22–32 mm). Abutting folds are separated by threads, ribbons, tapes, strips of medium, or continuous beads of glass, foam, or plastic spaced across the width of the medium. By organizing the panels into a “V”-array of sub-components (V-pack filter), as depicted in Figure 8.13, greater surface area of medium can be incorporated into the panel volume. This allows for higher flow volume, lower pressure drop, and greater filter life (dust holding capacity). The mini-pleat filters pictured in Figure 8.13 were produced by TDC Filter Manufacturing, Inc., Cicero, Illinois USA.
8.3.2.4 Round filters

Round HEPA filters are finding utility in room fresheners because of the stand alone nature of the unit. In the United Kingdom circular filters have been adopted for nuclear containment systems. A circular HEPA filter is depicted in Figure 8.14. What is not shown is a circular lip seal which allows the filter to be pressure sealed in place without clamping. ter Kuile and Doig\(^{177}\) indicate the following advantages to circular filters over square or rectangular HEPA filters:

1. Higher airflow and lower pressure drop
2. Easier installation
3. Less maintenance
4. Improved operation
5. Easier disposal – the spent filters can be crushed to disc-like dimensions.

8.3.2.5 HEPA media description and standards

HEPA media are wet laid fabrics composed mostly of glass microfibers. They were originally defined by MIL STD 282 as having 99.97% efficiency against 0.3 μm DOP smoke particles. The definition has been expanded by more recent standards. Among the standards governing the testing of HEPA media and filters are MIL STD-282, EN 1822, ASME AG-1, Section FC, and the RPs of the Institute of Environmental Sciences and
Technology (IBST). The ASME (American Society of Mechanical Engineers) standard has a section (FC-I-4000) for flat sheet testing of the media. EN 1822 has five parts of which EN 1822-3 is concerned with flat sheet testing to determine most penetrating particle size (MPPS). Testing of HEPA and ULPA media by small particle penetroimeters has been discussed in Chapter 6, Section 6.13.1.14.

8.3.2.4.1 EN 1822
EN 1822-1 is based on an MPPS. MPPS has been previously discussed in Chapter 2, Section 2.1.2 and in Chapter 6, Section 6.13.1.13. It applies to ULPA filters as well as HEPA filters. MPPS is determined from flat sheet testing of the filter medium in accordance with EN 1822-3, then the filter is tested at this predetermined particle size. The efficiency is determined by particle number counting. If the aerosol is quasi-monodispersed, the aerosol generated has to have a particle size near MPPS. If the aerosol is polydispersed its fractional efficiency counting is done to determine MPPS. The efficiency classes are presented in Table 8.13. Note the filter classes are an extension of EN 779 above (refer Table 8.8).

<table>
<thead>
<tr>
<th>Filter class</th>
<th>Overall value (%)</th>
<th>Local value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Efficiency</td>
<td>Penetration</td>
</tr>
<tr>
<td>H10</td>
<td>85</td>
<td>15</td>
</tr>
<tr>
<td>H11</td>
<td>95</td>
<td>5</td>
</tr>
<tr>
<td>H12</td>
<td>99.5</td>
<td>0.5</td>
</tr>
<tr>
<td>H13</td>
<td>99.95</td>
<td>0.05</td>
</tr>
<tr>
<td>H14</td>
<td>99.995</td>
<td>0.005</td>
</tr>
<tr>
<td>U15</td>
<td>99.9995</td>
<td>0.0005</td>
</tr>
<tr>
<td>U16</td>
<td>99.99995</td>
<td>0.000005</td>
</tr>
</tbody>
</table>

8.3.2.4.2 ASME AG-1, Section FC
The 2003 Edition of the “Code on Nuclear Air and Gas Treatment”, ASME AG-1-2003\textsuperscript{148} provides for standards on HEPA filters directed toward Nuclear Facilities. The Code, previously identified by Military Standards MIL-STD-51068 for HEPA filters and MIL-STD-51079D for HEPA filter media, was administered by the United States Department of Energy (DOE). The administration of this code has since been turned over to the ASME (American Society for Mechanical Engineers). ASME AG-1 Code “provides requirements for the performance, design, construction, acceptance testing, and quality assurance for high-efficiency particulate air (HEPA) used in nuclear safety-related air or gas treatment systems in nuclear facilities”. Although the AG-1 Code is written for nuclear power and nuclear fuel cycle facilities, the design requirements may be referenced for other types of facilities where high reliability and performance are required. Appendix FC-I of this code identifies the requirements and testing of the filter media. Future sections of AG-1 Code that are in the course of preparation include metal medium filters, special round, and ducted HEPA filters, other adsorbers (Type II – Tray type adsorber cell and Type III – Fixed, rechargeable adsorbers are currently addressed by the code), low efficiency filters and process gas treatment.
8.3.2.4.3 IEST recommended practice
The Institute of Environmental Science and Technology (IEST) issues RPs for testing HEPA and ULPA filters. Three such practices are:

1. IEST RP-CC-001.3: “HEPA and ULPA Filters” – Provides glossary, definitions, and classifications of HEPA and ULPA filters, test instruments, and requirements for other RPs.
2. IEST RP-CC-034.1: “HEPA and ULPA Filter Leak Tests” – Covers leak-scan test methods for HEPA and ULPA filters. It describes test conditions, aerosol generation, aerosol detection (either photometer or particle counter), methods, and test systems for each filter type.
3. IEST RP-CC-007.1: “Testing ULPA Filters” – Provides the test methodology for the overall efficiency of ULPA filters using particle counter(s). The penetration range of this procedure is 0.001–0.0001%.

The testing of HEPA filters is different than ULPA filters. The RPs recommend that the less efficient HEPA filters be tested with a photometer and the efficiency based on 0.3 μm particles. The assumption is that the particles are more or less the same diameter. The RPs recommendation for ULPA filters is that they be tested for fractional efficiency using particle counters. The size range for the particles is 0.1–0.2 μm. There is also a filter medium identified as a Super ULPA whose efficiency is rated at >99.9999%. MPPS is recommended as the rating method for this type of filter. Wang and Winters\(^1\) provided Table 8.14 which lists the HEPA and ULPA filter types defined by IEST RP-CC-001.3 and RP-CC-034.1. In their article, Wang and Winters also provided a detailed discussion comparing the RPs to EN 1822.

| Table 8.14 Comparing Test Standards for HEPA and ULPA Filters\(^4\) |
|----------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| RP Type              | Efficiency (%)  | At size (μm)    | Recommended     | Local            | Recommended     |
|                      |                 |                 | efficiency test | Penec. (%)       | scan test method |
|                      |                 |                 | method          |                 | method          |
| HEPA Type A          | 99.97           | 0.3             | MIL-STD-282     | –               | None            |
| (High Type B\(^*\)) | 99.97           | 0.3             | MIL-STD-282     | –               | None            |
| Efficiency Type C    | 99.99           | 0.3             | MIL-STD-282     | 0.01            | Photometer      |
| Particulate Type D   | 99.9999         | 0.3             | MIL-STD-282     | 0.01            | Photometer      |
| Air Filter Type E\(^*\) | 99.97          | 0.3             | MIL-STD-282     | NA              | Photometer      |
| ULPA Type F          | 99.9999         | 0.1–0.2         | RP-CC-007       | 0.005           | Particle counter|
| Ultra Low Type F     | 99.9995         | 0.1–0.2         | RP-CC-007       | 0.0025          | Particle counter|
| Penetration Type F   | 99.9999         | 0.1–0.2         | RP-CC-007       | 0.001           | Particle counter|
| Air Filter           |                 |                 |                 |                 |                 |
| Super ULPA Type G    | >99.9999        |                 | MPPS            | Not required    | 0.001           | NA              |

\(^*\) Type B and E filters require two flow leak tests.
Based on material from IEST-RP-CC-001.3 “HEPA and ULPA Filters” and IEST-RP-CC-034.1 “HEPA and ULPA Filter Leak Tests”.

\(^4\)The RPs IEST-RP-CC-001.3 and IEST-RP-CC-034.1 were updated in 2005 to IEST-RP-CC-001.4 and IEST-RP-CC-034.2 respectively.
8.3.3 ULPA filters

ULPA filters are defined by the high end of Table 8.13 in accordance with EN 1822. They are those with a U designation (U15, U16, and U17). RPs of IEST define ULPA media as having a filtration efficiency of 99.999% or greater against 0.1–0.2 μm particles. ULPA filter media are usually wet laid and formed from glass microfibers of 0.2 μm diameter or less.

8.3.4 Cleanrooms

Cleanrooms are defined by International Standard ISO 14644-1(179) as follows:

“A room in which the concentration of air-borne particles is controlled and which is constructed and used in a manner to minimize the introduction, generation, and retention of particles inside the room, and in which the relevant parameters, e.g. temperature, humidity, and pressure are controlled as necessary.”

Following are a listing of applications where cleanrooms may be required.

(a) Hospitals
(b) Biomedical
(c) Pharmaceutical
(d) Genetic research
(e) Universities
(f) Laboratories
(g) Food processing
(h) Photo processing
(i) Semiconductor
(j) Industrial processing systems.

There are two types of cleanrooms: nonunidirectional airflow type (also known as nonlaminar flow types or conventional cleanrooms) and unidirectional airflow type (also known as laminar flow cleanrooms). Figure 8.15 is a schematic of a non-unidirectional airflow type of cleanroom. Figures 8.16 and 8.17 are schematics of typical unidirectional airflow types of cleanrooms. Figure 8.16 illustrates a vertical laminar flow type of cleanroom and Figure 8.17 illustrates a horizontal laminar flow type of cleanroom.

In the nonunidirectional airflow type of cleanroom, HEPA filters are downstream of the blowers so that only HEPA-filtered air enters the ductwork connecting the mechanical equipment to the cleanroom. In the unidirectional vertical airflow type of cleanroom the HEPA filters consist of the ceiling while prefilters filter the air as it passes through the grated floor and is recycled. In the horizontal type of room, the prefilters and HEPA filters are the ceiling. Floor prefilters the air as it passes through the grated floor and is recycled.

Cleanrooms were originally classified in accordance with Federal Standard 209E(179). This standard was cancelled on November 29, 2001 and superseded by ISO 14644-1(180). The classes are based on a level of cleanliness and a maximum number of allowable particles in accordance with their particle size. ISO 14644-1 has nine classes identified by an ISO number from ISO 1 through ISO 9. The lower the class
number, the cleaner is the cleanroom. The classifications are based on the maximum number of particulates per cubic meter for that particle size. The particle sizes are 0.1 \( \mu \text{m} \), 0.2 \( \mu \text{m} \), 0.3 \( \mu \text{m} \), 0.5 \( \mu \text{m} \), 1 \( \mu \text{m} \), and 5 \( \mu \text{m} \). Table 8.15 tabulates the classifications of ISO 14644-1.
Table 8.15  Airborne particle cleanliness levels per ISO 14644-1

<table>
<thead>
<tr>
<th>ISO/TC209 14644-1</th>
<th>Class</th>
<th>Number of particulates per cubic meter by micrometer (μm) size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.1 μm</td>
</tr>
<tr>
<td>ISO 1</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>ISO 2</td>
<td>100</td>
<td>24</td>
</tr>
<tr>
<td>ISO 3</td>
<td>1000</td>
<td>237</td>
</tr>
<tr>
<td>ISO 4</td>
<td>10,000</td>
<td>2,370</td>
</tr>
<tr>
<td>ISO 5</td>
<td>100,000</td>
<td>23,700</td>
</tr>
<tr>
<td>ISO 6</td>
<td>1,000,000</td>
<td>237,000</td>
</tr>
<tr>
<td>ISO 7</td>
<td></td>
<td>352,000</td>
</tr>
<tr>
<td>ISO 8</td>
<td>3,520,000</td>
<td>832,000</td>
</tr>
<tr>
<td>ISO 9</td>
<td>35,200,000</td>
<td>8,320,000</td>
</tr>
</tbody>
</table>

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8.3.5 Paint spray booth filters

Spray booths are built with either downdraft or cross-draft ventilation flow. This is analogous to the down flow and laminar horizontal flow cleanrooms depicted in Figures 8.9 and 8.10. Spray booths require two types of filter assemblies: intake filters and exhaust filters. The intake filter filters the air coming into the spray booth. The exhaust filter captures excess paint particles from air emerging from the spray booth.

Intake filters are the first line of defense against large particles that might possibly mar the painted surface. They are either panels or pads. Cross-draft spray booths usually require panels mounted along one wall of the spray booth. Downdraft booths usually use pads mounted into the ceiling of the spray booth. Filter pads are often
referred to as diffusion media for intake filtration. The pads are usually a high loft medium, composed of synthetic fibers. They are available in either roll form or pads custom sized to the users application. In roll form, the user will cut the roll into pad sizes suitable for the application. Panel filters are typically made from medium pads, separated by a metal support. In the panel filters produced by Flanders, the upstream pad is more porous and acts to catch the larger particles. The downstream pad is tighter and designed to trap smaller particles.

Exhaust filters are often referred to as paint arrestors. The filters are usually in the form of pads. Cross-draft and semi-downdraft booths use cut pads, 20 in. × 20 ft. (51 × 51 cm) or 20 × 25 in. (52 × 63.5 cm) that are mounted into the wall of the booth. Downdraft booths usually use a long pad that is placed in a pit at the floor of the booth. Some downdraft booths use filter bags, cubes, and other products. Some examples of materials used for paint arrestor filter pads are fiberglass with polyester backing, various forms of fiberglass pads with a scrim backing for additional efficiency, and three layer polyester providing three layers of gradient density filtration. Usually the pads are 2.5 in. (6.35 cm) thick. Polyester media are often the materials used for cube filters. Sometimes an added layer is added to provide for increased efficiency. Polyester fiber with a scrim backing is a popular choice for bag filters.

Heated downdraft paint booths often have prefilters. These are generally installed in the ductwork bringing air into the booth. Prefilters are usually panel filters, however dual-ply polyester pads are also used. Media for panel filters can be a pleated high loft synthetic, a high loft thermo-bonded polyester pad enclosed within a support frame, or dual-ply panel filters using an embedded wire frame for support.

8.4 Respirators, Gas Masks, and Facemasks

8.4.1 Respirators and gas masks – 42 CFR (US), Chapter 1, Part 84

Respirators are a form of facemask (and often called facemasks) designed to provide respiratory protection against hostile environments. They come with a face piece that will cover nose, mouth, and very often the eyes. Respirators can range from simple fabric filters that cover the nose and mouth and provide home and workplace protection against dust and pollen to complex devices that provide protection against very dangerous dusts (such as asbestos), microbes, fumes, and chemical vapors.

Two types of respirators are air-purifying respirators (APRs) and air supplying respirators. The latter, either have a self-contained air supply or are supplied by an external air source.

APRs have three basic components:

1. A face mask
2. A filter or cartridge filter to remove dust, smaller particles, and mists
3. A cartridge filter to remove chemical gases and fumes.

Respirators are regulated by 42 CFR (US), NIOSH (the National Institute for Occupational Safety and Health) and MSHA (the Mine Safety and Health Administration) are
the United Stated Government agencies responsible for administering the regulation. Part 84 upgrades previous regulation 30 CFR 11 (often referred to as “Part 11”). The basic change is that Part 84 provides “More rigorous and demanding test conditions for certifying negative pressure particulate respirators” (Martin and Moyer)\(^{(182)}\). This is discussed in Section 8.4.1.4. The upgraded test conditions also apply to gas masks containing a particulate filter. Part 84 does not upgrade the test conditions for self-contained breathing apparatus (Section 8.4.1.1), gas masks not containing a particulate filter (Section 8.4.1.2), supplied air respirators (SARs) (Section 8.4.1.3), powered air-purifying respirators (PAPRs) (Section 8.4.1.5), chemical cartridge respirators (Section 8.4.1.6), and special use respirators. The test conditions for the latter are unchanged from Part 11.

The regulation defines a respirator “as any device designed to provide the wearer with respiratory protection against inhalation from a hazardous atmosphere”. It also defines two types of respirators: respirators for escape only and respirators for entry into and escape from. Escape only respirators are respiratory devices providing protection only during escape from hazardous atmospheres. Entry into and escape from respirators are respiratory devices providing protection during entry into and escape from hazardous atmospheres. The regulation identifies the following type of respirators:

8.4.1.1 Self-contained breathing apparatus
A self-contained breathing apparatus (SCBA) is used for entry into and escape from hazardous atmospheres and contains a source of oxygen. There is no filter or canister associated with an SCBA. The source of oxygen can be compressed oxygen, chemical oxygen, or liquid oxygen. There are two types of apparatus: closed-circuit apparatus and open-circuit apparatus. The closed-circuit apparatus provides for rebreathing of the exhaled air by removing carbon dioxide and restoring the air to a suitable oxygen content. An open-circuit apparatus does not recycle the exhaled air, but rather it is vented to the atmosphere and not rebreathed.

8.4.1.2 Gas masks
Gas masks, also known as an “air-purifying respirators” (APRs), are defined by the regulation as devices designed for use during entry into atmospheres not immediately dangerous to life or health or escape only from hazardous atmospheres containing adequate oxygen to support life. Types of gas masks are:

(a) Front mounted or back mounted – A gas mask which consists of a full face piece, a breathing tube, a canister at the back or front, a canister harness, and associated connections.
(b) Chin-style gas mask – A gas mask, which consists of a full face piece, a canister which is usually attached to the face piece, and associated connections.
(c) Escape gas masks – A gas mask designed for use during escape only from hazardous atmospheres, which consists of a face piece or mouthpiece, and associated connections. This type of mask often comes in the form of a half mask, which provides no eye protection.
A gas mask is designed to protect the face and lungs against noxious gases and fumes, chemical agents, and biological substances as in warfare or terror attacks or in certain industrial environments. The gas mask includes a cartridge or canister containing activated carbon and/or chemicals to remove dangerous gas and vapor contaminants. A particulate filter may be attached to the cartridge or canister. Gas masks are also described by the types of gases or vapors against which they are designed to provide protection as follows:

The regulation specifies canister bench tests to qualify a gas mask. The test conditions are based on the type of gas mask (front-mounted and back-mounted, chin-style, and escape), and the canister type in accordance with Table 8.16. For each gas mask type and canister type, the regulation specifies a challenge gas or vapor, a feed concentration, a flow rate, a specified number of tests, a maximum allowable penetration, and a minimum service life. As an example, Table 8.17, on page 363 below compares specific test requirements for ammonia as the challenge gas. The regulation also specifies particulate tests for those gas masks containing a particulate filter. In this regard, the gas mask becomes like a non-powered air-purifying particulate arrestor (NPAPPR) and is subject to the testing protocol as discussed in Section 8.4.1.4.

### Table 8.16 Gas mask protection categories

<table>
<thead>
<tr>
<th>Type of front-mouthed or back-mouthed gas mask</th>
<th>Acid gas</th>
<th>Ammonia</th>
<th>Carbon monoxide</th>
<th>Organic vapor</th>
<th>Other gases and vapor(s)</th>
<th>Combinations of two or more of the above</th>
<th>Combinations of all of the above</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of chin-style gas mask</td>
<td>Acid gas</td>
<td>Ammonia</td>
<td>Carbon monoxide</td>
<td>Organic vapor</td>
<td>Other gases and vapor(s)</td>
<td>Combinations of two or more of the above</td>
<td>Combinations of all of the above</td>
</tr>
<tr>
<td>Type of escape gas mask</td>
<td>Acid gas</td>
<td>Ammonia</td>
<td>Carbon monoxide</td>
<td>Organic vapor</td>
<td>Other gases and vapor(s)</td>
<td>Combinations of two or more of the above</td>
<td>Combinations of all of the above</td>
</tr>
</tbody>
</table>

Note: The regulation has further restrictions on whether a gas mask can be described as above. The regulation should be consulted for the details of these restrictions.

### 8.4.1.3 Supplied-air respirators

SARs rely on a source of supplied respirable breathing air. They are designed to provide respiratory protection during entry into and escape from atmospheres not immediately dangerous to life or health. Like the SCBAs discussed in section 8.4.1.1,
the SARs do not have a filter canister, cartridge, or element. The regulation defines three types of SARs:

**Type A** – Type “A” SARs provides air through a motor-driven or hand-operated blower. The device is designed to provide for the free entrance of air when the blower is not operating.

**Type B** – The wearer of a Type “B” SAR draws inspired air by use of his lungs alone.

**Type C** – Type “C” SARs are airline respirators. They differ from the Type “B” SARs in that they have a detachable coupling, a control valve, an orifice, and a demand valve or pressure demand valve.

All three SAR types above also have an “E” version (Type “AE,” Type “BE,” and Type “CE”). These versions have protection devices such as a helmet to protect the wearer’s head and neck against impact and abrasion from rebounding abrasive material.

8.4.1.4 Non-powered air-purifying particulate arrestors

NPAPPRs are also referred to as negative pressure particulate respirators. They utilize the wearer's negative inhalation to draw ambient air through the air-purifying filter elements (filters) to remove particulates from the ambient air. They are designed for use as respiratory protection against atmospheres with particulate contamination (e.g. dusts, fumes, mists) that are not immediately dangerous to life or health and that contain adequate oxygen to support life. Note that an NPAPPR differs from a gas mask in that:

(a) Gas masks are designed for atmospheres and hazardous atmospheres where the contaminants are vapors or gases. NPAPPRs are designed for atmospheres with particulate contamination.

(b) Gas masks are designed for entry and escape only situations, whereas NPAPPRs allow the wearer to stay in the contaminated area for as long as the filter holds out.

The regulation applies efficiency ratings for NPAPPRs and for gas masks with particulate filters based on three classification series; N-series, R-series, and P-series. N-series filters are restricted to use in those workplaces free of oil aerosols. The R- and P-series are intended for removal of any particulate that includes oil-based liquid particulates. The difference between R- and P-series filters is the end point at which minimum filtration efficiency is determined. The manufacturer is required to label certified filters with the appropriate rating. The filters ratings are determined and certified by NIOSH based on their testing:

(a) N100, R100, and P100 filters shall demonstrate a minimum efficiency level of 99.97%.

(b) N99, R99, and P99 filters shall demonstrate a minimum efficiency level of 99%.

(c) N95, R95, and P95 filters shall demonstrate a minimum efficiency level of 95%. 
N-series filters are tested against a sodium chloride or equivalent solid test aerosol. The median particle size is specified at an equivalent diameter of $0.075 \pm 0.020 \mu\text{m}$. The P- and R-series filters are tested against a liquid test aerosol of DOP. The median particle size is specified at an equivalent diameter of $0.185 \pm 0.020 \mu\text{m}$. The test is conducted until minimum efficiency is achieved or until $200 \pm 5$ mg of test aerosol has been loaded onto the filter. For P-series filters, if the efficiency is still decreasing when the $200 \pm 5$ mg challenge point is reached, the test is continued until there is no further decrease in efficiency. The value reported is the minimum efficiency during the course of the test. The test protocol calls for 20 filters to be tested. Each filter shall exceed the minimum efficiency criterion for which the filter is rated.

8.4.1.5 Powered air-purifying respirators

PAPRs utilize a blower to force air through the respirator filter or canister. Examples of PAPRs are depicted in Figures 8.18 and 8.19.

The testing requirements on PAPRs are regulated by Part 11, described in subpart KK of Part 84. Sub-part KK limits licensing of PAPR particulate filters to only high efficiency or HEPA filters. These are defined as "Air-purifying respirators, with replaceable filters, designed as respiratory protection against dusts, fumes, and mists having an air contamination level $<0.05 \text{mg/m}^3$, including but not limited to lithium hydride and beryllium, and against radio nuclides."

PAPRs are subject to either a silica dust test for dust type respirators or a lead fume test for fume type respirators. The test involves a filter test stand. Ground flint is the

![Figure 8.18. Protective clothing with PAPR.](image)

Photograph provided by Ernest S. Moyer, NIOSH, Morgantown, West Virginia, USA.
test contaminant for the silica dust test. The contaminant for the lead fume test is obtained by impinging an oxygen–gas flame on molten lead. The test requirement is that the total amount of unretained test suspension shall not exceed 1.5 mg for the silica test and 1.8 g for the lead fume test.

8.4.1.6 Chemical cartridge respirators
Chemical cartridge respirators are designed for use as respiratory protection during entry into or escape from atmospheres not immediately dangerous to life and health. They are described according to the specific gases or vapors against which they are designed to provide respiratory protection. These are ammonia, chlorine, hydrogen chloride, methylamine, organic vapor, sulfur dioxide, and vinyl chloride. Chemical cartridge respirators may have a blower. They differ from gas masks in that they are to be used in less hazardous atmospheres and accordingly should last longer. To illustrate, the author has chosen ammonia as the contaminant type and compared the test requirements in Table 8.17.

8.4.1.7 Filter media for respirators
Glass microfiber media of the ULPA and HEPA types or of the high efficiency ASHRAE® 52–92 or EN 779 types are well fit for the Part 84 performance requirements discussed above. Composite media containing a melt-blown layer, a nanofiber electrospun layer, or a membrane filter layer also find utility in applications where the flammability issue is not critical.
Activated carbon is the most frequently used adsorbent to remove dangerous chemical and fume components from the air. Usually the canisters contain a bed of activated carbon granules or pellets. In some applications, the activated carbon is combined with nonwoven layers to form a composite structure. Other forms of non-wovens containing activated carbon are utilized, such as wet laid webs impregnated with carbon particles and webs coated with activated carbon particles.

For severe chemical applications the activated carbon may be treated with metal salts of copper, silver, zinc, and molybdenum (ASZM) and with triethylenediamine (TEDA) for enhanced chem-sorption properties. ASZM–TEDA produced by Calgon Carbon Corporation of Pittsburgh, Pennsylvania USA is an activated carbon of this type used for military gas mask applications.

8.4.2 Surgical and healthcare face masks

The principal purpose of surgical and healthcare face masks is to protect the wearer against colloidal microorganisms and blood splatters associated with patient care and surgical procedures. Tuneval\textsuperscript{183} has suggested that in protecting patients, face masks worn by operating room personnel do very little to reduce bacterial levels in operating rooms. Rawson\textsuperscript{184} counters that “the use of surgical masks in protecting the surgical team from contaminated contacts is an important principle to consider.” The contamination can be in the form of blood, body fluids, secretions, and excretions. Often a shield is worn in conjunction with the facemask to provide eye protection.

Johnson\textsuperscript{185} identified five specific performance characteristics for facemasks:

(a) Bacterial filtration efficiency
(b) Sub-micron particulate filtration
(c) Differential pressure (an indication of breathing comfort)
(d) Fluid penetration resistance
(e) Resistance to flammability
Medical face masks generally follow the NIOSH requirements of 42 CFR (US), Chapter 1, Part 84.\textsuperscript{181} The efficiency ratings of Section 8.4.1.4 are usually applied. Surgical face masks are medical devices as defined by the United States Food and Drug Administration (FDA). As such they are regulated by the FDA. Other US organizations concerned with standards and guidelines for healthcare face masks are the Centers for Disease Control and Prevention (CDC), Atlanta, Georgia USA, the American National Standards Institute (ANSI), and the Association of periOperative Registered Nurses (AORN). ASTM International (ASTM) has established standards for filtration including ASTM F2101-01 (bacterial filtration efficiency, BFE), ASTM F2299-03 (initial efficiency by latex spheres), ASTM F1862-05 (resistance of medical face masks to penetration by synthetic blood).

8.5 Vacuum Cleaners

One of the newer ways to categorize vacuum cleaners is bagged or bagless.

Traditional filters for vacuum cleaners are bag filters composed of resin-treated filter paper. The filter paper for vacuum cleaner bags is of sufficient strength so as not to burst in its application. The Mullen burst test is commonly used for to test this property. The paper has to be processable in the bag-making equipment. Moisture content is related to a paper’s processability in a bag-making machine. Most vacuum bag media are composed of high quality wood pulp fibers. In some cases where superior strength is required, long vegetable fibers such as Manila hemp (abaca) and/or sisal are utilized. In some applications, the filter paper is creped to provide more surface area for filtration. Hsieh\textsuperscript{186} reports that there have been significant new developments in
the past few years. To name a few there are “synthetic ultra-fine fiber media, electrets, and composite media”. A popular form of composite medium that has developed in recent years is vacuum bag filter paper inner-lined with a melt-blown substrate. In most cases the filter bag is disposable after being filled with dirt. There are some filter bag designs whereby the bag can be emptied and reused. In some cases the bag is washable.

Bagless vacuum cleaners use filters to trap dirt in a dirt cup or chamber that can be emptied and reused. However, the filters often have to be brushed, washed, and dried, or completely replaced.

In many vacuum cleaner applications, the bag still leaks some dust and allergens to the local environment. This is bothersome to people with allergy problems. As a result many vacuum cleaners are now equipped with post-filters, often a HEPA filter to capture residual traces of dust leaking through the bag.

More elaborate filters are used for centralized and commercial vacuum systems.

ASTM F1977 is a standard test method used to determine the initial fractional efficiency of a number of different types of vacuum cleaners including household and commercial canister (tank type), stick, hand held, upright, and utility vacuum cleaner systems. The test tests the filter at six discrete particle sizes (0.3, 0.5, 0.7, 1.0, 2.0, and > 3 μm). Neutralized KCl is the challenge dust for this test.

8.6 Air Purifiers

Air purifiers are also known as room air cleaners and residential air cleaners. They are usually portable units whose purpose is to provide for clean air in residential environments to include particulate and odor removal. There is increasing customer interest in these units because of concerns about indoor air quality (IAQ). The concerns include odor, gaseous contaminants, microbial activity, allergens, and other particulate irritants such as dust, animal dander, and tobacco smoke. Air purifier units come in a number of shapes and sizes. The filters may be circular cartridge filters, panel filters, or something in between. Usually the medium is in pleated form. The unit may contain an adsorbent such as activated carbon. There is usually an electrostatic charge induced to improve the efficiency of particulate removal. Sometimes the charge is in the form of an electret filter medium. Technostat® needle punch felt media produced by Hollingsworth & Vose Company previously discussed in Chapter 3, Section 3.6.4 and Table 3.13 are these types of media and are marketed for air purifier applications. Other forms of filter media include glass microfiber HEPA media, blends of synthetic fiber and glass microfiber, and composite media using cellulose or synthetic fiber non-wovens as a backing support.

AHAM (the Association for Home Appliance Manufacturers, Washington, DC USA) has developed an ANSI (American National Standards Institute, Washington, DC USA) approved standard for air purifiers, ANSI/AHAM AC-1-2006. The ratings are based on CADR ratings. The ratings are based on room size and percentage of particles removed (smoke, dust, and pollen) as shown in Table 8.18.
Table 8.18  Estimated percentage of particle removal for portable units by CADR and by room size

<table>
<thead>
<tr>
<th>Room size</th>
<th>CADR</th>
<th>Percentage of particles removed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Smoke (20 min)</td>
<td>Dust (20 min)</td>
</tr>
<tr>
<td></td>
<td>AC</td>
<td>T</td>
</tr>
<tr>
<td>5 × 6</td>
<td>5 × 6 approximately 210 ft³</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>89%</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>95%</td>
</tr>
<tr>
<td>9 × 12</td>
<td>9 × 12 approximately 756 ft³</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>76%</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>89%</td>
</tr>
<tr>
<td>12 × 18</td>
<td>12 × 18 approximately 1512 ft³</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>74%</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>89%</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td>–</td>
</tr>
<tr>
<td>18 × 24</td>
<td>18 × 24 approximately 3024 ft³</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>73%</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td>–</td>
</tr>
<tr>
<td>20 × 30</td>
<td>20 × 30 approximately 4200 ft³</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td>–</td>
</tr>
</tbody>
</table>

AC = Removal by the air-cleaning device.
T = Removal by the air-cleaning device plus natural settling.

Note: Estimates ignore the effect of incoming air. For smoke and, to a lesser extent, dust, the more drafty the room, the smaller the CADR required. For pollen, which enters from outdoors, a higher CADR is needed in a drafty room.

Source: United States Environmental Protection Agency.

8.7 Air Demisters

Two fundamental types of air demisters are those used to remove moisture from industrial, commercial, and residential air streams and those used to remove hydrocarbon and oil mists from air streams.

8.7.1 Air-moisture demisters

Fiber bed mist eliminators are used for hundreds of chemical plant and industrial gas applications. One common form is vertically mounted cylindrical elements. Often referred to as candle filters, these can be quite large. Examples are depicted in Figure 8.21. Design operating pressures generally range from 100 to 500 mm water. Efficiencies range from 90% to 99% depending on application requirements. Moisture is a form of particle that is filtered and the separation generally follows filtration theory as discussed in Chapter 2. The difference is whereas dirt or solid particles remain imbedded in the medium till the end of the filtration cycle, moisture or liquid particles
have to continuously coalesce into larger particles and be removed from the medium as a separate stream. The removal mechanism is for the coalesced liquid to form a film on the downstream side of the filter medium surface and drain to the bottom of the housing.

Glass fiber or microfiber is generally the fiber of choice for the bed. The fineness offers the desired filtration efficiency and the surface properties are well suited for the coalescing phenomenon.

### 8.7.2 Air-oil demisters

The removal of oil mists from air streams is very important in applications such as crankcase ventilation, lubricated machining and cutting processes, and compressed air operations. Like air–moisture demisters it is important that provision be provided for removing the coalesced oil droplets from the medium. Demisting filters may have three or four filter stages, including a glass microfiber HEPA filter as the final stage.
CHAPTER 9

Engine Filtration

9.1 Introduction

Engine filtration is the term applied to the filtration requirements of engine powered vehicles and equipment. This includes automobiles, trucks, farm equipment, off the road construction equipment, aircraft, railroad trains, boats, and a multitude of specialty engine operated equipment ranging from mine drilling equipment to lawn mowers. Turbines are considered as a form of engine and therefore gas turbine filtration applications are included in this category. The global market size of engine filtration (estimated to be 150,000–200,000 tons/year in 2005) combined with the complexities of the various filtration mechanisms justifies a whole chapter in this book for the subject. To illustrate the complexities of engine filtration, Figure 9.1 provided by Durst et al.\textsuperscript{187} identifies 25 of the various filters that can be found in an automobile. An engine powered vehicle requires both liquid and air filters. Table 9.1 from Hollingsworth & Vose Company is a sampling of the broad range of filter grades used in engine filters.

Most of the medium tonnage for engine filtration is in the form of wet laid resin treated media, however there is a continuing development of dry formed media particularly in air filtration. The medium are usually used in a pleated forms, either as a cartridges or as a panel filters. The filter shape can be quite varied depending on application and location. Often the medium will be corrugated, particularly for lube oil applications. Traditionally, the base sheets for the resin treated media are cellulose, however there has evolved a growing increase of synthetic fibers. Composites are developing as basic media in many engine filter applications. The last 10–15 years has seen the emergence of cabin air filtration. Much of the filter media being presented for cabin air filtration are in composite form. Many of the composites include activated carbon.

As illustrated above, there are many filters within an engine powered vehicle. The major uses can be reduced to the following:

(a) Lube oil filtration
(b) Air intake filtration (AIF)
(c) Fuel filtration
(d) Cabin air filtration.
Figure 9.1. The filters of an automobile.
Reproduced with permission of Verlag Moderne Industrie Germany (1997) p. 5.
<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Application</th>
<th>Basis weight (g/m²)</th>
<th>Caliper (mm)</th>
<th>Corrugation depth (mm)</th>
<th>Mullen burst, kPa or MD/CD Tens. str (kg/cm)</th>
<th>Gurley stiffness (mg)</th>
<th>Maximum pore isopropanol (µm)</th>
<th>Mean flow pore (Coulter) (µm)</th>
<th>Permeability at 1/2 atm (12.7 mm WG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auto Air</td>
<td>No-cure</td>
<td>Radial air</td>
<td>147</td>
<td>.85</td>
<td>Flat</td>
<td>176</td>
<td>3.066</td>
<td>139</td>
<td>38.4</td>
<td>287</td>
</tr>
<tr>
<td></td>
<td>Economical no-cure</td>
<td>Radial and panel</td>
<td>129</td>
<td>.86</td>
<td>.355</td>
<td>276</td>
<td>3.355</td>
<td>139</td>
<td>36.1</td>
<td>329</td>
</tr>
<tr>
<td></td>
<td>Lightweight no-cure</td>
<td>Panel air</td>
<td>114</td>
<td>.55</td>
<td>Flat</td>
<td>272</td>
<td>2.200</td>
<td>120</td>
<td>33.8</td>
<td>283</td>
</tr>
<tr>
<td></td>
<td>Composite nonwoven dual-layer</td>
<td>Radial and panel</td>
<td>206</td>
<td>1.80</td>
<td>Flat</td>
<td>5.9/4.3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Auto Lube</td>
<td>Standard auto lube</td>
<td>Auto oil</td>
<td>121</td>
<td>.74</td>
<td>.267</td>
<td>143</td>
<td>2.933</td>
<td>133</td>
<td>12.6</td>
<td>216</td>
</tr>
<tr>
<td></td>
<td>Mid-range auto lube</td>
<td>Auto oil</td>
<td>130</td>
<td>.84</td>
<td>.279</td>
<td>255</td>
<td>3.500</td>
<td>96</td>
<td>30.3</td>
<td>214</td>
</tr>
<tr>
<td></td>
<td>Premium auto lube</td>
<td>Auto oil</td>
<td>205</td>
<td>1.26</td>
<td>.216</td>
<td>221</td>
<td>7.156</td>
<td>74</td>
<td>21.1</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>Heavy duty oil</td>
<td>Auto, heavy equipment</td>
<td>180</td>
<td>.83</td>
<td>.190</td>
<td>296</td>
<td>5.676</td>
<td>109</td>
<td>31.5</td>
<td>195</td>
</tr>
<tr>
<td>Heavy Duty</td>
<td>Economical, low energy resin</td>
<td>Heavy duty air</td>
<td>136</td>
<td>.80</td>
<td>.406</td>
<td>527</td>
<td>4.288</td>
<td>105</td>
<td>29.2</td>
<td>137</td>
</tr>
<tr>
<td>Air</td>
<td>Lightweight, low cure</td>
<td>Heavy duty air</td>
<td>106</td>
<td>.67</td>
<td>.360</td>
<td>207</td>
<td>3.000</td>
<td>38.7</td>
<td>15.0</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>Premium heavy duty air</td>
<td>Heavy duty air</td>
<td>134</td>
<td>.66</td>
<td>.254</td>
<td>322</td>
<td>2.538</td>
<td>82.8</td>
<td>22.3</td>
<td>94</td>
</tr>
<tr>
<td>Fuel</td>
<td>General purpose</td>
<td>Gasoline and diesel</td>
<td>130</td>
<td>.69</td>
<td>.355</td>
<td>465</td>
<td>5.378</td>
<td>54.0</td>
<td>14.2</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Standard general purpose</td>
<td>Wide range of fuels</td>
<td>165</td>
<td>.70</td>
<td>.241</td>
<td>307</td>
<td>4.566</td>
<td>46.4</td>
<td>14.2</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Lightweight</td>
<td>Diesel</td>
<td>152</td>
<td>.60</td>
<td>.152</td>
<td>256</td>
<td>3.022</td>
<td>36.3</td>
<td>11.6</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Glass, synthetic enhanced</td>
<td>High efficiency fuel</td>
<td>225</td>
<td>.813</td>
<td>.127</td>
<td>183</td>
<td>4.489</td>
<td>26.9</td>
<td>7.8</td>
<td>13.1</td>
</tr>
</tbody>
</table>

Reproduced with permission of Hollingsworth & Vose Company Inc. East Walpole, Massachusetts, USA. Hollingsworth & Vose makes no warranties, expressed or implied, as to the finished product provided from these fabrics. Physical properties tested are typical at time of manufacture and are not intended for specification purposes.
In addition, there are filters for transmission fluids, power steering fluids, brake systems, exhaust systems, crankcase emissions, etc. Computerization of the engine has required additional filters to protect electronic components. Gas turbine filtration is a major category in itself.

9.2 Lube Oil Filtration

Lubrication oil filters play the important role of protecting the engine from wear and damage due to particulate build-up. Particles develop in the engine from a number of sources. This includes fine particles of dust from the outside air that penetrates even the most efficient air-intake filters. There are residual contaminants from the initial production of the engine. The engine operation generates metal fines from wear and soot from fuel combustion. In addition, the oil gets contaminated with acids from the combustion process and diluted with unburned fuels. The oil itself is exposed to an adversarial environment of high temperatures and constant shear. In time decomposition occurs and the products of decomposition also become a member of the family of oil contaminants.

The purpose of the lubricating oil is to reduce friction in bearings, clearance gaps, and moving parts. It dissipates heat and provides protection against corrosion. Thin films of the oil provide a seal to the combustion chamber. Finally the oil keeps the engine clean by loosening and dispersing impurities and preventing them from forming deposits. If oil is not sufficiently clean, contaminants can cause wear and abrasion of engine parts. This is particularly significant where the oil operates in the narrow gaps between moving parts such as bearings and the annular space between piston and wall.

If the engine oil is not changed at appropriate intervals and/or it is not well filtered the engine will experience accelerated wear and tear, suffer in performance, and be exposed to an increased risk in damage. Figure 9.2 is a picture of an automotive cylinder and a sample of the wear that can be caused by particle abrasion.

Particle size is becoming increasingly important as a factor affecting engine wear. The control of contaminants and their particle size is an important function of the lube oil filter. Staley determined that clearances in diesel and gasoline engines ranged from 2 to 22 \( \mu \)m, suggesting that particles in this size range were most deleterious to engine wear. Staley also demonstrated that increasing the single-pass efficiency of the oil filter will effectively reduce abrasive engine wear. Durst et al. state that severe engine wear is caused by particles in the 8–60 \( \mu \)m range. They provided Figure 9.3 showing the effect of wear relevance (abrasion) as a function of particle diameter.

There is a large assortment of lube oil filters based on the make, year, and style of the vehicle in which they are installed. Figure 9.4 is an illustration of filters made from various media.

Knize has undertaken a methodical study of the various brands of lube oil filters by manufacturer and their internal construction. Figure 9.5 is a sampling from the large selection of lube oil filters that are being examined by Knize.
The general operation of a lubricating oil filter is based on full-flow, i.e. all the flow of oil is transported through the filter. It is recognized that a filter may plug, therefore, the flow may be diverted through a by-pass line. This is determined by a differential pressure signal. The rational is that, even if the oil is not filtered, the engine will continue to function for some period and the detrimental effect to the engine will be gradual. On the other hand, if the oil supply to the engine is cut-off by a plugged oil filter, the effect on the engine will be immediate and catastrophic.
The types of filters illustrated in Figures 9.4 and 9.5 are of the spin-on type. They consist of pleated medium configured into a star-shaped pleat configuration. A picture of a spin-on type of oil filter, showing the inside construction has already been demonstrated in Figures 7.9a and 7.9b of Chapter 7, Section 7.3.2.2.2. The spin-on is currently the most common form of lube oil filter used in vehicles. A modern and more expensive option is the oil filter module. A module for a four-cylinder diesel engine is depicted in Figure 9.6. The module combines the oil filter with other functions for managing the oil and its flow. This includes the oil cooler, oil pressure and temperature monitors, and liquid flow control (oil and water). A major advantage of the module is that it takes up less of the critical space in the engine compartment. It still provides for easy change of the disposable filter element.

Just as the design of filters for engine oil lubricants is in a state of dynamic change, so is the nature of the filter media. The traditional filter media for engine oil filtration are resin treated papers. The media are usually treated with a phenol formaldehyde resin to provide for resistance and durability in the hot oil environment. Most media are produced as “B-Stage” for the pleating operation and then fully cured for the application. B-stage is the condition where the medium has been dried to a specified volatiles content, but has not been fully cured. It is still soft and pliable for the pleating operation. This is the advantage of the phenolic resin, because once the paper is pleated and formed into a filter element, curing will provide the paper pleats with the
stiffness and rigidity to stand up to the adversity of hot oil flow (up to 120°C). Most often, resin treated paper for lube oil filtration is corrugated. Very often, it will be embossed with dimples to provide for pleat separation (see Figure 3.6 of Chapter 3, Section 3.5.2).

The demand for more modern forms of filter media is motivated by the following concerns:

(a) Environmental and safety concerns – Solvent based phenolics emit volatile organic compounds and formaldehyde, both undesirable for the air environment and regulated by the environmental protection organizations of many countries. Formaldehyde is recognized as a carcinogenic, therefore its emissions in the workplace are viewed as a safety hazard. US labeling laws require that filter media shipments to a customer be labeled as containing formaldehyde if
the emissions from the medium exceeds 1,000 ppm. Disposal of waste media treated with phenolic resin is a concern.

(b) Filtration performance - The need for higher quality filtration is demanded by the higher quality of engines being manufactured. Improved filtration efficiency is needed to address the increased concerns of engine performance. High dirt holding capacity is demanded because the filters are becoming smaller. There is also a desire for longer filter life so as to reduce the disposal quantities of used filters after replacement.

(c) Space – Space in the engine compartment is on short supply because of all the modernization occurring in this location of the vehicle. Smaller filters to fit in these spaces demand improved dirt holding capacity to maintain filtration quality.

In response to the challenges the following medium developments are in continuing progress:

(a) Increased use of synthetic fibers;
(b) The use of dry formed nonwovens;
(c) The advent of composite structures;
(d) The development of advance cure resin systems.

Durst et al.\textsuperscript{187} compared a number of different media including a composite structure as well as high synthetic content media. Their results are presented in Figure 9.7. The
data suggests that by the appropriate choice of synthetic fibers and/or composite structures, the filtration efficiency performance of a lube oil filter can be greatly improved.

The use of synthetic fibers can improve other properties in addition to filtration efficiency. The presence of synthetic fibers in filter media improves flex resistance. In one of their advertising brochures Ahlstrom (1990), a major manufacturer of filter media for engine filtration, demonstrated that synthetic fiber in one of their oil filter grades gave better wet oil burst strength after prolonged aging in hot oil (see Figure 9.8).

### 9.3 Air Intake Filtration

The purpose of an engine air induction system is to deliver clean air to the throttle body of the engine, while providing engine sound tuning with minimal power loss.
Critical to the operation of the system is the air induction filter. The air-intake system can be the major source of contaminants entering an engine, particularly if its filtration performance is inadequate. Jaroszczyk et al.\(^{(191)}\) suggest that “Airborne Contaminants are responsible for more than 3/4 of engine wear.” Engine wear caused by contaminants is a function of total contaminant mass, chemical composition, and size.

The two major AIF categories for engine powered vehicles are automotive air filtration and heavy duty air filtration (HDA). The media for these two applications are quite different in properties. Media for automotive air filters are more porous and the filters are comparatively small. They can be broken down into light duty AIF and medium duty AIE. They are designed to fit in the engine compartment of vehicles such as automobiles, sport utility vehicles (SUVs), panel trucks, vans, and small commercial trucks. The design attempts to maximize filter life (dirt holding capacity) and maintain adequate filtration efficiency to protect the engine. The medium grammage or basis weight ranges from as low as 110 g/m\(^2\) for light weight panel air filter media to as high as 210 g/m\(^2\) for composite dual-layer constructions. Air permeabilities range from 250 to 400 l/dm\(^2\)/min at 12.7 mm WG. Heat and temperature resistance are important requirements of an automotive air-intake filter exposed to the heat of a hot running engine. In some cases the medium is expected to be flame retardant. The filter elements are for one time use and disposed off after achieving their useful life. Very little effort is made to recover the used elements for reuse.

HDAs are designed for large trucks, trailer tractors, farm equipment, off the road construction equipment, buses, railroad engines, and military vehicles such as tanks and helicopters. The filters are much larger and usually installed outside the engine compartment. The engines they are designed to protect are high capital items, therefore the filtration efficiency demands for HDA are much greater than for automotive AIG. The grammage is in the range of 90–160 g/m\(^2\). Air permeabilities range from 30 to 90 l/dm\(^2\)/min at 12.7 mm. The size and efficiency requirements of HDAs may make them quite expensive, therefore they are designed to be washed and reused. A typical HDA is washed and reused 2–3 times before it is discarded.

Bugli\(^{(192)}\) has provided Tables 9.2 and 9.3 that compare the difference in requirements for light/medium duty AIF vs. heavy duty AIE. Table 9.2 compares service requirements. Note that the HDA AIF uses larger filters and are expected to last up to 500,000 miles (1,100,000 km) whereas; the light/medium duty filters are expected to last at the most to 100,000 miles (220,000 km). HDA life is optimized based on pressure drop. They are cleaned or replaced when they exceed a prescribed pressure drop. The filters for smaller vehicles are replaced based on the vehicle owner’s judgment. As a result, they tend to be underutilized. Note from the design specifications of Table 9.3 that HDA filters are expected to have much higher dust capacities and much higher filtration efficiencies.

Resin treated cellulose media from the wet lay process are the most frequently used media for AIF applications. In some applications, such as for military vehicles, the media may be reinforced with synthetic fibers for higher burst strength and greater durability.

Recently, interest has been generated for nanofiber coated filter media. Trautmann et al.\(^{(193)}\) illustrates the filtration effect in the microphotographs of Figure 9.9. Presumably, the nanofiber coating displayed here is from the electrospun process.
Table 9.2  Comparison of service conditions for light/medium duty AIF and HDA AIF

<table>
<thead>
<tr>
<th>Service conditions</th>
<th>Light/medium duty AIF</th>
<th>Heavy duty AIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum foil loading</td>
<td>Lower than design intent</td>
<td>Optimized</td>
</tr>
<tr>
<td>Aluminum foil efficiency</td>
<td>Lower than recommended</td>
<td>Optimized</td>
</tr>
<tr>
<td>Engine wear</td>
<td>May be higher</td>
<td>Significantly lower</td>
</tr>
<tr>
<td>Cost of ownership</td>
<td>Higher</td>
<td>Lower</td>
</tr>
<tr>
<td>Value to customer</td>
<td>Lower</td>
<td>Higher</td>
</tr>
</tbody>
</table>

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Table 9.3  Comparison of design specifications for light/medium duty AIF and HDA AIF

<table>
<thead>
<tr>
<th>Design specifications</th>
<th>Light/medium duty AIF</th>
<th>Heavy duty AIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dust capacity</td>
<td>≥100–400 g</td>
<td>&gt;1000–5000 g</td>
</tr>
<tr>
<td>Initial efficiency</td>
<td>≥97.9–99%</td>
<td>&gt;99.5–99.9%+</td>
</tr>
<tr>
<td>Overall efficiency</td>
<td>≥98–99%</td>
<td>&gt;99.9–99.99%</td>
</tr>
<tr>
<td>Filter restriction</td>
<td>~0–50 kPa</td>
<td>~0.125–0.5 kPa</td>
</tr>
<tr>
<td>AIS system restriction</td>
<td>&gt;2.0–4.0 kPa</td>
<td>&gt;2.0–3.5 kPa</td>
</tr>
<tr>
<td>Flow rates</td>
<td>2.5–18 m³/min</td>
<td>15–50 m³/min</td>
</tr>
<tr>
<td>Media face velocities</td>
<td>20–35 cm/s (paper)</td>
<td>1.5–5 cm/s (paper)</td>
</tr>
<tr>
<td>Media area</td>
<td>0.3–2.0 m²</td>
<td>2.5–15.0 + m²</td>
</tr>
<tr>
<td>Pre-separators</td>
<td>NA</td>
<td>Cyclonic/inertia type</td>
</tr>
<tr>
<td>Pre-separator efficiency</td>
<td>NA</td>
<td>~50–85%</td>
</tr>
<tr>
<td>Prefilters</td>
<td>Foam, felts</td>
<td>Foam, felts</td>
</tr>
<tr>
<td>Typical AIF sizes:</td>
<td>Panel (L × W × plHt)</td>
<td>150–400 × 125–300 × 25–75 mm</td>
</tr>
<tr>
<td></td>
<td>Cylindrical (OD × OHt × plHt)</td>
<td>100–300 × 150–300 × 20–63 mm</td>
</tr>
</tbody>
</table>

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The photographs are cross-sections of a cellulose medium with and without the nanofiber coating and at two levels of magnification. The photographs were taken after the medium had been tested in accordance with ISO 5011, the performance test standard for inlet air cleaning equipment for internal combustion engines and compressors. They show that without the nanofiber coating, the dust particles penetrate the medium, a depth filtration effect. On the other hand, the dust particles do not penetrate the nanofiber coated medium, but rather cake over the surface of the nanofiber coating. This is consistent with a study by Graham et al.\textsuperscript{16} reported in
Chapter 3, Section 3.6.1 that showed that dust particles have a greater affinity for the nanofiber layer of a nanofiber composite.

Trautmann et al.\textsuperscript{(193)} argue that the surface filtration effect provides not only for better filtration efficiency, but also for improved dust holding capacity. They provided Figures 9.10, 9.11, and other data to support the argument. Figure 9.10 compares standardized dust penetration for a standard AIF medium to a carrier paper with and without a nanofiber coating. Two grades of nanofiber coated carrier paper were tested. Figure 9.11 compares the standardized dust capacity for these media. The tests were conducted in accordance with ISO 5011 using coarse ISO test dust. The filter element configurations are depicted in the graphs. The data clearly indicates superior efficiency and dust holding capacity with the nanofiber coated filter medium. Trautmann et al. also ran tests with soot containing contaminants and continued to show improved efficiency and capacity performance with the nanofiber coated webs.
Figure 9.10. Improvement in efficiency for nanofiber coated carrier papers compared to noncoated carrier paper and standard paper. Test according to ISO 5011 with coarse ISO test dust.
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Figure 9.11. Improvement in dust holding capacity for nanofiber coated carrier papers compared to noncoated paper and standard paper. Test according to ISO 5011 with coarse ISO test dust.
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9.4 Cabin Air Filtration

According to Bräunling et al.[194] cabin air filtration began approximately 60 years ago when a cabin air filter was introduced in the 1938 Nash truck. In the 1970s, Ford explored a cabin air filter based on filter paper impregnated with activated carbon.
Also in the 1970s, a small Colorado company called Dickson Inc. introduced a hat-shaped fluted media composed of paper impregnated with activated carbon. This filter was inserted into the cowl area underneath the hood of the automobile. Testing revealed that the Ford and Dickson filters were quite effective in protecting the cabin against on the road automotive emissions, local odors from industry and farms (e.g., pig farms), and from allergy causing pollens. For various reasons, the developments did not reach the marketplace or were not successful if they did. The concepts lay dormant until the 1980s when Freudenberg Nonwovens introduced the first effective air filter to hold 100% of the pollen, mold spores and other contaminants found in air (Bräunling et al.1984). These filters were first produced for Ford, BMW, and Mercedes Benz. In 1994, Freudenberg introduced the first cabin air filters into the North American market. These were in the Ford Contour and Mystique platforms.

The primary function of cabin air filters is to provide for comfort and protection of the passengers by preventing the intake of particulates such as pollens, spores, allergens, and other harmful particles. Adsorbent filters also provide protection against odors and harmful gas pollutants. The filter has a second function in that it protects the vehicle heat, ventilation, air conditioning (HVAC) system from build up of dirt and debris that might impair the performance of these systems. The life span of the unit is thereby increased and the maintenance decreased.

Bräunling et al.1994 identify the following as types of medium that might be used in cabin air filters:

(a) Electrospun nonwovens, which combine electrostatic effects with nanofiber filtration.
(b) Triboelectrically charged needle-punched nonwovens.
(c) Split charged fiber media.
(d) Melt-blown media.
(e) Spunbonded nonwovens.
(f) Dry laid webs.
(g) Wet laid webs.
(h) Adsorptive media (activated carbon and activated alumina).
(i) Composite structures of the above.

Table 9.4 lists two composite filter medium grades produced by Hollingsworth & Vose Company, Inc. One is a laminated composite of dry formed synthetic fiber grades, the other a composite of a synthetic fiber nonwoven with a wet laid cellulosic medium.

Hollingsworth & Vose also promote a line of activated carbon media for cabin air filters. These are three-layer laminated media, the carbon layer being in the middle. Table 9.5 summarizes their target properties.

Ahlstrom has introduced its Trinetex® technology for cabin air particulate filtration. In this unique technology, a three-layer wet laid medium is formed, each layer containing a different furnish of synthetic fibers. The three-layer construction provides for a gradient density effect to increase dirt holding capacity. It combines mechanical and electrostatic filtration to optimize filtration efficiency. Ahlstrom reports that the media are available with optional flame retardancy and antimicrobial treatments. Table 9.6 lists typical properties of several Trinetex® cabin air filter grades.
Table 9.4  Hollingsworth & Vose - cabin air filter medium grades

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Laminated composite. 100% synthetic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Application</td>
<td>Auto cabin air</td>
<td>Auto cabin air</td>
<td></td>
</tr>
<tr>
<td>Basis weight, g/m²</td>
<td>1125</td>
<td>147</td>
<td></td>
</tr>
<tr>
<td>Caliper, mm</td>
<td>0.58</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>Gurley stiffness, mg</td>
<td>620</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>NaCl resistance, mmH₂O at 32 l/min</td>
<td>0.6</td>
<td>1.73</td>
<td></td>
</tr>
<tr>
<td>NaCl penetration, % at 32 l/min</td>
<td>36</td>
<td>29.3</td>
<td></td>
</tr>
<tr>
<td>Dioctyl phthalate (DOP) Resistance, mmH₂O at 32 l/min</td>
<td>-</td>
<td>1.74</td>
<td></td>
</tr>
<tr>
<td>DOP penetration, % at 32 l/min</td>
<td>-</td>
<td>50.6</td>
<td></td>
</tr>
<tr>
<td>Frazier air permeability, l/dm²/min at 12.7 mmH₂O</td>
<td>686</td>
<td>296</td>
<td></td>
</tr>
<tr>
<td>Coulter pore size</td>
<td>Maximum pore, μm</td>
<td>70.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean flow pore, μm</td>
<td>21.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Minimum pore, μm</td>
<td>10.1</td>
<td></td>
</tr>
</tbody>
</table>

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Table 9.5  Hollingsworth & Vose – adsorptive filter media (AFM) for cabin air filtration

<table>
<thead>
<tr>
<th>Grade</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grammage ISO 536 g/m²</td>
<td>410</td>
<td>310</td>
<td>530</td>
<td>510</td>
<td>550</td>
<td>520</td>
</tr>
<tr>
<td>Thickness (2 N/cm²) mm</td>
<td>1.1</td>
<td>0.9</td>
<td>1.7</td>
<td>1.5</td>
<td>1.8</td>
<td>1.7</td>
</tr>
<tr>
<td>Air permeability 1/m²/s (2 mbar – A = 20 cm²)</td>
<td>1450</td>
<td>1850</td>
<td>1450</td>
<td>1650</td>
<td>1300</td>
<td>1400</td>
</tr>
<tr>
<td>Activated carbon content g/m²</td>
<td>300</td>
<td>200</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>400</td>
</tr>
</tbody>
</table>

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Table 9.6  Ahlstrom's Trinetex® grades for cabin air particulate filtration

<table>
<thead>
<tr>
<th>Grade</th>
<th>Grammage (g/m²)</th>
<th>Thickness (μm)</th>
<th>Resin content (%)</th>
<th>Burst strength (kPa)</th>
<th>Stiffness (g)</th>
<th>Pressure drop (mmH₂O)</th>
<th>Air permeability (l/m²/sec at 0.5” water)</th>
<th>Frazier (cfm)</th>
<th>Max pore size (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T 806</td>
<td>100</td>
<td>115</td>
<td>805</td>
<td>19.5</td>
<td>370</td>
<td>2</td>
<td>1,2</td>
<td>4400</td>
<td>1,000</td>
</tr>
<tr>
<td>F 800</td>
<td>100</td>
<td>100</td>
<td>640</td>
<td>19.5</td>
<td>550</td>
<td>0.95</td>
<td>2.5</td>
<td>2580</td>
<td>480</td>
</tr>
<tr>
<td>K 476</td>
<td>100</td>
<td>100</td>
<td>560</td>
<td>19.5</td>
<td>740</td>
<td>1.55</td>
<td>3.5</td>
<td>1850</td>
<td>340</td>
</tr>
<tr>
<td>K 476</td>
<td>120</td>
<td>125</td>
<td>660</td>
<td>19.5</td>
<td>990</td>
<td>2.51</td>
<td>4.5</td>
<td>1580</td>
<td>260</td>
</tr>
<tr>
<td>F 778</td>
<td>115</td>
<td>115</td>
<td>670</td>
<td>19.5</td>
<td>415</td>
<td>0.95</td>
<td>6.4</td>
<td>1230</td>
<td>180</td>
</tr>
</tbody>
</table>

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A microphotograph of the PLEKX® three-layer medium produced by KX Industries, of Orange, Connecticut was shown in Chapter 3 (Figure 3.13). The medium contains activated carbon granules thermo bonded between two nonwoven layers.

9.5 Fuel Filtration

9.5.1 Engine fuel filtration

Basically, there are two types of fuel systems for vehicle engines: gasoline and diesel fuel. Figure 9.1 above identifies five filters for fuel filtration in a diesel fuel powered automobile. These include an in-tank fuel filter, a diesel particulate filter, a tank ventilation filter, a fuel filter module with a metal-free fuel filter element, and an in-line fuel filter. A range of filtration media are available for these filters depending on performance required and geographical considerations. Petri et al. (195) has identified the following as being part of that range.

100% Cellulose
- Cellulose: single-layer media
- Cellulose: single-layer gradient density

Cellulose–polyester blends
- Cellulose–polyester: single-layer media

Cellulose–microfiber glass blends
- Cellulose–microfiber glass: single-layer media
- Cellulose–microfiber glass: gradient density/dual-phase

Melt-blown composites
- Cellulose melt-blown
- Cellulose–microfiber glass melt-blown
- Cellulose (gradient density) melt-blown

The important test method for fuel filtration is ISO 4572. This is a multi-pass efficiency test. The test stand is capable of testing both flat sheet media and filter elements or cartridges.

9.5.2 Fuel transportation systems

There are a number of distribution systems that distribute oil and fuel to various locations. The transportation system includes ocean tankers, barges, rail, trucks, and pipelines. A pipeline system might direct fuel from a refinery to a terminal to a local terminal to the point of use. For example, the point of use for aviation fuel would be an airport. The airport would have a storage facility to receive the fuel and capabilities to deliver the fuel to the aircraft. Chevron Products Corporation (196) has issued a company publication that adequately describes the pipeline fuel distribution system for aviation fuel. Chevron particularly notes the problems of contamination
that may be inherent with pipeline fuel. These contaminants include particulate matter and moisture. Fuel surfactants are an interference because they inhibit the ability of water particles to coalesce in a fuel filter/separator system. Micro-organisms such as bacteria and fungi may have the ability to flourish in jet fuel. Their biogrowth may result in solids that are very effective in plugging fuel filters.

Chevron discusses the cleaning techniques for contaminated fuel. This includes filters to remove particulate matter and salt driers to remove moisture. Chevron states that “The filter/separator is the workhorse of the processes used to remove free water from aviation fuels.” A schematic of a fuel filter/separator is illustrated in Figure 9.12. A manufacturer of this type of equipment is Velcon Filters of Colorado Springs, Colorado, USA. The equipment consists of two filter elements: an inlet coalescing element that coalesces minute droplets of water into drops that are large enough to be gravity separated downstream of the coalescing element and a separator element that rejects any water particles that might be entrained in the exiting fuel stream. The rejected water gravity settles in the sump at bottom of the housing.

The typical coalescing media for the inlet element is usually a resin treated wet laid medium composed of a blend of cellulose fibers and glass microfibers. Sometimes synthetic fiber such as polyester is added for greater flex resistance. Coalescing efficiency is governed by the content and diameter of the glass microfibers. The surface energy of the medium are important. What is desired is a fairly hydrophilic fiber surface that attracts water droplets and holds on to them as they grow in size by being struck by additional droplets. Eventually the coalesced water particles will be of sufficient size to be blown off the fibers by the wind of the fluid stream passing through the medium. Downstream of the medium, the water droplets are of sufficient size to gravity settle in the settling sump. Media treated with phenolic resin generally have the right surface properties for good coalescing and separation efficiencies. On the other hand media with low surface energy coatings such as fluorocarbons or silicones will generally have poor coalescing and separation efficiencies.
The exit element or separator needs to be very hydrophobic. It must reject any small water particles that are entrained in the fuel stream. The media for the exit elements will be coated with a very low energy additive such as a fluorocarbon or silicone.

Fuel filter/separators are specified by American Petroleum Institute/Institute of Petroleum (API/IP)\(^1\) Specification 1581. A recognized laboratory for testing fuel filter/separators and other aviation fuel filtration devices is the Southwest Research Institute (SwRI) in San Antonio, Texas USA.

Filter monitors or fuse filters are a type of filter that will shut down a pipeline fuel stream when it is contaminated with an overabundance of water. They are usually installed at the point where fuel is loaded into the fuel tanks of an aircraft. The medium is highly absorbent material such as carboxy methyl cellulose (CMC) that can absorb several times its weight in water, and of the type that is used in highly absorbent hygienic pads. The medium will swell when it absorbs this much water and shut off all flow. The fuse filters are regulated by API/IP Specification 1583.

### 9.6 Gas Turbine Air Filters

#### 9.6.1 Turbines description

Turbines are a form of engine and therefore are included in this chapter on engine filtration. Turbines are rotating devices designed to generate energy, either mechanical or electrical. The gas turbine in a jet aircraft engine is an example of mechanical energy generation. The turbine rotates a compressor that compresses the inlet gas. One or more ignition chamber injects and ignites fuel to heat and expand the gas and provide the exhaust thrust necessary to drive the aircraft. In large-scale power plants, the turbine operates a rotating electrical generator to produce electricity for the realm that is serviced by the power plant.

There are several types of turbines: including steam turbines, hydroelectric, solar turbines, wind turbines, and gas turbines. The complexities of the gas turbine machine are of interest to the filter and filter medium manufacturer, because of stringent requirements for inlet gas cleanliness. According to the US Department of Energy\(^2\) gas turbines basically involve three main sections:

- The compressor, which draws air into the engine, pressurizes it, and feeds it to the combustion chamber literally at speeds hundreds of miles per hour.
- The combustion system, typically made up of a ring of fuel injectors that inject a steady stream of fuel (e.g. natural gas) into the combustion chamber where it mixes with the air. The mixture is burned at temperatures of more than 2,000°F. The combustion produces a high temperature, high pressure gas stream that enters and expands through the turbine section.

\(^1\)API is the American Petroleum Institute and IP is the Institute of Petroleum. API/IP specifications are joint performance specifications issued by both organizations.

\(^2\)The IP has merged with the Institute of Energy, forming the new Energy Institute. Although IP test methods will continue to be called IP, the Institute of Petroleum is now called the Institute of Energy.
• The turbine is an intricate array of alternate stationary and rotating aerofoil-section blades. As hot combustion gas expands through the turbine, it spins the rotating blades. The rotating blades perform a dual function: they drive the compressor to draw more pressurized air into the combustion section, and they spin a generator to produce electricity.

9.6.2 Air inlet filtration for gas turbines

A turbine system must contain other components, including an inlet section, an exhaust system, and an exhaust diffuser. Figure 9.13 is a diagram of the inlet air system for a typical turbine-generator layout. The air to the system comes in through the air filter house. In addition to filtration an air inlet system may have provision for noise reduction (silencers) and cooling. The latter is necessary for many installations in hot dry climates such as the Middle East. The cooling makes the air denser. Dense air is more efficient for the turbine process. For installations in cold climates, deicers may be necessary to prevent winter ice condensation.

Turbine rotor assemblies are large, generally 1.5–1.8 m and they spin very fast (several thousand rpm). Even the smallest dust particles can cause microscopic damage and erosion with repeated contact. For this reason, the filtration of the incoming air is very important. The filter houses can be quite large. Note the example in Figure 9.14.

Gas turbine filters are rated in accordance with HVAC standards previously discussed in Chapter 8. These are Eurovent 4/5 (Chapter 8, Section 8.2.2.1), EN779 (Chapter 8, Section 8.2.2.1), EN1822 (Chapter 8, Section 8.3.2.4.1), and (American...
There are two primary types of filter houses: static and pulse self-cleaning. Static filter houses are usually panel filters, often pocket filters mounted in filter modules. There are two filter stages: prefilter and final.

Self-cleaning filter houses use both panel filters and circular cartridge filters. AAF International, Louisville, Kentucky USA produces DuraVee® panel filters which are mini-pleat V-pack filters containing two layers of glass microfiber media for a gradient density effect. They are particularly designed to withstand high temperatures, high humidity, and areas with moisture laden air. An example of such an environment is off-shore platforms. A more rugged construction version of the DuraVee® is the DuraVee® XL. This is also a mini-pleat V-pack filter with glass microfiber media. It is particularly designed to withstand the rigors of centrifugal compressors, gas turbines, and engines where severe surging or pulsations occur.

Very often the filters are of the conical cylindrical pair as illustrated in Figure 9.15. The filters pictured were produced by TDC Filter Manufacturing, Inc., Cicero, Illinois, USA, one of the world’s largest producers of replacement filters for gas turbines.
Table 9.7  Air filter classification equivalency table

<table>
<thead>
<tr>
<th>Filter type</th>
<th>Eurovent</th>
<th>EN779</th>
<th>ASHRAE 52.1 efficiency</th>
<th>Measured by</th>
</tr>
</thead>
</table>
| For Coarse Dust | EU1      | G1a   | <65%                   | Synthetic dust weight 
|                 | EU2      | G2a   | 65 < 80%               |                                       |
|                 | EU3      | G3a   | 80 < 90%               |                                       |
|                 | EU4      | G4a   | >90%                   |                                       |
| For Fine Dust   | EU5      | F5b   | 40 < 60%               | Atmospheric dust spot efficiency      |
|                 | EU6      | F6b   | 60 < 80%               |                                       |
|                 | EU7      | F7    | 80 < 90%               |                                       |
|                 | EU8      | F8    | 90 < 95%               |                                       |
|                 | EU9      | F9    | >95%                   |                                       |
| European HEPA Standards | EU10 | H10   | 85%                    | Sodium chloride or liquid aerosol   |
|                 | EU11     | H11   | 95%                    |                                       |
|                 | EU12     | H12   | 99.5%                  |                                       |
|                 | EU13     | H13   | 99.95%                 |                                       |
|                 | EU14     | H14   | 99.995%                |                                       |
| US HEPA Standard |         |       |                        | 99.97% DOP test MIL Std 282         |

* Tested per EN 779
a HEPA: High efficiency;

Efficiency at 0.3 μm Particulate air filter.
Meeting global standards ASHRAE 52.1, EN 1779, Eurovent 4/5, British Standard (BS) 6540 Deutsches Institut für Normung (DIN) 24 183.

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(Table 9.8). This type of filter is used in Donaldson’s GDX® self-cleaning inlet air filter for gas turbines. The GDX® filter house schematic is illustrated in Figure 9.16.

The schematic of the GDX® system as diagrammed in Figure 9.17 includes the pulse cleaning action. Monitoring devices trigger a reverse blast of air when the pressure drop across the filters reaches a certain point. This point can be set to fit the conditions of the environment.

Donaldson Company also produces a TTD® self-cleaning system. The picture of Figure 9.14 above is that of a TTD® system. The system also utilizes a pulse cleaning action and is referred to as the TTD® huff and puff system. This system uses vertically mounted cylinder cartridges. Figure 9.18 illustrates the vertical installation of the filters.

9.6.3 Filter media for gas turbine filtration

Filter media for gas turbine filtration depend on a number of factors including location, environment, desired filtration efficiency, pressure drop, and mechanical properties. Medium types include cellulose, blends of cellulose and polyester, glass microfiber blends of glass microfibers and synthetic fibers, and composite structures containing a melt-blown or electrospun layer. High loft mats of glass or synthetic fibers are also available for prefilter applications. They can be used as a prefilter wrap around the final filters. For example, the conical/cylindrical cartridge filter combinations discussed above can be wrapped with a high loft prefilter mat.
TDC offers the following medium choices for their gas turbine filters:

Table 9.8  Filter media used in TDC filters

<table>
<thead>
<tr>
<th>Media type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CX</td>
<td>Proprietary blend of select fibers designed to provide excellent efficiency and high airflow capacity. This medium is 100% efficient capturing AC Fine test dust.</td>
</tr>
<tr>
<td>QX</td>
<td>A blend of premium synthetic and cellulose fibers for heavy-duty applications. Offers increased durability and efficiency. QX media are of great benefit in applications that have moisture-related problems or use frequent pulsating.</td>
</tr>
<tr>
<td>SX</td>
<td>Recommended for applications in severe environmental conditions that may adversely affect the operation of the intake system. Blend of fine denier synthetic and glass fibers. The fine fiber size limits the pore size and creates a filtration medium with superior efficiency. The increased strength of SX media assures long-term durability.</td>
</tr>
</tbody>
</table>

Reproduced with permission of TDC Filter Manufacturing Inc., Cicero, Illinois, USA.
Figure 9.16. Donaldson GDX® self-cleaning inlet air filter system for gas turbines.
Reproduced with permission from Donaldson Company, Inc. © Donaldson Company, Inc. All rights reserved.

Figure 9.17. Schematic of Donaldson's GDX® self-cleaning inlet air filter system for gas turbines.
Reproduced with permission from Donaldson Company, Inc. © Donaldson Company, Inc. All rights reserved.
Donaldson Company offers several medium choices for their gas turbine filters:

1. Synthetic – man-made fibers that are sturdy, durable, and moisture resistant.
2. Duratek® – a special blend of man-made fibers and natural (cellulose) fibers that has superior dust holding capacity and moisture resistance.
3. Cellulose – natural fibers that stop a range of particulate particles sizes.
4. Spider-Web® – an electrospun nanofiber layer that catches very fine particulates before they reach the medium substrate. The composite structure can be formed by adding the nanofiber layer (or coating as it is sometimes called) to either synthetic or Duratek® (Section 9.4).

AAF offers a broad variety of media for their various rotating machinery filter applications. This includes cellulose–polyester, glass microfiber media that include gradient density versions, high loft melt-blown, and continuous filament glass mats.
CHAPTER 10

Standards for Nonwoven Filter Media

10.1 Standards and Trade Organizations That Have Standards, Registrations, and/or Certifications Related to Filter Media

Listed in Section 10.2 below are several organizations, whose activities include developing, coordinating, promulgating, revising, amending, reissuing, interpreting, certifying, regulating, or otherwise maintaining standards that are related to filtration and filter media. The list is by no means complete. It is an attempt to identify at least some of the organizations that have standards related to filter media and their applications. In almost all the cases, the main concern of the organization is broader objectives that may include filters or filter media. For example, organizations such as Technical Association of the Pulp and Paper Industry (TAPPI), Technical Association of the Australian and New Zealand Pulp and Paper Industry (APPTA), and Scandinavian Pulp, Paper and Board Testing Committee (SCAN) set standards for pulp and paper testing, some of which may apply to filter media. An example is tensile strength. The test for this paper property is also used to determine the tensile strength of filter media. European Disposables and Nonwovens Association (EDANA) and Association of the Nonwovens Fabrics Industry (INDA) are interested in nonwoven standards, many of which are pertinent to filter media. Organizations that set standards for a particular industry may include standards for the filters that are part of the products of that industry. American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE-heat, ventilation, air conditioning or HVAC) and Society of Automotive Engineers (SAE-automotive) are examples. Organizations such as Association Française de Normalisation (AFNOR) (France), British Standards Institution (BSI) (England), and Deutsches Institut für Normung (DIN) (Germany) set standards for a particular country. In Europe, national organizations must stop work on a standard if it is going to become a European standard (Comité de Européen Normalisation (CEN)) or an international or global standard (International Organization for Standards (ISO)).

Some organizations do not by themselves develop standards, however they are entrusted with the responsibility of administering, regulating, certifying, and/or monitoring certain standards.
There is an ongoing global effort to harmonize standards and alleviate conflicts between the laws of different nations. Harmonized standards are standards on the same subject approved by different standardizing organizations to establish interchangeability of products, process and services, or mutual understanding of test results, or information provided according to these standards. The table of contents for INDA-EDANA harmonised standards is presented in Section 10.4 below.

10.2 Standards Organizations

AATCC – American Association of Textile Chemists and Colorists, One Davis Drive, PO Box 12215, Research Triangle Park, NC 27709-2215, USA. Telephone: +1 (919)-549-8141; Fax: +1 (919)-549-8933; Web site: www.aatcc.org/

AFNOR – Association Francaise de Normalisation, 11 rue Francis de Pressensé 93571 La Plaine Saint-Denis Cedex, France. Telephone: +33 (0)1 41 62 80 00; Fax: +33 (0)1 49 17 90 00; Web site: www.afnor.fr/portail.asp

AHAM – Association for Home Appliance Manufacturers, 1111 19th Street, NW, Suite 402, Washington, DC 20036, USA. Telephone: +1 (202)-872-5955; Web site: www.aham.org/; Email: info@aham.org


ANSI – American National Standards Institute, 1819 L Street, NW (between 18th and 19th Streets), 6th floor, Washington, DC 20036, USA. Telephone: +1 (202) 293 8020; Fax: +1 (202) 298 9287; Web site: www.ansi.org/

API/IP – Produces joint performance specifications for API and IP

API – American Petroleum Institute, 1220 L Street, NW Washington, DC 20005-4070, USA. Telephone: +1 (202) 682-8000; Web site: api-ec.api.org/frontpage.cfm


ASME – ASME International, Three Park Avenue, New York, NY 10016-5990, USA. Telephone: +1 (800) 843 2763 (US/Canada), +52 95-800-843-2763 (Mexico), (973) 882 1167 (outside North America); Fax: (973) 882-1717; Web site: www.asme.org/; Email: infocentral@asme.org

ASTM – ASTM International, 100 Barr Harbor Drive, West Conshocken, PA 19428-2959, USA. Telephone: +1 (610) 832-9585; Fax: +1 (610) 832-9555; Web site: www.astm.org/cgi-bin/SoftCart.exe/index.shtml?E=mystore

Standards for Nonwoven Filter Media

Drummond Street Carlton. Vic 3053. Australia. Telephone: +61 3 9347 2377; Fax: +61 3 9348 1206; New Zealand: PO Box 6042, Whakarewarewa.Rotorua, New Zealand. Telephone: +64 7 350 2252; Fax: +64 7 350 2252; Web site: www.appita.com.au

BSI – BSI British Standards, BSI Group Press Office, British Standards House, 389 Chiswick High Road. London W4 4AL, UK. Telephone: +44 (0) 208 996 9001; Fax: +44 (0) 208 996 7001; Web site: www.bsi-global.com/index.xalter; Email: info@bsi-global.com

CEN – CEN-CENELEC Comité Européen de Normalisation (French) – European Committee for Standardization (English) 36 rue de Stassart, B-1050, Brussels, Belgium. Telephone: +32 2 550 08 11; Fax: +32 2 550 08 19; Web site: www.cenorm.org/cenorm/index.htm; Email: infodesk@cenorm.be


CPPA – Canadian Pulp and Paper Association, 1155 Metcalfe Street, Quebec H3B 4T6, Canada. Telephone: +1 (514) 866-6621; Fax: +1 (514) 866-3035; Web site: www.open.doors.cppa.ca


EDANA – European Disposables and Nonwovens Association Avenue Eugène Plasky, 157 B-1030 Brussels, Belgium. Telephone: +32 2 734 93 10; Fax: +32 2 733 35 18; Web site: www.edana.org/: Email: info@edana.org


FDA – United States Food and Drug Administration, 5600 Fishers Lane, Rockville, MD 20857-0001, USA. Telephone: +1 888-463-6332; Web site: www.fda.gov

IEST – The Institute of Environmental Sciences and Technology. 5005 Newport Drive. Rolling Meadows. IL 60008-3841. USA. Telephone: +1 (847) 255-1561; Fax: +1 (847) 255-1699; Web site: www.iest.org/: Email: iest@iest.org.
INDA – Association of the Nonwovens Fabrics Industry. 1200 Crescent Green, Suite 100, PO Box 1288 Cary, NC 27511, USA. Telephone: +1 (919) 233-1210; Fax: +1 (919) 233-1282; Web site: www.inda.org

ISO – International Organization for Standardization. 1, rue de Varembé, Case postale 56 CH-1211 Geneva 20, Switzerland. Telephone: +41 22 749 01 11; Fax: +41 22 733 34 30; Web site: www.iso.org/iso/en/ISOOnline.frontpage

JSA – Japanese Standards Association. 4-1-24, Akasaka, Minato-ku, Tokyo 107-8440 Japan. Telephone: +81-3-3583-8005; Fax: +81-3-3586-2014; Web site: www.jsa.or.jp/default_english.asp; Email: sitemaster@jsa.or.jp


NAFA – National Air Filtration Association, PO Box 68639, Virginia Beach, VA 23471, USA. Telephone: +1 (757) 313 7400; Fax: +1 (757) 497 1895; Web site: www.nafahq.org/; Email: nafa@nafahq.org

NFPA – National Fire Protection Association, 1 Batterymarch Park, Quincy, Massachusetts, 02169-7471, USA. Telephone: US +1 (617) 770 3000, Mexico (toll-free) +95-800-844-6058; Fax: +1 (617) 770 0700; Web site: www.nfpa.com/; Email: info@nfpa.com

NIOSH – National Institute of Occupation Safety and Health (U.S.) – part of the Centers for Disease Control and Prevention (CDC) in the Department of Health and Human Services – Centers for Disease Control and Prevention, 1600 Clifton Rd, Atlanta, GA 30333, USA. Telephone: +1 (800)-356-4674; Fax: +1 (513)-533-8573; Web site: www.cdc.gov/niosh/email-pubs.html; Email: niosh-publications@cdc.gov

NIST – National Institute of Standards and Technology, NIST, 100 Bureau Drive Stop 1070, Gaithersburg, MD 20899-1070, USA. Telephone: +1 (301) 975 8295; Web site: www.nist.gov/; Email: inquiries@nist.gov

NSF – NSF International. World Headquarters, 789 N. Dixboro Road, Ann Arbor, MI 48105, USA. Telephone: +1 (800) 673 6275 or +1 (734) 769 8010; Fax: +1 (734) 769 0109; Web site: www.nsf.org; Email: info@nsf.org

SAE – Society of Automotive Engineers (U.S.), SAE World Headquarters, 400 Commonwealth Drive, Warrendale, PA 15096-0001, USA. Telephone: +1 (724) 776 4841; Fax: +1 (724) 776 0790; Web site: www.sae.org/servlets/index
10.3 Standards Related to Nonwoven Filter Media

Following is a list of standards that the author believes may be relevant to nonwoven filter media. The methodology for selecting the standards was to visit the web sites of the organizations listed above and browse their listings. Most of the organizations have listings that respond to key words. The key words used were filtration, filter media, paper properties, and nonwovens. From the listings the standards selected were those that appeared pertinent to nonwoven filter media and filters made from nonwoven filter media.

<table>
<thead>
<tr>
<th>Organization</th>
<th>Number</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>AATCC</td>
<td>AATCC 22-2005</td>
<td>Water Repellency: Spray Test</td>
</tr>
<tr>
<td></td>
<td>AATCC 13-1962</td>
<td>Flammability of Clothing Textiles</td>
</tr>
<tr>
<td></td>
<td>AATCC 35-2000</td>
<td>Water Resistance – Rain Test</td>
</tr>
<tr>
<td></td>
<td>AATCC 112-2003</td>
<td>Formaldehyde Release from Fabric, Determination of Sealed Jar Method</td>
</tr>
<tr>
<td></td>
<td>AATCC 127-1998</td>
<td>Water Resistance: Hydrostatic Pressure Head</td>
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<tr>
<td></td>
<td>AATCC 193-2005</td>
<td>Aqueous Liquid Repellency: Water/Alcohol Solution Resistance Test</td>
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(Continued)
### Standards Related to Nonwoven Filter Media (Continued)

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<th>Title</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>L41-123, July 1986</td>
<td>Contamination in Aircraft Hydraulic Circuits. Filters. Absolute Filtration Rating Measurement</td>
</tr>
<tr>
<td></td>
<td>NF EN 779, February 2003</td>
<td>Particulate Air Filters for General Ventilation – Determination of the Filtration Performance</td>
</tr>
<tr>
<td></td>
<td>NF M07-068, April 1966</td>
<td>Diesel Fuels and Middle distillates. Filter Blocking tendency at Ambient Temperature. Filtration Method</td>
</tr>
<tr>
<td></td>
<td>NF Q03-001, October 1999</td>
<td>Paper and Board. Determination of Tensile Properties. Constant Rate of Loading Method</td>
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<td></td>
<td>NF Q03-004, December 1973</td>
<td>Paper and Board Tests. Determination of the Wet tensile Strength of Paper and Board</td>
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<td></td>
<td>NF Q03-014</td>
<td>Bursting Strength</td>
</tr>
<tr>
<td></td>
<td>NF X45-301, September 2000</td>
<td>Filter cartridges – Test methods – Integrity Inspection by Determination of the First Bubble Point</td>
</tr>
<tr>
<td></td>
<td>NF X45-302, September 2000</td>
<td>Filter cartridges – Test methods – Determination of Differential Pressure versus Flowrate</td>
</tr>
<tr>
<td></td>
<td>NF X45-303, September 2000</td>
<td>Filter cartridges – Test methods – Measurement of Filtration Efficiency and Retention Capacity</td>
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<td>NF X45-304, September 2000</td>
<td>Filter cartridges – Test methods – Absolute Filter Rating</td>
</tr>
<tr>
<td></td>
<td>NF X45-308, September 2000</td>
<td>Filter cartridges – Test methods – Verification of Resistance to High Temperature</td>
</tr>
<tr>
<td></td>
<td>NF X45-309, September 2000</td>
<td>Filter cartridges – Test methods – Resistance to Flow Rate Cyclic Variations</td>
</tr>
<tr>
<td></td>
<td>NF X45-310, September 2000</td>
<td>Filter cartridges – Test methods – Verification of the Crushing or Bursting Strength</td>
</tr>
<tr>
<td></td>
<td>NF X45-311, September 2000</td>
<td>Filter cartridges – Test methods – Determination of air Permeability</td>
</tr>
<tr>
<td>AHAM</td>
<td>ANSI/AHAM AC-1-2006</td>
<td>Air Cleaners – Portable – CADR – Test Method for Performance of Portable Household Electric Room Air Cleaners</td>
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## Standards Related to Nonwoven Filter Media (Continued)

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<tr>
<th>Organization</th>
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<tr>
<td>API/IP SPEC 1583 (2005)</td>
<td>Specifications and Laboratory Tests for Aviation Fuel Filter Monitors with Absorbent Type Elements for Aviation Fuel</td>
<td></td>
</tr>
<tr>
<td>APPITA</td>
<td>AS 1 301.P431:1973</td>
<td>Methods of Test for Pulp and Paper - Stiffness of Paper and Paperboard</td>
</tr>
<tr>
<td></td>
<td>AS/NZS 1 301.404s:1998</td>
<td>Methods of Test for Pulp and Paper - Tensile Strength of Paper and Board (Constant Rate of Loading Method)</td>
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<td>AS/NZS 1 301.400s:2006</td>
<td>Methods of Test for Pulp and Paper - Bursting Strength of Paper</td>
</tr>
<tr>
<td></td>
<td>AS/NZS 1 301.426s:1994</td>
<td>Methods of Test for Pulp and Paper - Determination of Thickness and Apparent Bulk Density or Apparent Sheet Density</td>
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<tr>
<td></td>
<td>AS 1 301.420s:1989</td>
<td>Methods of Test for Pulp and Paper (Metric Units) – Gurley Air Permeance of Paper</td>
</tr>
<tr>
<td>ASHRAE ASHRAE 52.2 – 1999</td>
<td>Method of Testing General Ventilation Air-Cleaning Devices for Removal efficiency by Particle Size</td>
<td></td>
</tr>
<tr>
<td>ASME ASME 510</td>
<td>Testing of Nuclear Air-Cleaning Systems</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ASME AG-1, Code Section FC 2003</td>
<td>HEPA Filters</td>
</tr>
<tr>
<td>ASTM ASTM D689-03</td>
<td>Standard Test for the Internal Tearing Resistance of Paper</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ASTM D1117-01</td>
<td>Standard Guide for Evaluating Nonwoven Fabrics</td>
</tr>
<tr>
<td></td>
<td>ASTM-1230-6</td>
<td>Flammability of Clothing Textiles</td>
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<td>ASTM D2863-06a</td>
<td>Flammability of Plastics Using the Oxygen Index Method</td>
</tr>
<tr>
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<td>ASTM D3786-06</td>
<td>Standard Test Method for Hydraulic Bursting Strength of Textile Fabrics–Diaphragm Bursting Strength Tester Method</td>
</tr>
<tr>
<td></td>
<td>ASTM D5733-99</td>
<td>Standard Test Method for Tearing Strength of Nonwoven Fabrics by the TRAPEZOID Procedure</td>
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## Standards Related to Nonwoven Filter Media (Continued)

<table>
<thead>
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<tbody>
<tr>
<td>ASTM</td>
<td>D6830-02</td>
<td>Standard Test Method for Characterizing the Pressure Drop and Filtration Performance of Cleanable Filter Media</td>
</tr>
<tr>
<td>ASTM</td>
<td>E1545-05</td>
<td>Test Method for Glass Transition Temperature by Thermomechanical Analysis</td>
</tr>
<tr>
<td>ASTM</td>
<td>E1545-05</td>
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<tr>
<td>ASTM</td>
<td>E1824-02</td>
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<tr>
<td>ASTM</td>
<td>F316-03</td>
<td>Pore Size Characteristics of Membrane Filters by Bubble Point and Mean Flow Pore Testing</td>
</tr>
<tr>
<td>ASTM</td>
<td>F1862-05</td>
<td>F1862-05 Standard Test Method for Resistance of Medical Face Masks to Penetration by Synthetic Blood (Horizontal Projection of Fixed Volume at a Known Velocity)</td>
</tr>
<tr>
<td>ASTM</td>
<td>E1824-02</td>
<td>Standard Test Method for Assignment of a Glass Transition Temperature Using Thermomechanical Analysis Under Tension</td>
</tr>
<tr>
<td>ASTM</td>
<td>F2101-01</td>
<td>Standard Test Method for Evaluating the Bacterial Filtration Efficiency (BFE) of Medical Face Mask Materials, Using a Biological Aerosol of Staphylococcus aureus,</td>
</tr>
<tr>
<td>ASTM</td>
<td>F2100-04</td>
<td>Standard Specification for Performance of Materials Used in Medical Face Masks</td>
</tr>
<tr>
<td>ASTM</td>
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<td>Standard Test Method for Determining the Initial Efficiency of Materials Used in Medical Face Masks to Penetration by Particulates Using Latex Spheres</td>
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<td>BSI</td>
<td>BS 3321:1986</td>
<td>Method for Measurement of the Equivalent Pore Size of Fabrics (Bubble Pressure Test)</td>
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<td>BSI</td>
<td>BS 3748:1992</td>
<td>Method for Determination of Persistence to Bending of Paper and Board</td>
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<td>BSI</td>
<td>BS 4400:1969</td>
<td>Method for Sodium Chloride Particulate Test for Respiratory Filters</td>
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<td>BSI</td>
<td>BS 4415-1:1992</td>
<td>Determination of the Tensile Properties of Paper and Board – Constant Loading</td>
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<td>BSI</td>
<td>BS 4768:1972</td>
<td>Burst Method for Textiles</td>
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<td>BSI</td>
<td>BS 3137:1972</td>
<td>Methods for Determining the Bursting Strength of Paper and Board</td>
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<td>BSI</td>
<td>BS 3928-1969</td>
<td>Method for Sodium Flame Test for Air Filters (other than for air supply to I.C. engines and compressors)</td>
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<tr>
<td>BSI</td>
<td>BS 6410:1991</td>
<td>Methods of Test for Filter Papers</td>
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</table>

(Continued)
## Standards Related to Nonwoven Filter Media (Continued)

<table>
<thead>
<tr>
<th>Organization</th>
<th>Number</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS 6712-1:1995</td>
<td>Measurement of Hygroexpansivity of Paper and Board. Method for the Measurement of Hygroexpansivity up to a Maximum Relative Humidity of 68%</td>
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<tr>
<td>BS 7403-1:1998</td>
<td>Full-Flow Lubricating Oil Filters for Internal Combustion Engines. Methods of Test for Differential Pressure/Flow Characteristics</td>
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<td>BS 7403-3:1997</td>
<td>Full-Flow Lubricating Oil Filters for Internal Combustion Engines. Methods of Test for Resistance to High Differential Pressure and to Elevated Temperature</td>
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<td>BS 7403-4:1998</td>
<td>Full-Flow Lubricating Oil Filters for Internal Combustion Engines. Methods of Test for Initial Particle Retention Efficiency, Life and Cumulative Efficiency (Gravimetric Method)</td>
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<td>BS 7403-5:1990</td>
<td>Full-Flow Lubricating Oil Filters for Internal Combustion Engines. Method of Test for Cold Start Simulation and Hydraulic Pulse Durability</td>
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<td>BS 7403-7:1991</td>
<td>Full-Flow Lubricating Oil Filters for Internal Combustion Engines. Method of Test for Vibration Fatigue</td>
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<td>BS 7403-9:1995</td>
<td>Full-Flow Lubricating Oil Filters for Internal Combustion Engines. Method of Test for Inlet and Outlet Anti-drain Valves</td>
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<td>BS 7403-11:1998</td>
<td>Full-Flow Lubricating Oil Filters for Internal Combustion Engines. Methods of Test for Self-cleaning Filters</td>
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<tr>
<td>BS 7403-12:2000</td>
<td>Full-Flow Lubricating Oil Filters for Internal Combustion Engines. Filtration Efficiency Using Particle Counting, and Contaminant Retention Capacity</td>
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<tr>
<td>BS 7881:1997</td>
<td>Method of Test for Petrol Filters</td>
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<td>CEN</td>
<td>EN 149:2001</td>
<td>Respirators (European version of NIOSH)</td>
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<td>EN 779:2002 (E)</td>
<td>Particulate Air Filters for General Ventilation – Determination of the Filtration Performance</td>
<td></td>
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<tr>
<td>EN 1822-1:1998</td>
<td>High efficiency Air Filters (HEPA and ULPA) – Part 1: Classification, Performance Testing, Marking</td>
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</tbody>
</table>

(Continued)
## Standards Related to Nonwoven Filter Media (Continued)

<table>
<thead>
<tr>
<th>Organization</th>
<th>Number</th>
<th>Title</th>
</tr>
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<td>CPPA</td>
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<td>High efficiency Air Filters (HEPA and ULPA) – Part 1:</td>
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<td>Classification, Performance Testing, Marking –</td>
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<td>Part 4: Determining Leakage of Filter Element (Scan Method)</td>
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<td>EN 1822-5:1998</td>
<td>High efficiency Air Filters (HEPA and ULPA) – Part 5:</td>
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<td></td>
<td>EN 13328-1:2001</td>
<td>Breathing System Filters for Anaesthetic and Respiratory</td>
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<tr>
<td></td>
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<td>Use – Part 1: Salt Test Method to Assess Filtration</td>
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<td>Performance</td>
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<td>EN 29073-1:1992</td>
<td>Test Methods for Nonwovens. Part 1: Determination of</td>
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<tr>
<td></td>
<td></td>
<td>Mass per Unit Area</td>
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<tr>
<td></td>
<td></td>
<td>Tensile Strength and Elongation</td>
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<tr>
<td></td>
<td>D.8 (2005)</td>
<td>Bursting Strength of Paper</td>
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<tr>
<td></td>
<td>D.28P (1998)</td>
<td>Stiffness of Paper and Paperboard (Taber-Type Stiffness Tester)</td>
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<tr>
<td></td>
<td>D.39P (2005)</td>
<td>Internal Bond Strength of Paper and Paperboard (Scott-Type)</td>
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<td>DIN</td>
<td>DIN EN 13328-2</td>
<td>Breathing system filters for anaesthetic and respiratory use – Part 2:</td>
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<td>Non-filtration aspects (includes Amendment A1:2003) (FOREIGN STANDARD)</td>
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<td>DIN 24185</td>
<td>HVAC standard</td>
</tr>
<tr>
<td></td>
<td>DIN 24189</td>
<td>Testing of air cleaners for internal combustion engines and compressors: test methods</td>
</tr>
<tr>
<td></td>
<td>DIN 54305</td>
<td>Testing of textiles; determination of the compression elastic behavior of fibrous webs and nonwovens</td>
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<tr>
<td></td>
<td>DIN 71460-1</td>
<td>Air filters for passenger compartments; test for particulate filtration May 2003 draft</td>
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<tr>
<td>EUROVENT</td>
<td>EUROVENT 4/5</td>
<td>Testing of Air Filters Used in General Filtration</td>
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</tbody>
</table>

(Continued)
### Standards Related to Nonwoven Filter Media (Continued)

<table>
<thead>
<tr>
<th>Organization</th>
<th>Number</th>
<th>Title</th>
</tr>
</thead>
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<tr>
<td>IEC</td>
<td>IEC 312</td>
<td>Methods for Measurements of Performance of Vacuum Cleaners</td>
</tr>
<tr>
<td>FDA</td>
<td>21 CFR Part 177, §177.2260</td>
<td>Filters, Resin Bonded</td>
</tr>
<tr>
<td></td>
<td>21 CFR Part 182</td>
<td>Substances Generally Recognized as Safe</td>
</tr>
<tr>
<td></td>
<td>21 CFR Part 184</td>
<td>Direct Food Substances Affirmed as Generally Recognized as Safe</td>
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<td></td>
<td>21 CFR Part 186</td>
<td>Indirect Food Substances Affirmed as Generally Recognized as Safe</td>
</tr>
<tr>
<td></td>
<td>JIS B 8371-2:2000</td>
<td>Pneumatic Fluid Power – Compressed Air Filters – Part 2: Test Methods to Determine the Main Characteristics to be Included in Supplier’s Literature</td>
</tr>
<tr>
<td></td>
<td>JIS B 9901:1997</td>
<td>Gas Removal – Method of Test for Performance of Gas-Removal Filters</td>
</tr>
<tr>
<td></td>
<td>JIS B 9908:2001</td>
<td>Test Method of Air Filter Units for Ventilation and Electric Air Cleaners for Ventilation</td>
</tr>
<tr>
<td></td>
<td>JIS B 9927:1999</td>
<td>Clean Rooms – Air Filters – Test Methods</td>
</tr>
<tr>
<td></td>
<td>JIS D 0117-1:2005</td>
<td>Road Vehicles and Internal Combustion Engines – Filter Vocabulary – Part 1: Definitions of Filters and Filter Components</td>
</tr>
<tr>
<td></td>
<td>JIS D 1608:1993</td>
<td>Fuel Filter Test Method for Automotive Gasoline Engines</td>
</tr>
<tr>
<td></td>
<td>JIS D 1611-1:2003</td>
<td>Automotive Parts – Lubricating Oil Filters for Internal Combustion Engines – Part 1: General Test Methods</td>
</tr>
<tr>
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<td>JIS D 1617:1998</td>
<td>Automobile Parts – Fuel Filters for Diesel Engines – Test Methods</td>
</tr>
</tbody>
</table>

(Continued)
## Standards Related to Nonwoven Filter Media (Continued)

<table>
<thead>
<tr>
<th>Organization</th>
<th>Number</th>
<th>Title</th>
</tr>
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<tbody>
<tr>
<td>JIS D</td>
<td>3904:1997</td>
<td>Automotive Parts – Spin-On Type Oil Filters for Gasoline Engines</td>
</tr>
<tr>
<td>JIS L</td>
<td>0101:1978</td>
<td>Text System to Designate Linear Density of Fibres, Yarn Intermediates, Yarns, and Other Textile Materials</td>
</tr>
<tr>
<td>JIS L</td>
<td>1913:1998</td>
<td>Test Methods for Nonwovens Made of Staple Fibers</td>
</tr>
<tr>
<td>JIS K</td>
<td>0901:1991</td>
<td>Form, Size and Performance Testing Methods of Filtration Media for Collecting Airborne Particulate Matters</td>
</tr>
<tr>
<td>JIS K</td>
<td>2243:1993</td>
<td>Air Filter Oil</td>
</tr>
<tr>
<td>JIS K</td>
<td>3801:2000</td>
<td>Test Method of HEPA Filters for Microbiological Use</td>
</tr>
<tr>
<td>JIS K</td>
<td>3832:1990</td>
<td>Testing Method for Bubble Point of Membrane Filters</td>
</tr>
<tr>
<td>JIS P</td>
<td>3801:1995</td>
<td>Filter Paper (for Chemical Analysis)</td>
</tr>
<tr>
<td>JIS R</td>
<td>3421:1999</td>
<td>Textile Finished Glass Fabrics for Bag Filter</td>
</tr>
<tr>
<td>ISTT</td>
<td>3219:2005</td>
<td>Sterile Infusion Filter</td>
</tr>
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<td>3224:2005</td>
<td>Sterile Syringe Filter</td>
</tr>
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<td>ISTT</td>
<td>3225:2005</td>
<td>Sterile Transfusion Filter</td>
</tr>
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<td>ISTT</td>
<td>3232:2005</td>
<td>Blood Filters for Cardiopulmonary Bypass Systems</td>
</tr>
<tr>
<td>ISTT</td>
<td>7211:2005</td>
<td>Breathing System Filters for Anaesthetic and Respiratory Use – Part 1: Salt Test Method to Assess Filtration Performance</td>
</tr>
<tr>
<td>JIS Z</td>
<td>4812:1995</td>
<td>HEPA Filters for Radioactive Aerosols</td>
</tr>
<tr>
<td>JIS Z</td>
<td>8908:1998</td>
<td>Filter Fabrics for Dust Collection</td>
</tr>
<tr>
<td>IEST</td>
<td>IEST-RP-CC001.3</td>
<td>Recommended Practice for Testing and Certification of HEPA Filters</td>
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<td>IEST</td>
<td>IEST-RP-CC001.4</td>
<td>HEPA and ULPA Filters</td>
</tr>
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<td>IEST-RP-CC007.1</td>
<td>Testing ULPA Filters</td>
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<td>IEST-RP-CC0021.2</td>
<td>Testing HEPA and ULPA Filter Media</td>
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<tr>
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<td>IEST-RP-CC0034.2</td>
<td>HEPA and ULPA Filter Leak Tests</td>
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<td>INDA</td>
<td>IST No. 30.1</td>
<td>Bursting Strength</td>
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<td>IST No. 50.0-71</td>
<td>Flammability</td>
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<td>IST No. 90.2-86</td>
<td>Gurley Stiffness Test</td>
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<td>IST No. 100.0-70</td>
<td>Tear Test</td>
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<td>IST No. 100.1-70</td>
<td>Internal (Elmendorf) Tear</td>
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<tr>
<td>INDA</td>
<td>IST No. 100.2-70</td>
<td>Edge Tear</td>
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<td>IST No. 100.3-70</td>
<td>Trapezoid Tear Strength</td>
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<td>INDA</td>
<td>IST No. 110.1-4</td>
<td>Breaking Load and Elongation</td>
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<td>IST No. 110.3-84</td>
<td>Internal Bond Strength</td>
</tr>
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<td>INDA</td>
<td>IST No. 120.1-2</td>
<td>Basis Weight and Thickness</td>
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<td>INDA</td>
<td>IST No. 120.2</td>
<td>Thickness – High Loft Nonwovens</td>
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</table>

(Continued)
## Standards Related to Nonwoven Filter Media (Continued)

<table>
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<tr>
<th>Organization</th>
<th>Number</th>
<th>Title</th>
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<tr>
<td></td>
<td>ISO 2493:1992</td>
<td>Paper and Board – Determination of Resistance to Bending</td>
</tr>
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<td></td>
<td>ISO 2758:2001</td>
<td>Paper – Determination of Bursting Strength</td>
</tr>
<tr>
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<td>ISO 4020:2001</td>
<td>Road Vehicles – Fuel Filters for Diesel Engines – Test Methods</td>
</tr>
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<td></td>
<td>ISO 4548-4:1997</td>
<td>Full-Flow Lubricating Oil Filters for Internal Combustion Engines. Methods of Test for Initial Particle Retention Efficiency, Life and Cumulative Efficiency (Gravimetric Method)</td>
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<td></td>
<td>ISO 4548-5:1990</td>
<td>Full-Flow Lubricating Oil Filters for Internal Combustion Engines. Method of Test for Cold Start Simulation and Hydraulic Pulse Durability</td>
</tr>
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<td>ISO 4548-6:1985</td>
<td>Full-Flow Lubricating Oil Filters for Internal Combustion Engines. Method of Test for Static Burst Pressure</td>
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<tr>
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<td>ISO 5084:1996</td>
<td>Textiles – Determination of Thickness of Textiles and Textile Products</td>
</tr>
<tr>
<td></td>
<td>ISO 5270:2000</td>
<td>Pulps – Laboratory Sheets – Determination of Physical Properties</td>
</tr>
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(Continued)
### Standards Related to Nonwoven Filter Media (Continued)

<table>
<thead>
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<th>Organization</th>
<th>Number</th>
<th>Title</th>
</tr>
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<tbody>
<tr>
<td>ISO 5636-4:1986</td>
<td>Paper and Board – Determination of Air Permeance (medium range) – Part 4: Sheffield Method</td>
<td></td>
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<tr>
<td>ISO 8226-1:1994</td>
<td>Paper and Board – Measurement of Hygroexpansivity – Part 1 Hygroexpansivity up to a Maximum Relative Humidity of 68%</td>
<td></td>
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<td>ISO 8226-2:1990</td>
<td>Paper and Board – Measurement of Hygroexpansivity – Part 2 Hygroexpansivity up to a Maximum Relative Humidity of 86%</td>
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<tr>
<td>ISO 9237-1995</td>
<td>Textiles – Determination of the Permeability of Fabrics to Air</td>
<td></td>
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<tr>
<td>ISO 9865:1991</td>
<td>Textiles – Determination of Water Repellency of Fabrics by the Bundesmann Rain Shower Test</td>
<td></td>
</tr>
<tr>
<td>ISO 12103-1:1997</td>
<td>Road Vehicles – Test Dust for Filter evaluation – Part 1: Arizona Road Dust</td>
<td></td>
</tr>
<tr>
<td>ISO 14644-1:1999</td>
<td>Clean rooms and Associated Controlled Environments – Part 1: Classification of Air Cleanliness</td>
<td></td>
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</tbody>
</table>

**MIL-STD**

| MIL-STD-282 | Filter Units, Protective Clothing, Gas Mask Components, and Related Products: Performance Test Method |
| MIL-H-5606 | Hydraulic Fluids |
| MIL-STD-51068 | Filter, Particulate, High Efficiency, Fire Resistant |
| MIL-STD-51079D | Filter Medium, Fire-Resistant, High Efficiency |
## Standards Related to Nonwoven Filter Media (Continued)

<table>
<thead>
<tr>
<th>Organization</th>
<th>Number</th>
<th>Title</th>
</tr>
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<tbody>
<tr>
<td>MIL-STD-414</td>
<td>(1957)</td>
<td>Sampling Procedures and Tables for Inspection by Variables for Percent Defective</td>
</tr>
<tr>
<td>MIL-STD-105D</td>
<td>(1963)</td>
<td>Sampling Procedures and Tables for Inspection by Attributes</td>
</tr>
<tr>
<td>AIA</td>
<td>NAS 1638</td>
<td>Cleanliness Requirements of Parts Used in Hydraulic Systems</td>
</tr>
<tr>
<td>NFPA (Fire Protection)</td>
<td>NFPA 90A</td>
<td>Installation of Air Conditioning and Ventilating Systems (other than residence type)</td>
</tr>
<tr>
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<td>NFPA 90B</td>
<td>Installation of Warm Air Heating and Air Conditioning Systems (residence type)</td>
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<tr>
<td></td>
<td>NFPA-701</td>
<td>Fire Tests for Flame Resistant Textiles and Films</td>
</tr>
<tr>
<td></td>
<td>NFPA-702</td>
<td>Flammability of Clothing Textiles</td>
</tr>
<tr>
<td>NIOSH</td>
<td>42 CFR (US), Chapter 1, Part 84</td>
<td>Approval of Respiratory Protective Devices</td>
</tr>
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<td></td>
<td>APRS-STP-0051-00</td>
<td>Particulate Filter Penetration Procedure to Test Negative Pressure Respirators against Liquid Particulates</td>
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<tr>
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<td>APRS-STP-0057-00</td>
<td>Particulate Filter Penetration Procedure to Test Negative Pressure Respirators against Liquid Particulates</td>
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<td>NSF</td>
<td>NSF 50</td>
<td>Standard for Pools and Spas</td>
</tr>
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<td>SAE</td>
<td>SAE AIR 787:2003</td>
<td>Filter Element Cleaning Methods</td>
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<tr>
<td></td>
<td>SAE AIR 4057:2000</td>
<td>Secondary Filters for Fluid Systems Reliability</td>
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<td></td>
<td>SAE AIR 877:1993</td>
<td>Aerospace – Particle Count Data Conversion and Extrapolation</td>
</tr>
<tr>
<td></td>
<td>SAE ARP 598:2003</td>
<td>Aerospace Microscopic Sizing and Counting of Particulate Contamination for Fluid Power System</td>
</tr>
<tr>
<td></td>
<td>SAE ARP 725:2003</td>
<td>Evaluating Effectiveness of Filter Element Cleaning Methods</td>
</tr>
<tr>
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<td>SAE ARP 743:2001</td>
<td>Procedure for the Determination of Particulate Contamination of Air in Dust Controlled Spaces by the Particle Count Method</td>
</tr>
<tr>
<td></td>
<td>SAE ARP 900:1992</td>
<td>Methods for Evaluating Cryogenic Filters</td>
</tr>
<tr>
<td></td>
<td>SAE ARP 901:2001</td>
<td>Bubble-Point Test Method</td>
</tr>
<tr>
<td></td>
<td>SAE AS 4059</td>
<td>Aerospace Fluid Power – Cleanliness Classification for Hydraulic Fluids</td>
</tr>
<tr>
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<td>SAE J905:1999</td>
<td>Fuel Filter Test Methods</td>
</tr>
</tbody>
</table>

(Continued)
### Standards Related to Nonwoven Filter Media (Continued)

<table>
<thead>
<tr>
<th>Organization</th>
<th>Number</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAE</td>
<td>J124:1987</td>
<td>Glossary of Terms Related to Fluid Filters and Filter Testing, Recommended Practice</td>
</tr>
<tr>
<td>SAE</td>
<td>J1696:1997</td>
<td>Standard Fuel Filter Test Fluid</td>
</tr>
<tr>
<td>SAE</td>
<td>J1699:1994</td>
<td>Passenger Compartment Air Filter Test Code</td>
</tr>
<tr>
<td>SAE</td>
<td>2312:2005</td>
<td>Automatic Transmission Intake Filter Test Procedure</td>
</tr>
<tr>
<td>SAE</td>
<td>2321/1:2006</td>
<td>Disposable Hydraulic Filter Element – 21 MPa Collapse Pressure, Filtration Ratio = 75 at 10 μm, 190 l/min Flow</td>
</tr>
<tr>
<td>SAE</td>
<td>2321/2:2006</td>
<td>Disposable Hydraulic Filter Element – 175 l/min Flow, 1.0 MPa Collapse Pressure, Filtration Ratio = 75 at 6 and 10 μm</td>
</tr>
<tr>
<td>SAE</td>
<td>2321/3:2006</td>
<td>Disposable Hydraulic Filter Element – 190 l/min Flow, 1.0 MPa Collapse Pressure, Filtration Ratio = 75 at 6 and 10 μm</td>
</tr>
<tr>
<td>SAE HS806, 2001 Edition</td>
<td></td>
<td>SAE Oil Filter Test Procedure</td>
</tr>
<tr>
<td>SCAN</td>
<td>P16</td>
<td>Tensile Strength and Stretch of Paper and Paperboard Determined with a Pendulum Tester</td>
</tr>
<tr>
<td>SCAN</td>
<td>19:78</td>
<td>Paper and Board – Air Permeance – Gurley Method</td>
</tr>
<tr>
<td>SCAN</td>
<td>P 20:95</td>
<td>Papers and Boards – Wet Tensile Strength and Wet Tensile Strength Retention – Constant Rate of Elongation Method</td>
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<tr>
<td>SCAN</td>
<td>P24:99</td>
<td>Papers – Bursting Strength and Bursting Strength Absorption</td>
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<td>SCAN</td>
<td>P28:88</td>
<td>Dimensional Stability</td>
</tr>
<tr>
<td>SCAN</td>
<td>P29:95</td>
<td>Paper and Boards – Bending Resistance</td>
</tr>
<tr>
<td>SCAN</td>
<td>P67:93</td>
<td>Pulps, Papers, and Boards – Tensile Strength, Strain at Break, Tensile Energy Absorption and Tensile Stiffness – Constant Rate of Elongation Method</td>
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<tr>
<td>SCAN</td>
<td>P80:98</td>
<td>Papers and Boards – Z Directional Tensile Test</td>
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<tr>
<td>SCAN</td>
<td>P85:02</td>
<td>Paper and Board – Air Permeance – Bendsten Method with Pressure Correction</td>
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<tr>
<td>SCAN</td>
<td>P90:03</td>
<td>Paper and Board – Z-Directional Toughness</td>
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<td>TAPPI</td>
<td>T 234 cm-02</td>
<td>Coarseness of Pulp Fibers</td>
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<td>TAPPI</td>
<td>400 sp-06</td>
<td>Sampling and Accepting a Single Lot of Paper, Paperboard, Containerboard or Related Product</td>
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<td>TAPPI</td>
<td>401 om-03</td>
<td>Fiber Analysis of Paper and Paperboard</td>
</tr>
<tr>
<td>TAPPI</td>
<td>402 sp-03</td>
<td>Standard Conditioning and Testing Atmospheres for Paper, Board, Pulp Handsheets, and related Products</td>
</tr>
<tr>
<td>TAPPI</td>
<td>403 om-02</td>
<td>Bursting Strength of Paper</td>
</tr>
<tr>
<td>TAPPI</td>
<td>404 om-92</td>
<td>Tensile Breaking Strength and Elongation of Paper and Paperboard (Using Pendulum Type Tester)</td>
</tr>
<tr>
<td>TAPPI</td>
<td>410 om-02</td>
<td>Grammage of Paper and Paperboard (Weight per Unit Area)</td>
</tr>
</tbody>
</table>

(Continued)
### Standards Related to Nonwoven Filter Media (Continued)

<table>
<thead>
<tr>
<th>Organization</th>
<th>Number</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAPPI</td>
<td>T 411 om-05</td>
<td>Thickness (Caliper) of Paper and Paperboard and Combined Board</td>
</tr>
<tr>
<td>TAPPI</td>
<td>T 413 om-06</td>
<td>Ash in Paper and Paperboard (Used to determine organic content of glass microfiber HEPA and ULPA filter media)</td>
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<tr>
<td>TAPPI</td>
<td>T 414 om-04</td>
<td>Internal Tearing Resistance of Paper (Elmendorf-Type Tester)</td>
</tr>
<tr>
<td>TAPPI</td>
<td>423 cm-98</td>
<td>Folding Endurance of Paper (Schopper-Type Tester)</td>
</tr>
<tr>
<td>TAPPI</td>
<td>456 om-03</td>
<td>Wet Tensile Breaking Strength of Paper and Paperboard</td>
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<tr>
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<td>460 om-06</td>
<td>Air Resistance of Paper (Gurley Method)</td>
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<tr>
<td>TAPPI</td>
<td>461 om-00</td>
<td>Flame Resistance of Treated Paper and Paperboard</td>
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<tr>
<td>TAPPI</td>
<td>489 om-04</td>
<td>Stiffness of Paper and Paperboard (Taber Stiffness Tester)</td>
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<td>TAPPI</td>
<td>494 om-06</td>
<td>Tensile Properties of Paper and Paperboard (Using Constant Rate of Elongation Apparatus)</td>
</tr>
<tr>
<td>TAPPI</td>
<td>511 om-06</td>
<td>Folding Endurance of Paper (MIT Tester)</td>
</tr>
<tr>
<td>TAPPI</td>
<td>541 om-99</td>
<td>Internal Bond Strength of Paperboard (Z-Direction Tensile)</td>
</tr>
<tr>
<td>TAPPI</td>
<td>543 om-00</td>
<td>Bending Resistance of Paper (Gurley-type Tester)</td>
</tr>
<tr>
<td>TAPPI</td>
<td>550 om-03</td>
<td>Determination of Equilibrium Moisture in Pulp, Paper, and Paperboard for Chemical Analysis</td>
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<tr>
<td>TAPPI</td>
<td>569 pm-00</td>
<td>Test for Interfiber Bond Using the Internal Bond Tester</td>
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<tr>
<td>UL</td>
<td>UL 900</td>
<td>Test Performance of Air Filter Units</td>
</tr>
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<td>UL</td>
<td>586-90</td>
<td>Standard for Safety High Efficiency, Particulate Air Filter Units</td>
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<tr>
<td>VDI</td>
<td>VDI/VDE 2631</td>
<td>Form Measurement – Properties and Selection of Filters</td>
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<tr>
<td>VDI</td>
<td>3280</td>
<td>Testing of Cleanable Filter Media – Standard Test for the Evaluation of Cleanable Filter Media</td>
</tr>
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<td>VDI</td>
<td>3926 Blatt 1 (2004)</td>
<td>Filtering Separators – Surface Filters</td>
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<tr>
<td>VDI</td>
<td>3677 Blatt 1 (1997)</td>
<td>Filtering Separators – Depth Fiber Filters</td>
</tr>
</tbody>
</table>

### 10.4 INDA – EDANA Harmonized Test Methods

In 2005 INDA and EDANA collaborated to issue a set of “Standard Test Methods for the Nonwovens Industry”. Table 10.1 lists the detailed table of contents. Although not all the tests are relevant to filter media they do give a summary of the detailed testing and guidelines that exist with nonwoven media, whether they be for filtration or other purposes.
Table 10.1 INDA and EDANA standard test methods for the nonwovens industry

<table>
<thead>
<tr>
<th>Description</th>
<th>Method number</th>
<th>Equivalent methods</th>
<th>ISO reference</th>
<th>Page number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. GUIDANCE DOCUMENTS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glossary of Terms</td>
<td>WSP 1.0</td>
<td>New Document</td>
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<td>How to Write a Test Method</td>
<td>WSP 2.0</td>
<td>New Document</td>
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<tr>
<td>Sample and Laboratory Conditioning</td>
<td>WSP 3.0</td>
<td>ERT 60.2 (99)</td>
<td></td>
<td>1.57</td>
</tr>
<tr>
<td>Worldwide Associations</td>
<td>WSP 4.0</td>
<td>ERT Useful Addresses</td>
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</tr>
<tr>
<td>Sampling</td>
<td>WSP 5.0</td>
<td>ERT 130.2 (99)</td>
<td></td>
<td>1.67</td>
</tr>
<tr>
<td>List of Vendors</td>
<td>WSP 6.0</td>
<td>IST Useful Vendors List</td>
<td></td>
<td>1.71</td>
</tr>
<tr>
<td>Guidance to Nonwoven Test Methods</td>
<td>WSP 7.0</td>
<td>INDA Guidance Document</td>
<td></td>
<td>1.79</td>
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<tr>
<td>Guidance to Highloft Test Methods</td>
<td>WSP 8.0</td>
<td>INDA Guidance Document</td>
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<tr>
<td>2. ABSORPTION</td>
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<td></td>
</tr>
<tr>
<td>Nonwoven Absorption</td>
<td>WSP 10.1</td>
<td>ERT 10.4 (02)</td>
<td>9073 – 6:2000</td>
<td>2.1</td>
</tr>
<tr>
<td>Rate of Sorption of Wiping Materials</td>
<td>WSP 10.2</td>
<td>IST 10.2 (01)</td>
<td></td>
<td>2.11</td>
</tr>
<tr>
<td>Demand Absorbency</td>
<td>WSP 10.3</td>
<td>ERT 230 1 (02)</td>
<td>9073 – 12:2002</td>
<td>2.17</td>
</tr>
<tr>
<td>3. ABRASION RESISTANCE</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Inflated Diaphragm</td>
<td>WSP 20.1</td>
<td>Modified IST 20.1 (01)</td>
<td></td>
<td>3.1</td>
</tr>
<tr>
<td>Flexing and Abrasion</td>
<td>WSP 20.2</td>
<td>Modified IST 20.2 (01)</td>
<td></td>
<td>3.9</td>
</tr>
<tr>
<td>Double Rotary Platform (Tabor)</td>
<td>WSP 20.4</td>
<td>Modified IST 20.4 (01)</td>
<td></td>
<td>3.21</td>
</tr>
<tr>
<td>Modified Martindale</td>
<td>WSP 20.5</td>
<td>Modified IST 20.5 (01)</td>
<td></td>
<td>3.31</td>
</tr>
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<td>4. BURSTING STRENGTH</td>
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<td></td>
<td></td>
<td></td>
</tr>
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<td>Diaphragm Burst</td>
<td>WSP 30.1</td>
<td>Modified IST 30.1 (01)</td>
<td></td>
<td>4.1</td>
</tr>
<tr>
<td>Burst</td>
<td>WSP 30.2</td>
<td>ERT 80.4 (02)</td>
<td></td>
<td>4.7</td>
</tr>
<tr>
<td>5. ELECTROSTATIC PROPERTIES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Resistivity</td>
<td>WSP 40.1</td>
<td>IST 40.1 (01)</td>
<td></td>
<td>5.1</td>
</tr>
<tr>
<td>Decay</td>
<td>WSP 40.2</td>
<td>IST 40.2 (01)</td>
<td></td>
<td>5.7</td>
</tr>
</tbody>
</table>
### 6. OPTICAL PROPERTIES

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard 1</th>
<th>Standard 2</th>
<th>Reference 1</th>
<th>Reference 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opacity (INDA)</td>
<td>WSP 60.1</td>
<td>IST 60.1 (01)</td>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td>Brightness (INDA)</td>
<td>WSP 60.2</td>
<td>IST 60.2 (01)</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>Brightness (EDANA)</td>
<td>WSP 60.3</td>
<td>ERT 100.1 (78)</td>
<td>6.13</td>
<td></td>
</tr>
<tr>
<td>Opacity (EDANA)</td>
<td>WSP 60.4</td>
<td>ERT 110.1 (78)</td>
<td>6.19</td>
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### 7. PERMEABILITY

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard 1</th>
<th>Standard 2</th>
<th>Reference 1</th>
<th>Reference 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Permeability</td>
<td>WSP 70.1</td>
<td>Modified IST 70.1 (01)</td>
<td>7.1</td>
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<tr>
<td>Liquid Strike-through</td>
<td>WSP 70.3</td>
<td>ERT 150.5 (02)</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>Water Vapor Transmission Rate</td>
<td>WSP 70.4</td>
<td>IST 70.4 (01)</td>
<td>7.15</td>
<td></td>
</tr>
<tr>
<td>Mocon/INDA</td>
<td>WSP 70.5</td>
<td>EDANA New Method</td>
<td>7.27</td>
<td></td>
</tr>
<tr>
<td>Water Vapor Transmission Rate, Mocon/EDANA, Part 1</td>
<td>WSP 70.6</td>
<td>EDANA New Method</td>
<td>7.39</td>
<td></td>
</tr>
<tr>
<td>Repeated Liquid Strike-Through Time</td>
<td>WSP 70.7</td>
<td>ERT 151.0 (02)</td>
<td>7.45</td>
<td></td>
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<tr>
<td>Wetback after Repeated Strike-Through</td>
<td>WSP 70.8</td>
<td>ERT 154.0 (02)</td>
<td>7.57</td>
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### 8. REPELLENCY

<table>
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<th>Standard 2</th>
<th>Reference 1</th>
<th>Reference 2</th>
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<tr>
<td>Surface Wetting Spray</td>
<td>WSP 80.1</td>
<td>IST 80.1 (01)</td>
<td>8.1</td>
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<tr>
<td>Penetration by Water (Rain Test)</td>
<td>WSP 80.2</td>
<td>IST 80.2 (01)</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>Penetration by Water (Spray Impact)</td>
<td>WSP 80.3</td>
<td>Modified IST 80.2 (01)</td>
<td>8.13</td>
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<td>Penetration by Saline Solution (Automated Mason Jar)</td>
<td>WSP 80.5</td>
<td>IST 80.5 (01)</td>
<td>8.23</td>
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<tr>
<td>Water Resistance (Hydrostatic Pressure)</td>
<td>WSP 80.6</td>
<td>IST 80.6 (01)/IST 80.4 (01)</td>
<td>8.29</td>
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<tr>
<td>Penetration by Oil (Hydrocarbon Resistance)</td>
<td>WSP 80.7</td>
<td>IST 80.7 (01)</td>
<td>8.39</td>
<td></td>
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<tr>
<td>Alcohol Repellency</td>
<td>WSP 80.8</td>
<td>IST 80.8 (01)</td>
<td>8.45</td>
<td></td>
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<td>Run-Off</td>
<td>WSP 80.9</td>
<td>ERT 152.2 (02)</td>
<td>8.51</td>
<td></td>
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<tr>
<td>Coverstock Wetback</td>
<td>WSP 80.10</td>
<td>ERT 151.3 (02)</td>
<td>8.63</td>
<td></td>
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<tr>
<td>Wet Barrier Mason Jar</td>
<td>WSP 80.11</td>
<td>ERT 170.1 (02)</td>
<td>8.73</td>
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### 9. STIFFNESS

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard 1</th>
<th>Standard 2</th>
<th>Reference 1</th>
<th>Reference 2</th>
</tr>
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<tbody>
<tr>
<td>Cantilever Bending (INDA)</td>
<td>WSP 90.1</td>
<td>Modified IST 90.1 (01)</td>
<td>9.1</td>
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</tr>
<tr>
<td>Stiffness Using the Gurley</td>
<td>WSP 90.2</td>
<td>Modified IST 90.2 (01)</td>
<td>9.9</td>
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Table 10.1  
(Continued)

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<th>Description</th>
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<th>ISO reference</th>
<th>Page number</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSP</td>
<td>IST/ERT Reference</td>
<td>ISO Equivalent</td>
<td></td>
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<tr>
<td>Handle-O-Meter</td>
<td>WSP 90.3</td>
<td>Modified IST 90.3 (01)</td>
<td>9073 – 9:1995</td>
<td>9.15</td>
</tr>
<tr>
<td>Cusick Drape</td>
<td>WSP 90.4</td>
<td>ERT 90.4 (99)</td>
<td></td>
<td>9.21</td>
</tr>
<tr>
<td>Bending Length (EDANA)</td>
<td>WSP 90.5</td>
<td>ERT 50.5 (99)</td>
<td>9073 – 7:1995</td>
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**10. TEAR STRENGTH**

<table>
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<th>Method</th>
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<th>ISO reference</th>
<th>Page number</th>
</tr>
</thead>
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<tr>
<td>Elmendorf</td>
<td>WSP 100.1</td>
<td>Modified IST 100.1 (01)</td>
<td>10.1</td>
</tr>
<tr>
<td>Trapezoid Tear</td>
<td>WSP 100.2</td>
<td>IST 110.2 (01)/ERT 70.4 (99)</td>
<td>9073 – 4:1997</td>
</tr>
<tr>
<td>Tongue Tear</td>
<td>WSP 100.3</td>
<td>Modified IST 100.3 (01)</td>
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**11. TENSILE**

<table>
<thead>
<tr>
<th>Method</th>
<th>Equivalent methods</th>
<th>ISO reference</th>
<th>Page number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grab Tensile</td>
<td>WSP 110.1</td>
<td>Modified IST 110.1 (10)</td>
<td>11.1</td>
</tr>
<tr>
<td>Strip Tensile</td>
<td>WSP 110.4</td>
<td>IST 110.5 (02)/ERT 20.2 (89)</td>
<td>9073 – 3:1989</td>
</tr>
<tr>
<td>Ball Burst</td>
<td>WSP 110.5</td>
<td>New Method</td>
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**12. THICKNESS**

<table>
<thead>
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</tr>
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<tbody>
<tr>
<td>Thickness (INDA)</td>
<td>WSP 120.1</td>
<td>Modified IST 120.1 (01)</td>
<td>12.1</td>
</tr>
<tr>
<td>Thickness of Highloft</td>
<td>WSP 120.2</td>
<td>Modified IST 120.2 (01)</td>
<td>12.9</td>
</tr>
<tr>
<td>Compression and Recovery, Highloft</td>
<td>WSP 120.3</td>
<td>IST 120.3 (01)</td>
<td>12.15</td>
</tr>
<tr>
<td>Using Weights and Plates</td>
<td>WSP 120.4</td>
<td>IST 120.4 (01)</td>
<td>12.21</td>
</tr>
<tr>
<td>Compression and Recovery, Highloft</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Temperature/High Humidity</td>
<td>WSP 120.5</td>
<td>IST 120.5 (01)</td>
<td>12.29</td>
</tr>
<tr>
<td>Thickness (EDANA)</td>
<td>WSP 120.6</td>
<td>ERT 30.5 (99)</td>
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**13. WEIGHT**

<table>
<thead>
<tr>
<th>Method</th>
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<th>Page number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass per Unit Area</td>
<td>WSP 130.1</td>
<td>ERT 40.3 (90)</td>
<td>9073 – 1:1989</td>
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**14. BINDER/APPEARANCE/DRY CLEANING**

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<th>Method</th>
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<th>Page number</th>
</tr>
</thead>
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<tr>
<td>Binder Distribution/Penetration</td>
<td>WSP 150.1</td>
<td>IST 50.1 (01)</td>
<td>14.1</td>
</tr>
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### Appearance and Integrity of

**Highloft Batting**

<table>
<thead>
<tr>
<th>Test Description</th>
<th>Standard</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSP 150.2</td>
<td>IST 50.2</td>
<td>(01)</td>
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### 15. LINTING

<table>
<thead>
<tr>
<th>Test Description</th>
<th>Standard</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulate Shedding, Dry</td>
<td>WSP 160.1</td>
<td>IST 160.1</td>
</tr>
<tr>
<td>Particulate Shedding, Wet</td>
<td>WSP 160.2</td>
<td>IST 160.2</td>
</tr>
<tr>
<td>Fibrous Debris from Nonwovens</td>
<td>WSP 160.3</td>
<td>IST 160.3</td>
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<tr>
<td>Fibrous Debris from Hydrophobic Nonwovens</td>
<td>WSP 160.4</td>
<td>IST 160.4</td>
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### 16. GEOTEXTILES

<table>
<thead>
<tr>
<th>Test Description</th>
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</thead>
<tbody>
<tr>
<td>Conditioning</td>
<td>WSP 3.0</td>
<td>ERT 60.2</td>
</tr>
<tr>
<td>Sampling</td>
<td>WSP 5.0</td>
<td>ERT 130.2</td>
</tr>
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<td>Bursting Strength</td>
<td>WSP 30.1</td>
<td>Modified IST 30.1</td>
</tr>
<tr>
<td>Air Permeability</td>
<td>WSP 70.1</td>
<td>Modified IST 70.1</td>
</tr>
<tr>
<td>Cantilever Stiffness</td>
<td>WSP 90.1</td>
<td>Modified IST 90.1</td>
</tr>
<tr>
<td>Trapezoid Tear</td>
<td>WSP 100.2</td>
<td>Modified IST 100.3</td>
</tr>
<tr>
<td>Force and Elongation Grab</td>
<td>WSP 110.1</td>
<td>Modified IST 110.1</td>
</tr>
<tr>
<td>Breaking Force Strip Test</td>
<td>WSP 110.4</td>
<td>IST 110.5</td>
</tr>
<tr>
<td>Thickness</td>
<td>WSP 120.1</td>
<td>Modified IST 120.1</td>
</tr>
<tr>
<td>Thickness of Highloft</td>
<td>WSP 120.2</td>
<td>Modified IST 120.2</td>
</tr>
<tr>
<td>Mass per Unit Area</td>
<td>WSP 130.1</td>
<td>ERT 40.3</td>
</tr>
</tbody>
</table>

### 17. SUPERABSORBENT MATERIALS

<table>
<thead>
<tr>
<th>Test Description</th>
<th>Standard</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH of Polycrylate (PA) Powders</td>
<td>WSP 200.2</td>
<td>ERT 400.2</td>
</tr>
<tr>
<td>Residual Monomers</td>
<td>WSP 210.2</td>
<td>ERT 410.2</td>
</tr>
<tr>
<td>Particle Size Distribution</td>
<td>WSP 220.2</td>
<td>ERT 420.2</td>
</tr>
<tr>
<td>Mass Loss upon Heating</td>
<td>WSP 230.2</td>
<td>ERT 430.2</td>
</tr>
<tr>
<td>Free Swell Capacity in Saline, Gravimetric Determination</td>
<td>WSP 240.2</td>
<td>ERT 440.2</td>
</tr>
<tr>
<td>Fluid Retention Capacity in Saline, After Centrifugation</td>
<td>WSP 241.2</td>
<td>ERT 441.2</td>
</tr>
<tr>
<td>Absorption Under Pressure, Gravimetric Determination</td>
<td>WSP 242.2</td>
<td>ERT 442.2</td>
</tr>
</tbody>
</table>

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(Continued)
### Table 10.1 (Continued)

**Table of Contents**  
All methods revised in 2005

<table>
<thead>
<tr>
<th>Description</th>
<th>Method number</th>
<th>Equivalent methods</th>
<th>ISO reference</th>
<th>Page number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flowrate, Gravimetric Determination</td>
<td>WSP 250.2</td>
<td>ERT 450.2 (02)/IST 250.2 (02)</td>
<td>17190 – 8:2001</td>
<td>17.59</td>
</tr>
<tr>
<td>Density, Gravimetric Determination</td>
<td>WSP 260.2</td>
<td>ERT 460.2 (02)/IST 260.2 (02)</td>
<td>17190 – 9:2001</td>
<td>17.67</td>
</tr>
<tr>
<td>Extractable</td>
<td>WSP 270.2</td>
<td>ERT 470.2 (02)/IST 270.2 (02)</td>
<td>17190 – 10:2001</td>
<td>17.75</td>
</tr>
<tr>
<td>Respirable Particles</td>
<td>WSP 280.2</td>
<td>ERT 480.2 (02)/IST 280.2 (02)</td>
<td>17190 – 11:2001</td>
<td>17.85</td>
</tr>
<tr>
<td>Dust in Collection, Sodium Atomic Absorption/Emission Spectrometry</td>
<td>WSP 290.2</td>
<td>ERT 490.2 (02)/IST 290.2 (02)</td>
<td>17190 – 12:2002</td>
<td>17.93</td>
</tr>
<tr>
<td><strong>18. BACTERIAL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filtration Efficiency</td>
<td>WSP 300.0</td>
<td>ERT 180.0 (89)</td>
<td></td>
<td>18.1</td>
</tr>
<tr>
<td>Dry Bacterial Penetration</td>
<td>WSP 301.0</td>
<td>ERT 190.1 (02)</td>
<td></td>
<td>18.13</td>
</tr>
<tr>
<td>Wet Bacterial Penetration</td>
<td>WSP 302.0</td>
<td>ERT 200.1 (02)</td>
<td></td>
<td>18.21</td>
</tr>
<tr>
<td><strong>19. FORMALDEHYDE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Extraction Method I</td>
<td>WSP 310.1</td>
<td>ERT 210.1 (99)</td>
<td></td>
<td>19.1</td>
</tr>
<tr>
<td>Stressed Extraction Method II</td>
<td>WSP 311.1</td>
<td>ERT 211.1 (99)</td>
<td></td>
<td>19.11</td>
</tr>
<tr>
<td>Free Formaldehyde Determination HPLC, Method III</td>
<td>WSP 312.0</td>
<td>ERT 212.0 (96)</td>
<td></td>
<td>19.13</td>
</tr>
<tr>
<td>Free Formaldehyde in Processing Method IV</td>
<td>WSP 313.0</td>
<td>ERT 213.0 (99)</td>
<td></td>
<td>19.21</td>
</tr>
<tr>
<td><strong>20. ABSORBENT HYGIENE PRODUCTS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syngina Method (Tampons)</td>
<td>WSP 350.1</td>
<td>ERT 350.0 (02)</td>
<td></td>
<td>20.1</td>
</tr>
<tr>
<td>Ethanol – Extractable Organotin I</td>
<td>WSP 351.0</td>
<td>ERT 360.0 (02)</td>
<td></td>
<td>20.9</td>
</tr>
<tr>
<td>Synthetic Urine – Extractable Organotin II</td>
<td>WSP 352.0</td>
<td>ERT 361.0 (02)</td>
<td></td>
<td>20.35</td>
</tr>
<tr>
<td><strong>21. USEFUL METHODS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Lining</td>
<td>WSP 400.0</td>
<td>New Method</td>
<td></td>
<td>21.1</td>
</tr>
<tr>
<td>Lamination Strength</td>
<td>WSP 401.0</td>
<td>New Method</td>
<td></td>
<td>21.11</td>
</tr>
</tbody>
</table>

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Nomenclature

**English Alphabet Symbols**

- **a**: The long axis of a prolate ellipsoid. *m*, *b* is the short radius, *m*.
- **a**: The radius of the fiber in cylinder or cell models. *m*
- **A**: 1. Filter area, m²
   2. Tensile test – the area under the load-elongation curve, J.
   3. ASHRAE air resistance. ASHRAE 52-1, %
- **a/b**: The length/diameter ratio of a prolate ellipsoid. dimensionless
- **b**: Diameter of a prolate ellipsoid at its center or thickest part. *m*
- **B**: The radius of the outer cylinder in cylinder or cell models. *m*
- **BL**: Langmuir correction factor for determining the resistance of fibers transverse to the flow from the resistance of fibers parallel to the flow. dimensionless
- **B**: Bechhold correction factor or capillarity constant for tortuosity in the bubble point test. It has the value of 0.715 in ASTM F316. dimensionless
- **BL**: Breaking length, *m*
- **c**: The mass concentration of fiber per unit volume of medium, kg/m³
- **c_p**: Particle concentration of an air stream approaching a filter element. particles/m³
- **C**: 1. A constant in the solution to the biharmonic equation
   2. Brunauer, Emmet, Teller (BET) Equation – a constant relating the adsorption energy of a gas to a solid substrate as compared to the liquefaction energy of the gas. dimensionless
- **C_d**: The drag coefficient. dimensionless
- **C_dA**: Drag coefficient of a cylinder moving in a tank – White’s equation. dimensionless
- **C_D**: Payet correction to single fiber efficiency models. dimensionless
- **C_D and C_R**: Correction terms applied by Rubow to the Lee and Liu single fiber efficiency models. dimensionless
- **d**: 1. The maximum pore diameter in the bubble point test, μm.
   2. The pore diameter in Kelvin’s law, *m*
- **d_b**: Inter-fiber distance. *m*
- **d_f**: Mean fiber diameter. *m*
$d_{ef}$  
Effective fiber diameter, m

$d_p$  
Particle diameter, m

$\bar{d}$  
The mean fiber diameter in the Piekaar and Clarenburg structure model, m

$2\bar{d}$  
Thickness of a layer in the Piekaar and Clarenburg structure model equal to twice the mean fiber diameter, m

$dp/dz$  
Pressure gradient across the z-direction or thickness direction of a medium, Pa/m

$D$  
1. The particle diffusion coefficient, m$^2$/s
2. The diameter of a fiber in the aspect ratio L/D, m

$D$  
A constant in the solution to the biharmonic equation

$D_c$  
The inside diameter of the cylinder in the Hagen–Poiseuille Equation, m.

$D_f$  
Fiber diameter, m

$D_h$  
Hydraulic diameter, m

$\bar{D}_{AB}$  
Particle diffusion coefficient describing the motion of particles A, in a fluid B, m$^2$/s

$e$  
1. The distance between layers in layered fiber structures, m
2. Liquid filtration efficiency by gravimetric or number means, %

$E$  
1. Single fiber efficiency, dimensionless
2. Young’s modulus, N/m$^2$
3. ASHRAE atmospheric dust spot efficiency (ASHRAE 52.1)

$E_D$  
Single fiber efficiency by diffusion, dimensionless

$E_D^*$  
Single fiber efficiency by diffusion – correction by Payet, dimensionless

$E_{DR}$  
Combination term for $E$ efficiency due to diffusion and interception in the Kuwabara flow field, dimensionless

$E_I$  
Single fiber efficiency by inertia, dimensionless

$E_R$  
Single fiber efficiency by interception, dimensionless

$E_{RI}$  
Combined single fiber efficiency term from $E_R$ and $E_I$ – Stechkina et al. model, dimensionless

$E'$  
A constant in the solution to the biharmonic equation

$F$  
1. A constant in the solution to the biharmonic equation
2. The drag force in the drag equation, N

$F_L$  
The force to move a prolate ellipsoid with its long axis parallel to the flow, N or m kg/s$^2$

$F_T$  
The force to move a prolate ellipsoid with its long axis transverse to the flow, N or m kg/s$^2$

$F_T/F_L$  
Force ratio, dimensionless

$g$  
The gravitational constant (981 cm/s$^2$)

$g$  
The acceleration of gravity, m/s$^2$

$G$  
The grammage of the web, g/m$^2$

$h$  
Height of the liquid reservoir in the bubble point test, cm

$k$  
The permeability constant of Darcy’s law, m$^2$

$k'$ and $k''$  
Constants of White’s drag equation, dimensionless

$k_4$ and $k_5$  
Constants of Chen’s drag model equation, dimensionless

$k_0$  
A factor of the Kozeny constant that depends on the shape and size of the cross-sectional areas of the pores
\( K \)  
The Kozeny constant

\( l \)  
Length of a fiber in the Piekaar and Clarenburg structure model, m

\( L \)  
1. The length of a fiber in the aspect ratio \( L/D \), m
2. \( 2L \) – The distance between parallel fibers within a layer of layered fiber structures, m

\( L_e \)  
1. Thickness of a filter fabric, pad, or medium, m
2. Length of the cylinder in the Hagen-Poiseuille Equation, m
3. Original length of a specimen in the tensile test, mm

\( L_f \)  
1. The length of fiber in the unit thickness \( \delta x \) of a filter pad, m
2. Fiber length in a medium, m

\( \bar{L} \)  
\( \bar{L} \) – A unit of distance in Kahn’s “offset screen model”, m. \( \bar{L} \times \bar{L} \) is an area of a layer in the offset screen model composed of \( N \) equally spaced fibers in the first layer and \( \bar{M} \) equally spaced fibers in the second layer and perpendicular to the fibers in the first layer. \( N \) and \( \bar{M} \) are dimensionless.

\( L/D \)  
The length to diameter or aspect ratio of a fiber, dimensionless

\( L_e/L \)  
Tortuosity factor, dimensionless

\( \Delta l \)  
1. An end correction for the fluid entering the cylinder in the Langmuir cylinder model, m
2. The change in length of the specimen in the tensile test, mm

\( \Delta l/L \)  
Strain

\( m \)  
Brunauer, Emmet, Teller (BET) – the mass of the specimen being tested, g

\( m_h \)  
The hydraulic radius in the Piekaar and Clarenburg structure model, m

\( m_{hg} \)  
Geometric mean radius based on a log-normal hydraulic radius distribution in the Piekaar and Clarenburg structure model, m

\( M_d \)  
The downstream mass of a contaminant in liquid filtration, kg

\( M_{h} \)  
The maximal hydraulic radius in the Piekaar and Clarenburg structure model, m

\( M_s \)  
The medium grammage g/m\(^2\)

\( M_u \)  
The upstream mass of a contaminant in liquid filtration, kg

\( n \)  
1. The concentration of aerosol particles leaving the filter – single fiber theory, particles/m\(^3\)
2. The total number of line interceptions per unit of surface area in Piekaar and Clarenburg structure model, number/m\(^2\)
3. The mean number of vertices of a polygon – Piekaar and Clarenburg structure model, number

\( n_0 \)  
The concentration of aerosol particles entering a filter – single fiber theory, particles/m\(^3\)

\( n_p \)  
Number of polygons per unit of surface area – Piekaar and Clarenburg structure model, number/m\(^2\)

\( n'_p \)  
Corrected total number of pores in a slice of thickness \( 2\bar{d} \), and a unit square \( \bar{l}^2 \) – Piekaar and Clarenburg structure model, number/m\(^2\)
$n_v$ Number of polygons sharing one vertex – Piekaar and Clarenburg structure model, number

$N$ Number of lines per unit surface area Piekaar and Clarenburg structure model, number/m$^2$

$N_{d,D}$ The downstream particle count for particles of diameter $d$ or greater in a liquid filtration system

$N_{d,U}$ The upstream particle count for particles of diameter $d$ or greater in a liquid filtration system, number

$N_f$ The number of fibers per unit area of medium, number/m$^2$

$N_p$ The number of pores per unit area of medium, number/m$^2$

$p$ 1. Pressure, Pa
2. The bubble point test, pressure at which the first bubble is observed, Pa

$P$ 1. The probability that two lines intersect – Piekaar and Clarenburg structure model, dimensionless
2. The penetration of particles through a filter medium, percent or fraction

$p_a$ Average pressure ($\left( P_0 - P_L \right) / 2$) in the Langmuir cylinder model, Pa

$p_0$ Brunauer, Emmet, Teller (BET) Equation and Kelvin’s law – equilibrium vapor pressure, Pa

$p_v$ 1. Brunauer, Emmet, Teller (BET) Equation – gas vapor pressure, Pa
2. Kelvin’s law – the vapor pressure at which condensation occurs, Pa

$P$ Penetration in the single fiber efficiency model, dimensionless

$P_L$ The pressure at the exit side of the cylinder in the Hagen–Poiseuille Equation, Pa

$P_0$ The pressure at the inlet side of the cylinder in the Hagen–Poiseuille Equation, Pa

$\Delta P$ Pressure drop across the thickness of a fabric or medium, Pa

$Q$ Volumetric flow rate, m$^3$/s

$r$ Radial component in a polar coordinate system, m

$r_c$ The inside radius of the cylinder in the Hagen–Poiseuille Equation, m

$r_f$ Fiber radius, m

$r_h$ Hydraulic radius, m

$R$ 1. The resistance to flow in the Langmuir cylinder model, Pa s. Piekaar and Clarenburg structure model, m$^{-3}$
2. The viscous drag distance in the Stokes Number, m
3. The interception parameter, $d_p / d_f$ in the Lee and Liu model, dimensionless
4. Grammage in breaking length equation, g/m$^2$

$R'$ Basis weight in breaking length equation, lb 3,000/ft$^2$

$R_0$ The Hagen–Poiseuille resistance of the flow within a cylinder, Pa s/m$^3$

$R_{pa}$ Anisotropy parameter in Kahn’s “offset screen model”, $R_{pa} = \frac{\bar{M}}{N}$, dimensionless
s and \( t_2 \)  Factors in the Piekaar and Clarenburg structure model equation for hydraulic radius

\( \bar{s} \)  Mean surface area of a polygon in the Piekaar and Clarenburg structure model, \( m^2 \)

\( \bar{s}' \)  "Corrected" mean surface area of a polygon in the Piekaar and Clarenburg structure model, \( m^2 \)

\( \bar{s}_h \)  Mean hydraulic surface area of the polygons in the Piekaar and Clarenburg structure model, \( m^2 \)

\( \bar{s}_h' \)  Term which corrects for the mean line width or fiber diameter in the Piekaar and Clarenburg structure model, \( m^2 \)

\( S \)  Flow exposed surface of fibers per unit mass of medium, commonly called the specific surface area, \( m^2/kg \)

\( S_d \)  The total "on" time for the downstream sampler during the test – intermittent sampling, ASHRAE 52-1, min

\( S_t \)  Tensile stiffness, \( N/m \)

\( S_0 \)  The effective surface area per unit volume of solid material in a medium, \( m^2/m^3 \)

\( S_u \)  The total "on" time for the upstream sampler during the test – intermittent sampling, ASHRAE 52-1, min

\( T \)  
1. Absolute temperature, \( K \)
2. Tensile strength, \( kN/m \)

\( T' \)  Tensile strength in the breaking length equation, \( lbf/in \)

\( T/E/A \)  Tensile energy absorption as determined from the tensile test \( J/m^2 \)

\( T_g \)  Glass transition temperature, \( ^\circ C \)

\( T/I \)  Tensile index, \( m \)

\( T_m \)  Melting point, \( ^\circ C \)

\( u \)  
1. The velocity of the cylinder in the Happel theory, \( m/s \)
2. The velocity of an object moving through a fluid in drag theory, \( m/s \)
3. The velocity of an object moving through a fluid in drag theory, \( m/s \)

\( u' \)  The average velocity through the cylinder in the Hagen–Poiseuille Equation, \( m/s \)

\( V \)  Pore volume, \( m^3 \)

\( \bar{V} \)  The molar volume of the condensed vapor in Kelvin’s law, \( m^3/mol \)

\( W \)  
1. Brunauer, Emmet, Teller (BET) Equation – the amount of adsorbed gas, \( mol \)
2. Width of a specimen in the tensile test, \( mm \)

\( W_d \)  The weight of synthetic test dust fed to the test filter – ASHRAE 52-1

\( W_u \)  The weight of synthetic test dust captured on the final filter – ASHRAE 52-1

\( W_m \)  Brunauer, Emmet, Teller (BET) Equation – the amount of gas to form a monolayer, \( mol \)

\( x \)  
1. Particle size of packed beds, \( m \)
2. The distance along an axis in the Langmuir cylinder model, \( m \)
3. The direction of fluid flow normal to the surfaces of a filter in the single fiber efficiency model, \( m \)
The width of a stream some distance upstream of a fiber where all the particles in this stream are the ones that will strike the fiber – single fiber efficiency model, m

\( Y_d \)
The opacity of the upstream target – intermittent sampling, ASHRAE 52-1

\( Y_u \)
The opacity of the downstream target – intermittent sampling, ASHRAE 52-1

\( Z_d \)
The opacity index of the downstream target – constant flow sampling, ASHRAE 52-1

\( Z_u \)
The opacity index of the upstream target – constant flow sampling, ASHRAE 52-1

### Greek Alphabet Symbols

\( \alpha \)
1. The volume of swollen fiber per unit mass of fiber in a medium, m³/kg
2. Brunauer, Emmet, Teller (BET – cross-sectional area of an adsorbed gas molecule, cm²)

\( \beta \)
The conversion factor from effective polygon area to real polygon area in the Piekaar and Clarenburg structure model, dimensionless

\( \beta_w \)
Bulk or a web or medium, cm³ g

\( \beta \)-ratio
The ratio of upstream particles to downstream particles in a liquid filtration system, dimensionless

\( \gamma \)
Filtration index in single fiber efficiency – \( \gamma = E L d_f \), m⁻¹

\( \gamma_{rel} \)
Shearing strain, dimensionless

\( \Delta f \)
The difference between the two force level in the determination of tensile stiffness, N

\( \nabla \)
Operator, m⁻¹

\( (\nabla \cdot \rho \nu) \)
Vector operator indicating the divergence of the mass flux \( \rho \nu \), kg/m³/s

\( [\nabla \cdot \tau] \)
Viscous force on an element per unit volume, kg m²/s²

\( \varepsilon \)
Total void volume or porosity of a porous structure expressed as a decimal fraction of the total media volume, m³/m³

\( \varepsilon_0 \)
The permeable or extra-fiber porosity of a porous medium expressed as a decimal fraction of the total medium volume, m³/m³

\( \varepsilon_{eff} \)
Effective flow porosity, the volume fraction of pore space open to flow

\( \varepsilon_{rel} \)
The fraction of total pore space open to flow, dimensionless

\( \varepsilon_{rr} \)
Normal strain, m/m

\( \theta \)
1. Angular component in a polar coordinate system, rad
2. Bubble point test – the contact angle between the reservoir liquid and the pore wall, (°)
3. Wetting angle in Kelvin’s law, (°)

\( \eta \)
Absolute viscosity, N-s/m²

\( \lambda \)
The mean free path of gas molecules, m

\( \mu \)
Fluid viscosity, kg/m/s or Pa s

\( \mu_p \)
The particle mobility, s/kg
\( \nu \) 1. The velocity through a tortuous pore, m/s
2. Mean velocity inside a filter medium, m/s
\( \nu_f \) Superficial velocity of the cylinder in the Happel theory, m/s
\( \nu_0 \) Velocity component in the angular direction, m/s
\( \nu_r \) Velocity component in the radial direction, m/s
\( \delta x \) Length of a filter element in a fibrous filter of unit cross-section – Davies theory, m
\( \rho \) Density, kg/m\(^3\) or g/cm\(^3\)
\( \rho_f \) Density of the fiber in a medium, g/cm\(^3\)
\( \rho_p \) The particle density in the Stokes number, kg/m\(^3\)
\( \rho_i \) Density of the reservoir fluid at 20°C used in the bubble point test, g/cm\(^3\)
\( \rho_m \) Density of the materials (fibers, resins, etc.) in a nonwoven medium
\( \rho_w \) The density of a web or medium, g/cm\(^3\)

\( \rho \frac{D\sigma}{Dt} \) Rate of momentum accumulation per unit volume, kg/m\(^2\)

\( \sigma \) 1. Surface tension, at 20°C N/m
2. The superficial tension in Kelvin’s law, N/m
\( \sigma_{hg} \) The standard deviation radius based on a log-normal hydraulic radius distribution in the Piekaar and Clarenburg structure model, m
\( \sigma_{rr} \) Normal stress, Pa
\( \sigma_{tg} \) Shearing stress, Pa
\( \boldsymbol{\tau} \) The shear stress tensor, kg/m/s\(^2\)
\( \mathbf{v} \) Velocity vector, m/s
\( \nu_0 \) Face velocity of a filter m/s
\( \nu_0 \) Superficial velocity of Darcy’s law, m/s
\( \nu_0 \) The particle velocity in the Stokes number, m/s
\( \varphi \) A reciprocal function in Langmuir’s cylinder model
\( \chi_0 \) The apparent solidity of a porous web that would include voids or cells within the surface of the filter media fibers or particles as part of the solid volume expressed as a decimal fraction of the total medium volume, m\(^3\)/m\(^3\)
\( \chi \) Solidity or packing density – solid volume of a porous structure expressed as a decimal fraction of the total volume, m\(^3\)/m\(^3\)
\( \psi \) Stream function, m\(^2\)/s

**Numbers and Constants**

\( C_k \) Cunningham slip factor, dimensionless:

\[
C_k = 1 + \left( \frac{\lambda}{d_p} \right) \left[ 2.492 + 0.84e^{\left( -0.435d_p / \lambda \right)} \right]
\]
$k_b$ Boltzmann’s constant, $1.3805 \times 10^{-23}$ J/K

$Kn$ Knudsen number, $Kn = \frac{2\lambda}{d_f}$

$Ku$ Kuwabara hydrodynamic factor, $Ku = -\frac{1}{2} \ln (\chi - \frac{3}{4}) + \chi - \frac{\chi^2}{4}$

$q_p$ or $\gamma$ Gamma number relating penetration to pressure drop

$N$ Avagadro’s number, $6.02 \times 10^{23}$ molecules or atoms/mol

$Pe$ Peclet Number, $Pe = \frac{1 \times 10^{-6} \nu d_f}{D}$ where $D$ is the particle diffusion coefficient

$R$ The universal gas law constant, $8.31$ J/mol/K

$Re$ The Reynolds number

1. $Re = \frac{\rho v x}{\mu}$ for packed beds, Wakeman and Tarleton

2. $Re = \frac{v d_f}{\mu}$ for fibrous media, Davies

3. $Re = \frac{u d_p \rho}{\mu}$ for an isolated fiber, Lamb

$St$ Stokes number, $St = \frac{d_p \rho_p \nu_p}{9 \mu R}$
Absorption Involves the taking of molecules of one substance directly into another substance. It is contrasted with adsorption in which the molecules adhere only to the surface of the second substance. The process may either be physical or a chemical. Physical absorption involves such factors as solubility and vapor–pressure relationships. Chemical absorption involves chemical reactions between the absorbed substance and the absorbing medium.

Acrylic resin Any of numerous thermoplastic or thermosetting polymers or copolymers of acrylic acid, methacrylic acid, esters of these acids, or acrylonitrile used to produce latex resins and other polymeric forms such as paints, synthetic rubbers, and lightweight plastics.

Additive Any number of materials used to modify the properties of nonwoven webs, polymer resins and fibers. Categories of additives include reagents, fillers, viscosity modifiers, pigments, flame retardants, anti-microbial agents, water repellents, and wet strength agents.

Adsorption A separation process by which molecular fluid contaminants are attracted to the surface of the filter medium. There are three forms of adsorption:

1. Physical Adsorption: A molecular species is attracted to a surface and held in place by weak forces. It is a reversible process.
2. Chemical Adsorption: A molecular species is attracted to a surface and reacts with that surface or something on that surface to form a chemical bond which holds it in place. Typically considered irreversible at constant conditions.
3. Catalysis: A molecular species is attracted to the surface which encourages a chemical reaction. The reaction product(s) move away leaving the surface unchanged. Typically, the reaction is considered irreversible.

Aerosol A system of colloidal particles dispersed in a gas, smoke, or fog.

Air permeability or permeance The property of a medium that measures the passage of air when a pressure difference exists across the boundaries of the specimen.

Air purifier A device which aims to free air from contaminants. Various techniques are used to accomplish this which includes filters, adsorbents like charcoal or activated carbon, and electrostatic charges.
Anisotropic  A feature of most nonwoven filter media in that they have different properties in different directions. This is a result of fiber orientation when the medium was made. The properties are usually referred to as machine direction (MD) properties and cross direction (CD) properties. There are also Z-direction properties in the direction perpendicular to the surfaces of the medium.

Anti-microbial  An additive’s ability to inhibit microbes (bacteria, fungus, mildew) from propagating on the surface and/or interior fiber surface of a filter medium.

Arrestance  In the ASHRAE 52.1 air duct test procedure it is referred to as the ASHRAE arrestance. It is the percentage ($A$) of the test dust fed, $W_d$, that is captured by the test filter. It is determined by measuring $W_d$ and the weight of test dust, $W_u$ captured by an absolute filter downstream of the test filter.

$$A = 100\left[1 - \frac{W_u}{W_d}\right]$$

Ash content  The non-combustible content of a filter medium (see loss on ignition).

Aspect ratio  The length to diameter ratio of a short cut, staple, or pulp fiber.

Atactic  Random substituent groups along the chain of a vinyl polymer.

Atmospheric dust spot efficiency  In the ASHRAE 52.1 air duct test procedure, it is referred to as the ASHRAE atmospheric dust spot efficiency:

$$E = 100x \left[1 - \frac{S_u}{S_d}(Y_d/Y_u)\right]$$

$E$ is the ASHRAE atmospheric dust spot efficiency ($\%$)

$S_u$ is the total “on” time for the upstream sampler during the test

$S_d$ is the total “on” time for the downstream sampler during the test

$Y_d$ is the opacity of the upstream target

$Y_u$ is the opacity of the downstream target

Bacterial filtration efficiency (BFE)  A test used to determine the filtration efficiency of a filter material such as face mask by using an aerosol of bacteria organisms. The test procedure is in accordance with ASTM F2101-1.

Bag house  Large dust collection systems that consist of a large number of filter elements. The filter elements are usually fabric bags or fabric envelopes. Cartridge filter elements are also used in these systems. The fabrics for the bag or envelope filter elements are either woven fabrics or nonwoven felts.

Base sheet  Wet lay medium that is either not yet resin treated downstream of the forming operation or will not be resin treated for its application. See raw stock.

Basis weight  The weight of a unit area of medium. It is synonymous with the term grammage, however it is more often used with non-metric units such as lb/3,000 ft$^2$ or oz/yd$^2$.

Bast fibers  Vegetable fibers obtained from the inner bark or phloem of a woody plant.

Beater  An oval shaped mixing vessel used for the preparation of laboratory pulp fiber slurries for handsheet making. The slurry or stock circulates the oval path of the beater and in each cycle passes past a beater roll that is rotating at a high speed. The beater roll contains protruding bars that rub the fibers against a flat plate
beneath the roll causing separation and dispersion of the individual fibers. Fibrillation and possible cutting of the fibers also occurs, the amount depending on the beating time and the pressure of the beating roll against the flat plate.

**Beater addition (beater ad)** The process of adding a non-fibrous additive to the stock slurry in the wet end of a wet lay operation. The beater additive, often called a beater ad, can be a bonding latex, a wet strength agent, a powder filler such as diatomaceous earth or activated carbon, or other agents designed to provide some specific property or process capability to the web.

**BET (Brunauer, Emmet, Teller) Theory** Theory based on the attraction of an inert gas to the surface of the substrate being tested. A technology for measuring the specific surface area and pore structure of a filter medium.

**Beta (β) ratio** The efficiency term for multi-pass filter testing. It is the number of particles upstream of the filter divided by the number of particles downstream of the filter. The particles are grouped by particle size so that there is a β-ratio for each particle size or each group of particle sizes.

**Biharmonic equation** A fourth-order partial differential equation which arises in elasticity theory, often expressed as $\nabla^4 \psi = 0$ where $\psi$ is the streaming function.

**Bone dry** The basis weight or grammage of the web after all volatiles have been removed, often determined by oven heating the web at a specified temperature for a specified length of time (usually 10 min at 150°C).

**B-Stage** The state of a medium, treated with a thermosetting resin, which has been dried to a specified volatiles content, but has not yet been cured to the final end-use state. The term is most often applied to a resin treated filter medium that will be subject to a pleating operation and cured after pleating.

**Bubble point** The term often used to express the maximum pore size of a filter medium. See maximum pore size.

**CADR value** Clean air delivery rate – a rating for air purifiers or room air cleaners as determined by ANSI/AHAM AC-1 which is an ANSI approved standard developed by AHAM.

**CD direction** The direction across a medium perpendicular to the direction of the machine on which the medium was made.

**Calender** A set of at least two highly polished nip rolls that apply a very high pressure to a web in order to give it a smooth surface treatment.

**Card** A machine used to form dry laid nonwoven webs consisting of a series of rolls coated with spirally wound saw-tooth wire often referred to as metallic clothing. Fiber is carded when it passes between two such rolls (or two metallic clothed surfaces) moving at different speeds. If the points of the metallic clothing are opposite a combing action takes place that parallelizes the fiber and forms it into a structured web.

**Cartridge filter** That part of a filtration system that is removable from the main body of the system for disposal and replacement, or for cleansing and reuse. Generally associated as being cylindrically shaped, although not necessarily so.
Chopped fiber  See short cut fibers.

Chopped strand  Rovings, usually glass, that have been chopped to shorter lengths for nonwovens manufacture.

Cleanroom  A room in which the concentration of air-borne particles is controlled and which is constructed and used in a manner to minimize the introduction, generation, and retention of particles inside the room, and in which the relevant parameters (e.g. temperature, humidity, and pressure) are controlled as necessary.

Coarseness, (fiber)  The weight of fiber wall material in a specified fiber length, usually expressed in units of mg/100 m fiber.

Coat hanger type distributor  A type of polymer feed distributor in the die block for melt-blown and spunbond processes. It is referred to as a coat hanger, because the parabolic shape of the wall around the distributor chamber.

Coir  Coconut fiber.

Collector  A porous or foraminous device on a nonwoven former that collects the fibers and helps form them into a web. Often the device is a foraminous belt, fabric, or screen. In a wet lay process, the Fourdrinier wire would be considered as the collector. In many cases, the collector is in the form of a belt transversing between rollers that provide guidance and tension. Sometimes the collector is the foraminous surface of a rotary drum. In composite structures one of the layers may serve as collector for the other layer(s).

Colloid  A substance made up of a system of particles with linear dimensions in the range of .001–0.5 μm dispersed in a continuous gas, liquid, or solid medium whose properties depend on large surface area. The particles can be large molecules like proteins or solid, liquid, or gaseous aggregates and they remain dispersed indefinitely.

Comber noils  The short fibers removed by a combing operation. Usually refers to cotton.

Condensing roll  Rolls in the carding process that work with the doffer rolls to randomize the structure and put more fibers in the cross direction.

Consistency  The Papermakers term for the solids or bone dry fiber content of a wet end stock or slurry.

Copolymer  A polymer composed of more than one monomer, usually two.

Corona discharge  An electrical discharge brought on by the ionization of a fluid surrounding a conductor.

Corrugation  A sine wave configuration in the cross direction of filter medium (usually wet laid) obtained by embossing the media between two embossing (corrugating) rolls that have a meshing sine wave configuration.

Creep  Also known as “cold flow”, the change in dimensions, with time, of a medium that is under constant load.

Creeping Flow  A region of very slow flow, and of very low Reynolds number, Re << 1.

Creping  A process which continuously applies cross direction wrinkles to a filter medium to increase its surface area and its extensibility.
Cross direction  The direction of a web perpendicular to the direction in which it was formed.

Cross layering  A process step for producing thicker and heavier carded or garnetted webs by lapping them back and forth unto a conveyor moving at a right angle to the cross-layering motion.

Curtain coater  A type of applicator of bonding resin or coating that applies the resin unto the medium as a falling film from an inclined flat surface.

Decigrex  Papermakers units for coarseness, the weight in milligrams of 100 m of fiber or the weight in decigrams of 10 km of fiber.

Decitex (dtex)  The weight of fiber in grams of 10,000 m of fiber. See tex.

Deckle  A term for wet lay machines that indicate the width of the web that can be formed on the machine.

Degree of polymerization (dp)  Describes the molecular size of a polymer. The number of repeat units in the polymer structure.

Demister  A coalescing type filter designed to remove moisture and/or organic liquid particles from gas streams.

Denier  The weight of fiber in grams of 9,000 m of fiber.

Die  The part of a spinnerette that contains small holes through which molten or solution polymer passes through to form fibers.

Die block  The part of a melt spinning (or solution spinning) that distributes the polymer flow and forces it through the spinnerette to form fibers.

Die cutting  A machine operation that cuts media into filter sheets or filter pads of various desired shapes. It is like using a cookie cutter. A die-cutting machine uses steel rule die shapes to cut through a wide range of filter materials quickly and easily.

Diffusion coefficient (particle) $D_{AB}$  relates the movement of a particle A in a binary mixture of A and B.

Dimensional stability  The ability of a medium to maintain its structural dimensions when exposed to changes in humidity and moisture content, temperature, the application of load, and/or the passage of time.

Dioctyl phthalate (DOP)  An oily type of fluid used to generate liquid test aerosols in many high efficiency air filtration test procedures.

Dirt holding capacity  A measure of filter life as determined by a prescribed filter test. It is the amount of test dust or dirt a filter will hold under test flow conditions until the filter reaches a predetermined pressure drop. At this point the test is terminated and the dirt or dust on the filter is measured to determine its dirt holding capacity.

Disintegrator  A laboratory device used to disperse pulp fibers in water for hand-sheet making. The disintegrating action is similar to that of a Waring blender.

Dispersion  A system of dispersed particles suspended in a solid, liquid, or gas.
**Distributor** The part of a die block that controls and balances the polymer flow.

**Doffer rolls** Rolls in the carding process that are used to transfer the web from the master cylinder to a moving bed.

**Drum dryer** Hollow cylindrical drums mounted in a frame so they can rotate. They are heated with steam and are used to dry nonwoven fabrics and/or paper it passes around the perimeter of the can.

**Dry smoke** A form of industrial fume usually consisting of solid particles in air such as that emitted by welding operations or certain types of machining operations. Contrast to wet smoke below.

**Earlywood** See springwood.

**Efficiency** See filtration efficiency.

**Electret** Materials that have an electrostatic charge or exhibit an external electric field in the absence of an applied field.

**Electrokinetic** Electrical charges in moving substances such as water. It concerns particle motion which is the direct result of applied electric fields. It relates to the property (often referred to as zeta potential) of a filter medium that has electrically charged sites, usually positive (cationic) to enhance its filtration performance in liquid filtration applications.

**Electrospun** A process that creates nanofibers through an electrically charged jet of polymer solution or polymer melt.

**Electrostatic** Refers to a filter with a static electric charge, usually opposite to the electrical charge of the particles it needs to attract. Particles drawn to the fiber surface are trapped by their electrostatic attraction to the fibers.

**Elmendorf tear test** A tear test that involves a swinging pendulum. The specimen is slit so that one side of the slit is attached to a stationary clamp and the other side to the moving pendulum. When the pendulum is released it continues the tear along the slit. The force to propagate the tear is then determined.

**Elongation** Tensile property that has several possible definitions or understandings in connection with paper and nonwovens. It is generally a measure of the change in length of a specimen when a stress is applied. It can be used as an alternate or synonym for strain:

1. The change in length ($\Delta L$) of a nonwoven specimen, in mm or inches as stress is applied.
2. A synonym for strain that is the percent of original length a nonwoven specimen is stretched when a stress is applied.
3. The fraction of original length a nonwoven specimen is stretched when a stress is applied.

It can also be used as an expression of stretch:

1. % Elongation – A synonym for stretch as defined in TAPPI 494. That is the maximum strain before rupture when a stress is applied.
2. Elongation – TAPPI T404 defines elongation as tensile strain at maximum tensile strength before rupture.

**Embossing** A three-dimensional pattern pressed into a filter medium as a result of pressing the medium between two engraved hard surfaces. The surfaces are most often two embossing rolls engraved with the desired pattern. The embossing is applied by passing the medium under pressure and heat through the nip of the embossing rolls. This is a technique used for point thermobonding of nonwoven webs. It is also a process for putting dimples or pleat separators into a filter medium that is to be pleated. Corrugation is a form of embossing.

**Emulsion** Colloidal suspension of a liquid in another liquid.

**Equilibrium moisture content** The moisture content at which a material neither gains nor loses moisture at a given relative humidity.

**Extruder** A part of a melt-blown or spunbond line that contains a rotating screw shaft to force polymer through several heating zones. The polymer is in a molten state by the time it reaches the filter screen on the exit side of the extruder.

**Face mask** A filter designed to cover nose and mouth and protect the wearer from irritating, toxic, or infectious contaminants in the air. Face masks have different definitions and they are not the same. A dust mask typically has one supporting strap and does not have a NIOSH rating. A surgical face mask is designed to protect medical workers from infectious diseases and microorganisms and often receives a NIOSH rating. A respirator, on the other hand, is a device to protect you from inhaling dangerous substances such as chemicals and infectious particles. See respirator.

**Fancy roll** A roll associated with a garnett used to help produce high loft mats.

**Fiber coarseness** The papermaker’s designation for fiber density. It is the weight in milligrams of 100 m of fiber or the weight in decigrams of 10 km of fiber. See decigrex.

**Fibril** Bundles of cellulose molecules composing the S2 layer of a tracheid or pulp fiber. Sometimes referred to as micro-fibrils.

**Fibril angle** The orientation of fibrils in a pulp fiber.

**Fibrillation** The shearing of wet wood pulp fibers to loosen the micro-fibrils from the fiber surface and fiber wall.

**Filament** A very slender natural or synthetic fiber. Continuous filaments are very long or never ending fibers before they have been cut or chopped.

**Filter element** That part of the filter that fits inside the housing and contains the medium that does the actual filtering.

**Filter house** The air inlet structure of a gas turbine-generator construction where the filters are located.

**Filter life** The amount of time a filter will last till it is no longer functioning in its specified manner or until failure occurs. Dirt holding capacity may be one measure of filter life, however other factors such as degradation due to mechanical agitation.
chemical exposure, and climate and environmental influences may all affect filter life and be a cause of failure.

**Filtration**  Filtration is a mechanism or operation for separating substances from a fluid by passing the fluid through a porous medium. Filtration may be used to separate contaminants from a fluid or recover-value added materials, such as minerals, chemicals, or foodstuffs in a process operation.

**Filtration efficiency** The percentage of contaminant removed by the filter. Usually based on mass or weight of the contaminant:

\[
e = 100 \left( \frac{M_u - M_d}{M_u} \right)
\]

where
- \( e \) is the filtration efficiency, %;
- \( M_u \) is the upstream mass of the contaminant;
- \( M_d \) is the downstream mass of the contaminant;

**Finish**
1. A substance or mixture of substances added to textile materials to impart desired properties.
2. A process, physical or chemical, applied to textile materials to produce a desired effect.
3. A property such as smoothness, drape, luster, water repellency, flame retardancy, or crease resistance which is produced by 1 and/or 2 above.
4. The state of a textile material as it leaves a process.

**Flame resistance** The characteristic of a fabric to resist ignition and to self-extinguish if ignited.

**Flame retardant** A chemical substance used to impart flame resistance to a nonwoven fabric. It is not part of the basic web chemistry.

**Flash spinning** A variation of the spunbond process in that the polymer is spun from a solution rather than a hot melt.

**Fleece** A fabric with a soft pile such as that that might come out of a carding process prior to any bonding activity.

**Fluff pulp** A chemical, mechanical or combination chemical–mechanical pulp, usually bleached, used as an absorbent medium in disposable diapers, bedpads, and hygienic personal products. This type of pulp imparts bulk to filter media and is an important fiber raw material for wet laid cellulosic filter media.

**Fluid** Any liquid or gas or generally any material that cannot sustain a tangential, or shearing, force when at rest and that undergoes a continuous change in shape when subjected to such a stress.

**Foam bonding** A method of applying a latex binder to a nonwoven medium by applying it as a foam or froth.
**Foraminous** A material such as metal screen, netting, woven fabric, etc that has openings, holes, punctures, etc penetrating through its entire depth.

**Fourdrinier headbox** See headbox. A classical or traditional type of paper machine headbox which passes the stock slurry through a slice and unto a forming fabric often called a Fourdrinier wire.

**Fractional efficiency** A filtration efficiency system that rates filter efficiency over a range of particle sizes or particle size groups. It is also used to rate different filter efficiencies for the same particle size.

**Freeness** A wet lay process fiber property. It is related to the rate at which water drains from a stock or slurry suspension of wet lay fibers or pulps through a mesh screen. Although freeness is an important pulp property for the manufacture of paper and paperboard, it is not commonly used in wet laid filter medium products. For filter media, air permeability is a better indicator of the “tightness” or “openness” of the fibers.

**Furnish** Papermaker’s term– the recipe of fibers and other ingredients that are slurried in water to produce the media of the wet lay process.

**Gamma number** A measure of filtration quality that relates the filtration penetration and the pressure drop. $\gamma = \frac{\ln(\frac{1}{P})}{|\Delta P|}$.

**Garnett** A machine very similar to a card for forming dry laid webs. In general, garnetts differ from cards in that they form more randomized webs. They also produce higher loft webs for filter applications.

**Gas mask** A mask-like device containing or attached to a component that filters the air inhaled by the wearer for protecting the face and lungs against noxious fumes, as in warfare or in certain industrial processes.

**Ginning** The process by which cottonseed is separated from the fiber.

**Glass microfiber** Glass fibers used for high efficiency filtration having diameters in the micron and sub-micron range. Generally a glass fiber whose diameter is 10 microns or less can be considered as a glass microfiber.

**Glass transition temperature** ($T_g$) The temperature at which a polymer transforms from a hard glassy state to a soft rubbery state. The polymer loses its hardness or brittleness, becomes more flexible, and takes on rubbery or leathery properties. At this transition temperature, noticeable changes in the specific volume, thermal conductivity, refractive index, stiffness, heat content, and dielectric loss are apparent.

**Glazing** The process by which a web (usually a felt or needlefelt) passes through a set of heated, high temperature, nip rolls that are rotating at slightly different surface speeds. The effect is to “iron” into the web a glazed glass-like surface.

**Gradient density medium** A type of nonwoven filter medium that has a variation in porosity and density through the depth of the medium. X The usual purpose is to provide a filter medium that will remove the largest particles at or near its upstream surface, and more efficiently remove smaller and smaller particles, as the fluid flow transports through the depth of the medium. Generally this is accomplished by using more than one ply to the medium, however there are other techniques for doing this.
**Graft polymer** A polymer containing a main chain or backbone that has attached to its side chains containing atoms or groups different from those in the main chain.

**Grain ratio** An expression of fiber orientation in a nonwoven. It is determined by the CD tensile strength divided by the MD tensile strength.

**Grammage** The weight of a unit area of medium. It is synonymous with the term basis weight, however it is more often used with metric measures such as g/m$^2$.

**Gravure press** A resin applicator that contains a Gravure cylinder which is engraved with small recessed cells (or “dots”) that act as tiny wells. Their depth and size control the amount of resin that gets transferred to the substrate.

**Gurley unit** The unit of measurement for the Gurlet stiffness tester. One gurley unit equals one milligram force (mgf) equivalent to 102 millinewtons (mN). One mN = 9.807 × $(10)^{-3}$ Gurley unit.

**Hagotan** Spindle for abaca.

**Handsheet** A sheet of wet lay fiber formed by draining the fiber slurry through a laboratory sheet mold which contains a forming fabric or wire at its bottom through which the slurry drains. The fiber is filtered on the wire to form the handsheet. The handsheet is then dried on a thermal device for subsequent testing.

**Headbox** That part of a wet lay or paper machine where the stock or fiber slurry is distributed to a forming fabric or collector (often called a wire). The headbox is designed to provide a continuous and uniform flow to the wire or forming fabric.

**High loft** A low density fiber structure characterized by a high ratio of thickness to weight per unit area. Often referred to as a high loft mat or batting, high loft nonwovens are generally defined as having a solidity of less than 10% and a thickness of at least 3 mm (.12 in).

**Homopolymer** A polymer consisting of a single species of monomer.

**Hurd** An impurity in hemp fiber.

**Hydroentanglement** A process that uses very fine high velocity jets of water to entangle the fibers in a nonwoven web – see spunlace.

**Hydrophobic** A material that has little or no affinity for water.

**Hydrophylic** A material that has a strong affinity for water.

**Hygroexpansivity** The change in dimensions of a medium due to changes in humidity and associated moisture content.

**Inclined wire** A type of wet lay headbox specifically designed for filter media and wet lay nonwovens that forms the wet lay web unto a moving forming fabric or wire that is inclined as it passes through forming area in the pond of the headbox. The inclined configuration allows for high levels of water to dilute the stock slurry and allow for the forming of webs from long fibers.

**Internal bond strength** Generally refers to the Z-direction tensile strength or the delamination strength of a medium.
**Isotactic** All the substituent groups are the same on every repeat unit of a vinyl polymer chain.

**Isotropic** A nonwoven medium that has identical properties in all directions. Such a medium would be unusual because most nonwovens are inherently anisotropic due to the manufacturing process.

**Latex** Any emulsion in water of finely divided particles of synthetic rubber or plastic.

**Latexwood** See summerwood.

**Likerin roll** The likerin roll accepts lap or batting that is condensed from fibers fed from a chute or hopper, opens them into small tufts, and feeds them to the master cylinder.

**Limiting oxygen index (LOI)** The minimum oxygen content in air that will sustain combustion of a material.

**Linear density** The density of a fiber in terms of its mass per specified length. Fiber coarseness, denier, decitex, and decigrex are examples of linear density.

**Linters** The fine, silky fibers which remain adhered to the seeds of the cotton plant after ginning, including parts of the longer textile fibers, or “lint”, as well as coarse, short fuzz fibers.

**Loss on ignition** The combustible part of a filter medium that is burned off when exposed to a high temperature in a muffler furnace. The non-combustible residue, often called the ash content is a measure of inorganic content. It is a way of determining fiber content in a filter medium composed of inorganic fibers such as glass microfibers.

**Lumen** The central canal of a wood pulp or vegetable fiber.

**Master cylinder** The main roll in a card or garnett. Its function is to transfer the web from one point in the process to the next. It also provides the surface on which other rolls such as stripper rolls and worker rolls can do their work.

**Maximum pore size** A test on a filter medium that relates to its largest pore size. Assuming cylindrical pores through the medium, the maximum pore size (also known as the “bubble point”) is determined at the pressure drop at which the first air bubble is observed emerging from the medium wetted with a layer of liquid of known surface tension. The maximum flow pore size is calculated as follows:

\[ D_m = \frac{4\gamma \cos \theta}{\Delta P} \]

where
- \( D_m \) is the maximum pore size, \( \mu m \);
- \( \gamma \) is the surface tension of the liquid layer wetting the medium, \( mN/m \);
- \( \theta \) is the contact angle between the pore surface and the liquid layer, \( rad \);
- \( \Delta P \) is the pressure drop at which the first air bubble is observed to emerge from the medium, \( kPa \).

**Mean flow pore size** A test on a filter medium that relates to its pore size. Assuming cylindrical pores through the medium, the mean flow pore size is determined at the pressure drop at which the flow through a medium wetted with a liquid of known...
surface tension is 50% of the flow through a dry medium at that same pressure drop. The mean flow pore size is calculated from the following equation:

\[ D_m = \frac{4\gamma \cos \theta}{\Delta P} \]

where

- \( D_m \) is the mean flow pore size, \( \mu \text{m} \);
- \( \gamma \) is the surface tension of the wetting liquid, \( \text{mN/m} \);
- \( \theta \) is the contact angle between the pore surface and the wetting liquid, rad;
- \( \Delta P \) is the pressure drop where the flow through the wetted medium is 50% of the flow through the dry medium, kPa.

**MD direction** The direction of a medium parallel to the direction of the machine on which the medium was made.

**Medium** A nonwoven structure of the type that can be used for filtration. The plural form is media.

**Medium migration** The release into the fluid stream of “fines” or small fibers and particles in the medium structure that were there as a result of the manufacturing process.

**Melt-blown** A process for forming nonwoven webs by forcing molten thermoplastic polymer such as polypropylene through a multi-hole spinnerette and collecting the formed fibers on a moving collector to form the web. Airflow action on the fibers as they leave the spinnerette serves to attenuate them and randomize their direction, so as to form a random nonwoven fiber structure on the collector.

**MERV rating** Minimum efficiency reporting value: an efficiency rating for heat, ventilation, air conditioning (HVAC) filters determined by the testing methodology and criteria of ASHRAE 52.2-1999.

**Metallic clothing** A coating of spirally wound saw-tooth wire used on the rolls in dry formed operations.

**Microfiber** Generally defined as a fiber whose diameter is 10 \( \mu \text{m} \) or less.

**Micron** Synonym for micrometer – the length measurement that is one-millionth of a meter or \( .000039 \text{ in.} \) In filter media it is used for the measurement of fiber diameter and pore size.

**Micronaire** A measurement of the fiber fineness or linear density of cotton expressed as \( \mu \text{g/in.} \). It is converted to denier by dividing by 2.82.

**Minimum penetrating particle size (MPPS)** A particle size in the range of 0.04–0.4 \( \mu \text{m} \), that, because it is too large for substantial diffusion effects and yet too small to have sufficient momentum for inertial effects, is the most difficult to capture by a filter medium. It is referred to as the “Most penetrating particle size” (MPPS). Efficiency ratings in EN 1822-1\(^1\), the European standard for high efficiency particulate air (HEPA) and ultra low penetration air (ULPA) media, are based on MPPS.

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\(^1\)See Chapter 8, paragraph 8.3.2.1 for a discussion of EN1822-1.
**Mini-pleat** A panel filter construction utilizing 7/8–1 1/4-in. deep pleats with very narrow air spaces (1/8-in.) between, making it possible to pack more filter paper into the standard frame sizes than can be done with conventional deep-pleat, corrugated separators.

**Modacrylic** Fiber whose acrylonitrile content is 35–85%.

**Motes** Small, immature seeds with attached fiber that are removed at a different stage of the cotton gin stand than the mature seeds. The cotton fiber can be removed from the motes using a delinting machine. This fiber is called gin mote fiber and is used in nonwoven products.

**Mullen Burst** A strength test for paper and nonwovens, wherein the medium specimen is placed between annular clamps and subject to an increasing pressure from a rubber diaphragm pressed against it by a hydraulic pressure. The pressure is increased at a controlled rate till the specimen ruptures. The burst strength is the pressure at which rupture occurred.

**Nanofibers** Term generally applied to fibers with diameters less than 0.5 microns. Typical nanofibers have diameters between 50 and 300 nm. They cannot be seen without visual amplification. Other terms often applied to very fine fibers are micro-denier, sub-micron and superfine.

**Neat resin** The condition and properties of a resin as produced by the manufacturer and as received by the customer or user. The resin may be further modified and diluted by the user in his formulating process.

**Needlefelt** A nonwoven structure formed by the mechanical bonding of a fiber web or batt by needle punching.

**Needle punch** The process by which needlefelt is produced by using vertical barbed needles to puncture the web (usually carded), entangle the fibers, and consolidate the structure. Sometimes referred to as needling.

**Neps** Small tangled knots of cotton fiber caused by mechanical processing.

**Novolak** A form of phenol formaldehyde resin that is the result of an acid catalyzed reaction of phenol and formaldehyde.

**Packing density** See solidity.

**Padder** A device used to apply latex resin to a nonwoven web by using an applicator roll rotating through a resin bath and applying the resin film to the web that is in surface contact with the applicator roll. Often the applicator action is followed by nip roll squeezing to remove excess resin.

**PAN based carbon fiber** Carbon fiber whose source is the alteration of organic fibers such as rayon, acrylics, etc.

**Part 11** Refers to 42 CFR (US), Part 11.

**Part 84** Refers to 42 CFR (US), Chapter 1, Part 84.
Particle filtration efficiency  A test to determine filtration efficiency of surgical face mask materials by using a challenge aerosol of aerolized latex particles, usually at 0.1 microns in diameter.

Penetration  The fraction of upstream particles that penetrate the filter. Penetration = one minus the efficiency.

Phenolic resin  A resin used as a bonding agent for wet laid filter media. It is the result of a reaction between phenol and some form of aldehydes. Phenol formaldehyde resin is, by far, the most commonly used form of phenolic resin.

Pitch based carbon fiber  Carbon fiber whose source is the remains of petroleum or tar distillation.

Pleat pack  The pleated medium cut to size as it comes out of the pleating machine and before it is assembled into a panel or cartridge type filter element.

Pocket filter  Filters containing multiple pockets to offer extended surface areas and increased dirt holding capacity.

Pond regulator  A device in a Rotoformer® or inclined wire type of wet lay machine that controls the flow of water and stock over the forming fabric or wire at the point where fibers are deposited on the fabric and where the medium is formed. The amount of flow and its relationship to the speed of the forming fabric has an important effect on the properties, formation, and fiber orientation of the medium.

Porometry  Methods to determine pore size distribution data on a medium that is wetted with a liquid wetting agent. Extrusion flow porometry utilizes air to force the liquid from the pores of the medium. The pore size distribution is calculated from the flow–pressure relationship. Capillary flow porometry uses a non-reacting gas to displace liquid from the pores.

Porosimetry  There are two forms of porosimetry: liquid intrusion porosimetry and liquid extrusion porosimetry. Liquid intrusion forces a liquid such as mercury into the porous medium. By measuring the volume of liquid forced into the pores and the pressure, pore volume, and diameter can be determined. Liquid extrusion works in the opposite manner by using a gas to force the liquid from the pores. Again the pore volume and diameter can be determined.

Porosity  The volume fraction in a filter medium that is void or empty space. The porosity is the unit volume of medium minus the solidity (see solidity).

Pot life  A measure of how long a resin formulation will last after it has been prepared.

Potential flow  An idealized theoretical fluid flow in which there is no viscosity.

Presser foot  That part of a thickness gauge that rests on top of a medium when the thickness measurement is made. It is the distance between the presser foot and the base on which the medium rests that determines the caliper or thickness.

Prolate ellipsoid  Obtained by rotating an ellipse around its long axis so that the three-dimensional shape is something like an egg. An oblate ellipsoid is obtained by
rotating an ellipse around its short axis. The three-dimensional shape is something like a pancake.

**Pulp**  A mass of wood or vegetable material composed of cellulose that has been reduced to a fibrous form.

**Pulper**  A machine, usually a tank with suitable agitation, designed to break up, defiber, and disperse pulps and other fibers into a suitable slurry for the wet lay process. It is also used for blending other materials into the slurry.

**Pulse jet cleaner**  A filter that is cleaned by applying a high pressure reverse air flow to remove the cake from the filter and enabling its reuse. The reverse flow is usually from a high pressure pulse jet or fan pulse.

**Qualitative filter papers**  Laboratory filter paper for use in qualitative analytical techniques designed for identifying materials. They are intended for laboratory use.

**Quantitative filter papers**  A laboratory filter paper designed for use in analytical techniques intended to quantify the composition of materials; where purity and composition of the filter paper are of crucial importance.

**Randomizing roll**  Carding process – a high-speed roll inserted between the master cylinder and the doffing roll. The randomizing roll doffs the web from the master cylinder and by centrifugal force transfers the fibers to the doffing roll. Random webs with MD:CD ratios of 4:1 are obtainable with this arrangement.

**Raw stock**  Wet laid base sheet that will later be resin treated in-line with the forming process or will later be resin treated off-line. In some instances it is a synonym for base sheet.

**Reel**  A cylinder that turns on an axis and is used for winding and storing paper and nonwoven media. The reel winder is usually located at the end of a web forming machine or a web converting operation to wind up the finished web as a jumbo roll. The reel is then used to transport and support the jumbo roll to a downstream operation such as a rewinder.

**Reentrainment**  The release of particles, trapped in the filter medium, back into the fluid stream. The release can be caused by a number of factors, such as high fluid velocity, high pressure drop, mechanical vibrations, flow fluctuations, etc.

**Refining**  A paper making or wet lay process step that mechanically treats pulp fibers in aqueous suspension by shearing them between two surfaces, at least one of which contains metal bars, the two surfaces not moving at the same speed. The effect is to hydrate, fibrillate, and/or cut the fibers to shorter lengths. Refining generally results in wet laid webs that are stronger and tighter (lower permeability).

**Resin**  The general term for a chemical binder. A resin is a polymeric material that bonds the fiber cross-sections in a nonwoven web. It includes polymeric additives such as cross-linking agents that support the resin system. A resin may be a thermobonding resin or it may be water based or solvent based. Water based forms include latex emulsions, dispersions, and solutions. Solvent based resins are usually solutions of the resin dissolved in organic solvent.
**Resin penetration**  The process by which a liquid resin applied to a nonwoven filter medium transports from the surface of the medium to the center or interior of the medium. The goal of a fully penetrated or saturated medium is to achieve uniform resin content throughout the depth of the medium. If the center of the medium has not been penetrated, “soft centers” may result, that is the medium is unbonded at its center and can easily be delaminated into two layers.

**Resin treated filter paper**  Filter paper treated with a polymeric binder or resin to provide strength and structural properties.

**Resole**  A form of phenol formaldehyde resin that is the result of a base catalyzed reaction of phenol and formaldehyde.

**Respirator**  Any device designed to provide the wearer with respiratory protection against inhalation from a hazardous atmosphere. A *respirator for escape* only means respiratory devices providing protection only during escape from hazardous atmospheres. *Respirators for entry into and escape* from means respiratory devices providing protection during entry into and escape from hazardous atmospheres.

**Retting**  A natural, enzymatic process lasting approximately 2 weeks that breaks down vegetable fiber masses into individualized fibers. The process breaks down the woody or vegetable cores holding the fiber bundles together. The fibers are then easily separated. Hemp, flax, and coir are among several vegetable fibers processed by this technique.

**Reverse air cleaner**  A means of cleaning a filter by reversing the fluid flow through the medium so as to dislodge the cake, dirt, and/or dust from the medium. The reverse flow is relatively low pressure as compared to pulse jet cleaners.

**Rewinder**  A converting machine that accepts a jumbo roll from a web making process or a web converting operation and rewinds the web so that it can be trimmed and slit into finished rolls either for shipment to a customer or for further downstream processing. A rewinder that does both trimming and slitting is often referred to as a slitter/rewinder.

**Reynolds number (Re)**  A dimensionless number that describes the nature of a fluid flow. In a filter medium it is determined by a characteristic distance of the medium, such as fiber diameter or pore size, multiplied by the flow velocity through the medium times the density of the fluid divided by the fluid viscosity.

**Rotoformer®**  A type of wet lay headbox specifically designed for filter media and wet lay nonwovens that contains a rotating drum to which the forming fabric or wire is attached. The wet lay medium is formed on the fabric of the rotating drum and transferred from the drum to downstream processing.

**Rovings**  A collection of bundles of continuous filaments in untwisted strands.

**Scrim**  A lightweight base fabric, usually woven, used as a support for nonwoven fabrics such as needleflets.

**Secant modulus**  The slope of a line drawn from the origin of the stress–strain to a point of interest on the stress–strain curve. Usually this point of interest is the
maximum stress where the tensile strength is determined. In this case the secant modulus is the tensile strength divided by the stretch.

**Sheet mold** A device used for making paper or wet laid handsheets. It includes a vertical tank resting over a woven paper making wire. Water and handsheet slurry or stock is added to the vertical tank and mixed. A valve underneath the wire is opened and the water drains through the wire at the bottom. Fiber is retained on the wire to form a wet handsheet. The vertical tank can then be opened to remove the wire and wet handsheet.

**Shelf life** A measure of how long a resin or chemical will last in ambient storage conditions.

**Short cut fibers** Filament fibers that have been cut to shorter lengths. Also known as chopped fibers. Lengths generally range from 3 to 40 mm.

**Singeing** An operation that burns off protruding surface fibers from a felt or needlefelt.

**Single fiber efficiency** The theoretical development of filtration efficiency based on the filtration efficiency of a single fiber in a fluid stream. The efficiency is based on the probability of a particle in that stream striking the fiber. Interception, diffusion, impaction, and combinations thereof are all considered.

**Size press** A device that applies liquid resins, chemicals, and/or additives to a wet lay web by passing the web through a set of rolls that either apply the liquid material as a coating or as a saturant. The rolls may apply the coating or saturant as a film by contacting the web with the coated surface of the rolls, or the rolls may be used to squeeze out excess coating and/or saturant already applied to the web from a size press pan, a shower, a spray, or other applicator device. The size press is the papermaker's version of the "padder" used to apply liquid additives to textile materials.

**Slice** In a traditional type of wet lay machine or paper machine, the slice is the long horizontal gap across the width of the machine through which the diluted stock flows from the pond of the headbox to the forming area over forming fabric or Fourdrinier wire. The slice gap is adjustable and ranges from 1 to 8 cm. It fixes the jet:wire ratio of the water flow over the wire. This in turn determines the MD–CD fiber orientation of the wet laid web.

**Slitter** A form of rewinder that rewinds and slits rolls into smaller sizes for customer requirements or for further downstream processing. A slitter differs from a rewinder in that is designed for special roll sizes that cannot be handled on a rewinder or that is awkward on a rewinder. An example is very narrow rolls less than 25 mm in width. The slitter is usually smaller than a rewinder and often accepts split rolls from a rewinder for further slitting to smaller roll sizes.

**Solidity** The volume of fibers or solid material per unit volume of filter medium. Synonyms are packing density and volume fraction. The solidity is equal to one minus the porosity.

**Solution resin** A resin system, either water based or solvent based, where the polymer is dissolved in the solvent to the point where particle size is on the order of molecular dimensions.
**Solvent**  An organic or non-aqueous liquid that is used for resin solutions.

**Solvent based resin**  A resin that is solubilized in an organic solvent such as methanol, isopropanol, toluene, methylene chloride, et al. and applied either as a coating or saturant to a nonwoven web. Phenolic resins dissolved in methanol or isopropanol are a large volume example of a solvent based resin.

**Spinnerette**  The part of a die block assembly for the spunbond process that contains the little holes through which the molten or solution polymer is spun into a fiber form. It is a single block of metal having several thousand drilled orifices or holes.

**Spin on filter**  A replaceable filter cartridge, usually used for engine lube oil filtration applications, where the cartridge can be spun on or screwed on to the engine housing.

**Spin pump**  Also known as a gear pump or a metering pump. A positive displacement pump for feeding molten polymer into the die assembly of a spunbond or meltblown process.

**Springwood (earlywood)**  That part of a tree that grows in the spring. Usually characterized by thin wall structure and large lumen.

**Spunbonded**  A non-woven forming process by which filaments are extruded from a spinnerette, drawn, and then laid on a moving belt or collector. Air turbulence acting on the fibers as they are drawn to the collector disorients the fibers and causes a random fiber orientation to the formed web.

**Spunlace**  An accepted generic term for hydroentanglement – see hydroentanglement.

**Standards organization**  An organization whose activities include developing, coordinating, promulgating, revising, amending, reissuing, interpreting, certifying, regulating, or otherwise maintaining standards that are related to filtration and filter media.

**Staple fibers**  Non-filament fibers such as cotton or filament fibers cut to fiber lengths of 25–200 mm. Staple fibers differ from short cut or chopped fiber by the way they are cut and because they are longer. Used for dry formed carding operations.

**Stereoregularity**  The degree to which successive configurations of a polymer in space along the chain follow a simple rule. Also called tacticity.

**Stock**  The aqueous slurry of fibers and ingredients that are fed to the headbox of the wet lay machine. “Thick stock” refers to the stock as prepared in the pulper and processed in the wet end. “Thin stock” refers to the slurry after it has been diluted for sheet forming in the headbox.

**Stokes number, St**  Dimensionless group expressing the ratio of kinetic energy of a moving particle divided by the viscous drag forces acting on it.

**Strain**  Tensile property – The increase in length of a nonwoven specimen as stress is applied. Strain is measured as a percent of the original length before the load was applied.

**Stream function**  In fluid mechanics, a mathematical concept which satisfies identically, and therefore eliminates completely, the equation of mass conservation. In a flow field of two space coordinates, \(x\) and \(y\), a single and very useful stream function,
ψ (x, y), will arise. The stream function not only is mathematically useful but also has physical meaning. Lines of constant ψ are streamlines of the flow; i.e., they are everywhere parallel to the local velocity vector. No flow can exist normal to a streamline; thus, selected ψ lines can be interpreted as solid boundaries of the flow. ψ is also quantitatively useful. For any two points in the plane flow field, the difference in their stream function values represents the volume flow between the points.

**Streamline**  The path of one particle in a flowing fluid.

**Stress**  Tensile property – The load applied to the specimen, ever increasing, as the tension increases. It is measured in force per unit width of specimen.

**Stretch**  Tensile property – The maximum strain on a nonwoven specimen before rupture. Like strain, it is measured as percent of original specimen length. It is often referred to as % elongation (see strain and elongation).

**Stripper roll**  In the carding process stripper rolls are used to transfer the web from one roll to another. They have the wire points in the same direction as the master cylinder.

**Summerwood (latwood)**  That part of a tree that grows in the summer. Usually characterized by thick wall structure and small lumen.

**Super absorbent polymers (SAP)**  Polymer structures that absorb many times their weight in water.

**Surgical face mask**  A form of respirator used in hospital operating rooms mainly intended to protect operating room personnel from infectious contamination including blood splatter, large particles from patient coughing and sneezing, secretions and excretions. et al. Surgical face masks are defined as medical devices and as such are regulated by the United States Food and Drug Administration (FDA).

**Suspension**  A state in which particles are mixed with a fluid but are not dissolved. A mechanical suspension is one in which the particles are kept dispersed by agitation. A colloidal suspension is one in which the particles are kept dispersed by the molecular motion in the surrounding medium.

**Swollen fiber**  The fiber cell structure in a porous filter medium that is not available to permeable fluid flow.

**Syndiotactic**  The substituent groups alternate on the repeat units of a vinyl polymer chain.

**Tear strength**  The force to begin or continue a tear in a fabric under specified conditions.

**Tenacity**  The tensile stress on a fiber when expressed as a force per unit linear density of the unstrained specimen (g/den, N(tex, or cN/dtex). The breaking tenacity is the tenacity at the point of rupture.

**Tensile Energy Absorption (TEA)**  An indication of the toughness of a medium. In the constant rate of elongation tensile test, it is the integrated area under the stress-strain curve up to the point of rupture.
Terpolymer  A polymer consisting of three different monomers.

Tex  The weight in grams of 1,000 m of fiber. Decitex or dtex is the weight in grams of 10,000 m of fiber.

Thermobonding  A way of bonding nonwoven materials by using a low melting thermoplastic polymer. The polymer is melted in process and fuses with neighboring fibers so as to form thermobonds between the fibers. The thermobonding polymer may be in the form of a powder, a fiber, a low melting bead applied to the web, or a bicomponent fiber where one component is the low melting polymer.

Tongue tear test  A tear test where a slit is cut down the middle of a 3 × 8 in² (7.6 × 20.3 cm²) specimen. The specimen is tested on a CRE tensile test machine by fastening one side of the slit to an upper clamp. The other side is turned down and fastened to a lower clamp. When the clamp movement is turned on, the tongue tear strength is the force necessary to propagate the tear from the slit.

Tortuosity factor  The ratio of the length of the tortuous pore path through a filter medium divided by the thickness of the medium as defined for the Kozeny–Carman Equation.

Tracheid  The long tapering cells of wood that become the fibers.

Transverse  A cylinder, or a fiber, or a set of fibers, or a filter medium containing fibers whose orientation is perpendicular to the direction of flow.

Trapezoid tear test  A trapezoid shaped test specimen is tested. The specimen is clamped in a constant-rate-of-extension (CRE) tester so that the diagonal sides of the specimen are in the clamp fixture. The pull is in-plane and normal to the direction of the slit cut at the top of the specimen. It tears the specimen by pulling it apart at the slit.

Triboelectric  An electrostatic charge imparted by the rubbing or intimate contact of two dissimilar dielectric materials. The kinetic energy dissipated from the rubbing action induces a charge transfer.

Turbine  A rotating device designed to generate energy – either mechanical energy or electrical energy. The turbine rotates by the action of a fluid flowing past the vanes of the turbine. The fluid can be gas, water, steam, or wind. There has to be a driving force to force the fluid flow past the vanes. In the case of water, hydroelectric turbines are driven by the gravity flow of water from a waterfall or dam that is channeled through the turbine. Gas turbines are driven by injected fuel ignition that heats and expands compressed gas to force its flow past the turbine.

Ultimate  The fusiform (taper ended) cells that make up a sisal fiber or filament.

Viral filtration efficiency (VFI)  A test procedure for microbial filtration efficiency using Bacteriophage OX174 as the challenge aerosol. The bacteriophage is one of the smallest of viral organisms having a diameter of range of .025–.027 micron. The testing is very similar to the BFE test.

Volume fraction  See solidity.
**V-pack**  Panel filters, organized into a “V”-array of subcomponents. The subcomponents are usually panels of mini-pleat media. By organizing the panels into the V-pack design, greater surface area of medium can be incorporated into the panel volume. This allows for higher flow volume, lower pressure drop, and greater filter life (dust holding capacity).

**Water based resin**  A resin form where the polymer is contained in a water medium. This includes solution resins, emulsions, dispersions, lattices, and any other polymer form contained in a water medium.

**Water repellency**  The ability of a substrate to resist wetting by water.

**Water repellent**  A material that has a finish that resists, but is not impervious to water.

**Wet smoke**  A form of industrial fume that is an aerosol of liquid particles, such as oil mists. Contrast to dry smoke above.

**Wire**  A moving fabric or woven screen upon which fibers of paper or wet laid products are formed. Often called a Fourdrinier wire, it filters the fiber from the stock or fiber slurry and forms it into a continuous web.

**Worker roll**  In the carding process, worker rolls act in conjunction with the master cylinder to do the fundamental carding action. Carding takes place between the tangent point of the master cylinder and the worker roll.

**X-ray microtomography**  A radiation technique that can reproduce graphic three-dimensional images of small sections of nonwoven and paper structures.

**Z-direction**  The direction in a medium that is perpendicular or normal to the surfaces.

**Zeta potential**  The potential across diffuse layers of ions surrounding a charged colloidal particle.
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Index

29 CFR 1910.1048, 246
30 CFR 11. 358
3M Company, 145
42 CFR (US), Chapter 1, Part 84, 357, 364

a2z Filtration Specialties, New Delhi, India, 237, 238
AAF International, 331, 334, 388, 392
AATCC 127, 279
AATCC-112-2003, 246
abaca (Manila hemp), 5, 105, 116, 118, 131, 132, 136, 137, 141
abaca fiber, 136, 137, 138
  grades, 137
  length, 138
  process, 137
absorbent materials, 179
absorbs, 71
media, 7
AC Fine Test Dust (ACFTD), 294, 318
AC Rochester Division of General Motors, 318
Acordis, 146
Acordis Cellulosic Fibers, Inc., 146
Acrivos, A.., 52
acrylic fiber, 149, 150
  bicomponent, 150
  dry spun, 150
  fibrillated, 150
  modacrylic, 149
  polyacrylonitrile (PAN), 149
  process, 149, 150
  properties, 150
  wet spun, 150
acrylics, 185
Actipure*, 98, 99
activated carbon, 7, 81, 98, 99, 100, 102, 189, 363, 365
ASZM-TEDA, 189
filter paper, 98
  impregnated, 189
  sources, 189
  activated carbon fiber, 167
  additives, 103, 113
  adsorbent materials, 7, 188
  activated alumina, 188
  activated carbon, 188
  baking soda, 189
  ion exchange resins, 189
  silica gel, 189
  zeolite, manmade, 189
  zeolite, natural, 189
adsorbents
  media, 6
  adsorptive media, 97
  adsorption, 1, 97, 98, 99
  catalysis, 98
  chem-sorption, 98
  physical adsorption, 98
  adsorption media, 98
  factors for choosing, 98
aerosol filtration, 220
AFFCO (American Felt and Filter Company), 168, 326
AHAM (Association for Home Appliance Manufacturers), 344, 365
Ahearn, D.G., 102
Ahlstrom, 73, 97, 234, 295, 377, 382
air cleaning devices, 334
  deep pleated filters, 335
  electret filters, 335
  electronic air cleaners, 335
  fiberglass filters, 334
  pleated filters, 334
  washable/reusable, 335
air demisters, 366
air extraction devices, 330
Air Filters, Inc., 145
air filtration, 27
Air Guard, 145
air induction system, 56
air intake filtration (AIF), 377
    automotive air filtration, 378
    heavy duty air filtration (HDA), 378
air laid, 10, 14, 71
    bonding, 195
    fibers, 10
    process, 10, 195
    properties and characteristics, 71
air permeability, 38n, 39, 114, 127, 130, 248, 251
    Frazier permeability, 38n
    units of measurement, 248
Air Products and Chemicals, Inc., 183
Air Products Polymers (APP), 183
air purifiers, 365
    residential air cleaners, 365
    room air cleaners, 365
Airflex®, 183
Airguard, 334
air-purifying respirators (APRs), 358
Albrecht, F., 44
American Air Filters International (AAF), 145
American National Standards Institute (ANSI), 344, 364
American Petroleum Institute (API), 386n
American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE), 85, 86, 336, 339
atmospheric dust spot efficiency, 343
    dust-spot efficiency, 287
    synthetic test dust, 343
ASHRAE 52.1-1992, 287, 342, 344
ASHRAE 52.2-1999, 286, 287, 335, 339, 341, 344
ASME AG-1, Section FC, 280, 347, 348, 351
Para FC-5160, 347
Para FC-5150, 347
The Association of periOperative Registered Nurses (AORN), 364
ASME AG-1-2003, 352
ASTM D828, 267
ASTM D2261, 273
ASTM D4632, 272
ASTM D774, 272
ASTM F1862-05, 364
ASTM F1977, 365
ASTM F2101-01, 290, 364
ASTM F2299-03, 290, 364
ASTM F316-86, 254, 257
ASTM International (ASTM), 3, 364
ASZM–TEDA, 363
Auburn University, 147, 149, 150, 154, 155
Avtex Fibers, 145
Baas, J., 187
bag filters, 304, 311
bagasse, 131, 143, 144
baghouses, 325
    modular MBT, 326
    modular MBW, 326
Bahnhof, W.P., 60, 61n
Barker, R.L., 2
basalt, 168
basis weight, 245
Batra, S.K., 2
beaters, 129
beating, 127
Bechold, H., 254n
Beckman Coulter, Inc., 257
Bell, J.R., 176
Bell, R.C., 178
Bensch, L., 317, 319
BET isotherm, 264
beta (β) ratio, 286, 316
Bevan, E., 145
bicomponeit and multi-component fiber, 169
  comparison to other technologies, 172
  crossections, 169
bicomponeit fiber, 71, 112, 207
  island-in-the-sea, 171, 172
  segmented, 171
  sheath-core, 71, 169, 227
  splittable, 171
biharmonic equation, 48, 53
binder fiber, 112
  sheath-core, 169
Bird, R.B., 36, 38, 44, 61n
Birtwhistle, W.K., 151
Bloch, J.E., 261
BMW, 382
Boltzmann constant, 61n
bonding processes, 202
  chemical bonding, 207
  hydroentanglement (spunlace), 204
  needle punch, 202
  stitch bonding, 205
  thermal bonding, 207
Bouland, D., 60, 64
boundary element method, 53
Boyer, J., 119, 133
Brady, P.H., 116, 120
Bräuning, V., 381
Brenner, H., 34
Bresee, R.R., 121, 258
bristle, 145
British Standard BS 3137, 272
British Standard BS 3928, 288
British Standard BS 4400, 94
Brock, R.J., 97
Brodkta, M., 206
Broughton, R.M., 116, 120
Brouwer, P.H., 187
Brown, R.C., 50, 51, 52, 53, 93
Brown, S.R., 194
Brownian motion, 31
B-stage, 82, 83, 374
bubble point, 254, 257, 258
  apparatus, 254
  reservoir fluids, 255
Buchanan, R.I., 2
Buckeye Cellulose Corporation, 130
Bugli, N., 378
bulk, 114, 122, 123, 124, 127, 130, 133,
  140, 143, 144
Bundemann test, 280
burst strength, 272
Butler, L., 1, 20
cabin air filters
  activated carbon, 382
  media types, 382
  cabin air filtration, 381
  CADR (clean air delivery rate), 365
Cady, D., 259
cake filtration, 291
calendering, 17, 72, 81
Calgon Carbon Corporation, 189, 363
caliper, 247
candle filters
  coalescing, 366
  high temperature, 325
Capillary Flow Porometer®, 258
carbon fiber
  PAN based, 166, 167
  pitch based, 166
carboxy methyl cellulose, 10, 71
card, 15, 16, 22, 97, 196, 234
  bale opening, 200
  blending, 200
  feeding, 200
  feeding devices, 202
  layering, 199
  roller top, 196
card rolls, 15
carded webs, 71
Carl Freudenberg Co, 18, 214
Carman, P.C., 39
Carothers, W.H., 151, 153
cartridge filters, 291, 304
  construction and assembly, 304
  dirt holding capacity, 306
  reclaimable, 304
  service-cleanable, 304
Cashin, A., 194
Celanese AG, 152
Ticona, 152
Celanese Corporation, 183n
Celanex®, 152
cell model theory, 34, 36, 42, 47, 51
  adjacent fibers, 51, 52
cellulose, 104, 112, 119, 120, 121, 122,
  127, 133, 134
CEN (Comité de Européen Normalisation), 287, 336
CEN ratings, 287
CEN Standard EN779, 287, 336
The Centers for Disease Control and Prevention (CDC), 364
ceramic fibers, 165
Cerex Advanced Fabrics, 76, 77, 78
Cerex®, 18, 75
Chandler pleater, 235
Chandler Pleating Co., 235
channel theory, 34, 37
Chardonnet, H. de, 145
chemical bonding, 18, 23, 207
  curtain coating, 208
  foam bonding, 208
  gravure bonding, 208
  impregnator, 207
  saturation, 207
  spot bonding, 208
  spray bonding, 208
chemical cartridge respirators, 362
Chen, C.Y., 54, 55
Chen screen model, 54
Chen, C., 56
Chen, Da-Ren, 56
Chevron Phillips Chemical Co. LP, 156
Chevron Products Corporation, 384
Chicopee Nonwovens, 73
Choi, Sung-Seen, 220
chopped fibers, 117
Ciba Specialty Chemicals, 194
Clarenburg, L.A., 65, 66, 67
cleanliness levels, 319
clean rooms, 354
Cloetens, P., 261
closed pores, 252
Clusthe, C.E., 178
coalescing, 7
coalessing media, 7, 95
  gas/liquid separation, 95, 96
  liquid/liquid separations, 95
coarseness, 130
cloth hanger type flow distributor, 218
coconut fiber, 143
coffee filter, 23
Coffin, D., 282
coir, 145
coir fiber, 143, 144
  process, 143
  properties, 143
Committee on Nuclear Air and Gas Treatment (CONAGT), 348
composite structures, 8, 10, 24, 71, 88, 96, 97, 233
  activated carbon, 97, 99
  air laid, 10
  containment, 97
  definition, 25
  electrospun webs, 88
  entanglement, 234
  gradient density media, 97
  laminating, 234
  multi-ply forming, 234
  processes, 25
  purposes, 24
  scrim reinforced needle felts, 96
  SMS process, 97, 234
computational fluid dynamics (CFD), 56
condensation particle counters (CPCs), 288
Conex®, 154
constant-rate-of-extension (CRE) tensile testing machine, 267
contaminant, 27, 28
conversion factors
  grammage and basis weight, 245, 250
  pressure drop, 248
corona discharge, 90
  polymers, 90
corrugated filter media, 247
  corrugation height, 247
corrugating press, 229
corrugation, 83
cotton, 105, 112, 118, 119, 121, 131, 132, 133, 134, 136
  bleaching, 134
  comber noils, 134
  ginning, 132
  micronaire, 133
  motes, 133, 134
  nep count, 134
  raw cotton, 134
  scouring, 134
cotton fiber
  shape, 134
Cotton Incorporated, 133, 134, 135
cotton linters, 117, 131, 133, 134
Coulter-I Porometer®, 255, 257
Courtalds, 145, 146
Cove, M.G., 176
creep, 281
creping, 232, 294
Index 461

Crook, L., 196, 197, 198, 199, 200, 201, 202, 203
cross layering, 16, 199
cross linking agents, 188
formaldehyde, 188
formaldehyde-free, 188
Cross, C., 145
crystallinity, 134
Cunningham slip factor, 61
Cuno Incorporated, a 3M Company, 8, 298, 311
Cut-N-Fit™, 334
CWS type 6 gas mask media, 347
Dacron, 151
Dahira, A., 73
Dan-Webb former, 13, 195
Dan-Webiformin, Denmark, 195
Darcy’s Law, 37, 38, 39, 40, 42, 248
Davies equation, 42
Davies, C.N., 31, 42, 43, 47n, 50, 57, 59, 115
decigrex, 119
decitex, 119
degree of polymerization, 104, 134
Delta Former®, 23
demisters, 96
denier, 119
Dexter Corporation, 73
diatomaceous earth, 29
Dickenson, T.C., 325, 326, 330, 332
Dickson, J.T., 151
Dickson, Inc., 382
die assembly, 215
die nosepieces, 218
capillary type, 218
drilled hole type, 218
diethylhexylsebacate (liquid DEHS), 339
diffusion filter, 2
dimensional stability, 280, 281
dioctyl phthalate (DOP), 348
test, 86
Dixit, A.S., 119, 133
Docan®, 214
Doig, R., 351
Donaldson
GDX® system, 389
TTD™ gas turbine air filter, 389
Donaldson Company, Inc., 73, 87, 220, 255, 329, 388, 389, 392
DOP, see dioctyl phthalate
drag coefficient, 53, 54, 55
drag model theory, 34, 36, 53
drag equation, 53
dry formed, 6, 10, 26, 195
dry processes, 10
dry laid, 10, 13, 15, 71, 73, 93
drying, 16
process, 13
properties and characteristics, 71
Dugan, Jr., 116, 119, 171
DuPont, 19, 73, 145, 151, 152, 153, 154, 157, 204, 214, 294, 301
DuPont Fibersilk Company, 145
DuPont style T-980, 294
Dupré, Rick, 177
Dura-Life™, 329
Duran, A., 336
Duratek®, 392
Dur-o-set® C310, 183
Durst, M., 369, 372, 376, 378, 380
dust collection systems, 325
Eash, C., 210, 214
Eastman Chemicals Products, Inc., 151
EDANA, 4, 5, 409
EDANA Test Method 30.5-99, 247
Egalia, A., 56
E-glass, 160
Einstein equation, 61
Elaftherakis, I., 27
electrets, 87, 365
dipolar, 87
electrostatic charging, 90
fibrillated film, 88
needle felt, 94
space charge, 87
electro-filtration, 7, 60
electrets, 7
electrokinetic filtration, 8
electrostatic media, 7
electrokinetic charged filter media, 311
electrospinning, 219
electrospun, 10, 12, 20, 21, 87, 116
fiber diameter, 87
nanofibers, 220
process, 20, 87
web thickness, 87
embossing, 9, 17
EN 1822, 351, 352
EN 1822-1:1988, 31, 339
EN 779, 336
Encyclopedia Britannica, 2, 61
engine filtration, 291, 305, 369
equation of continuity, 36
equation of motion, 36
equilibrium moisture content, 246
esparto, 105, 118, 131, 132, 141, 142, 143, 144
esparto grass, 141
properties, 141
esparto pulp, 347
ethylene vinyl chloride (EVCL), 183
Euler equation, 37
European Flame Retardants Association (EFRA), 193
European Synchrotron Radiation Facility, France, 261
Eurovent 4/5, 336
Evanite Corporation, 160
Evanite Fiber Corporation, 164
extraction, 8
extruder, 212, 216
face mask filter, 27
facemasks, 357
performance characteristics, 363
Fallon, S., 378
fan model approach, 51
Fardi, B., 53
Fathom®, 312
Fecralloy®, 167
Federal Standard 209E, 354
Federal Trade Commission, 149
felts, 14
aspect ratio, 118, 119
cellulose, 119
classification, 112
classified by source, 112
crimped, 75
crosssection, 51, 75, 119
crosssection shape, 119
crystallinity, 120
curl, 130
density, 118
diameter, 115, 116, 123
equilibrium moisture content, 121
filament, 116
linear density, 119
melting point, 121
modulus, 117, 119, 122
moisture absorption, 120
moisture content, 120
physical characteristics, 112
physical chemical characteristics, 113
short cut, 117
staple, 116
swelling, 120, 280
tenacity, 122
fiber diameter, 115, 123
measurement, 116
Fiber Innovation Technology, Inc., 156
fiber length, 115, 117, 118, 127, 133, 141
by process, 117
Fiberfax®, 348
Fiberweb™, 17, 75, 76, 99, 101, 102, 148, 294, 301
AQF® Technology, 99
Fibersource, 153
fibril angle, 127
fibrillated film, 88
process, 89
fibrillation, 127
filter, 1, 2, 6, 7, 8, 9, 10, 13, 14, 16, 17, 18, 19, 20, 22, 23, 24, 25, 27, 28
definition, 27
home furnace, 89
ventilation, 89
filter element, 303, 305
filter fabrics, 332
chemical resistance, 326
physical resistance, 326
properties, 332
temperature resistance, 326
Filter Manufacturers Council, 285
filter mats, 334
filter media, 1, 2, 6, 7, 8, 9, 10, 13, 14, 16, 17, 18, 19, 20, 22, 23, 24, 25, 233
definition, 6
electret, 87
embossing, 83
pleat pack, 83, 84
purposes, 27
resin bonded, 22, 23, 82, 83
filter sheets, 81, 297
filter support, 8
filtration and separation categories, 1
cumulative efficiency, 285
definition, 1
filtration efficiency, 115, 120, 123, 142, 284, 285, 314
β ratio, 286
fractional efficiency, 286
MERV ratings, 286
micron rating, 285
multi-pass efficiency, 286
single pass efficiency, 285
filtration mechanisms
cake filtration, 29
depth filtration, 29
depth straining, 29
surface straining, 29
filtration quality, 91
Filtrete™, 89, 145
fine fiber processes, 116
Fire and Flame Resistant Standards, 347
flame resistance, 190
burning mechanism, 190
test, 190
flame retardants, 190, 192
Antimony Trioxide (Sb2O3), 191
diammonium phosphate (DAP), 193
halogenated compounds, 191
inorganic compounds, 193
nitrogen, 193
phosphorous containing compounds, 191
Flanders Corporation, 99
Flanders Filters, 189
Flanders-Precisionaire, 336, 348
flash spinning, 18
flash-spun system, 214
flax, 105, 140, 141
flow through fibrous media, 43
flow through porous media, 42
fluff pulps, 71
fluid
definition, 2
Fluon®, 157
Ford, 381
formaldehyde, 181
formaldehyde resins, 175
Formhals, A., 20, 219
Fortron®, 156
Foss Manufacturing Co., Inc., 194
Foss, S.W., 194
Fossgard® antimicrobial technology, 102
Fossguard®, 194
Fourdrinier machine, 222
Fourdrinier wire, 220, 222
fractional efficiency, 316, 339
Fram Filters, 195
Frazier 2000®, 248
Frazier Air Permeameter, 248
Frazier Instrument Company, 248
Frazier Precision Instrument Company, Inc., 248
Freudenberg Nonwovens, 382
Fuchs, H., 206
Fuchs, N.A., 50, 51, 62, 65
fuel filter/separator, 96, 385
fuel systems for vehicle engines
diesel fuel, 384
gasoline, 384
fuel transportation systems, 384
pipeline system, 384
Fulko, S., 329
fumes and vapor emissions, 329
gamma number, 91n, 93
Gao, X., 73
garnett, 15, 196
gas turbine filters, 386
cleaning filter houses, 88
filter house, 387, 388
filter media, 389, 392
self cleaning filter houses, 388
Gas/Vapor Adsorption (BET), 264
GDV, Germany, 142
GDX® gas turbine inlet air filter, 389
GE Plastics, 152
George, T.W., 2
Gerkins, L., 214
Gibson, P., 220
Gilbert, H., 348
glass fiber, 159
cAT process, 159
chemical composition, 159
classification, 159
duplex process, 159
fiber diameter, 161
flame attenuation process, 159
process, 159
rotary process, 159
glass microfiber, 5, 72, 85, 168, 295, 362
glass transition temperature, 82, 104, 121, 122
glazing, 72
Glens Falls Interweb, Inc., 23, 222, 224
Global Material Technologies, Inc., 168
Gogins, M., 88
Goldsmith, S.H., 31
Goodwin, G., 194
GORE-TEX® ePTFE, 326
Goudreault, K., 194
grab tensile strength, 272
gradient density filter, 8
Grafe, T., 21, 51, 87, 168, 379
Graham, K., 21, 51, 87, 88, 168, 379
grammage, 245
graphite fiber, 167
Gras, J., 138
Greisner, H., 157
Gupta, B.S., 2
Gupta, K., 41, 258, 263, 265
Habeger, C., 282
Hagen–Poiseuille equation, 39, 46
Hagwood, J., 172
Handbook of Nonwoven Filter Media, 6
handsheet
couching, 129
testing, 127, 130
Hansen, J., 195
Hao, P., 204, 329
Happel–Kuwabara cell models, 47, 49, 50
Happel cell model, 59
Happel equation, 50
Happel, J., 34, 47, 49, 50, 54, 115
harmonized standards, 394
headbox, 22
Fourdtinier, 23
inclined wire, 23
Rotoformer®, 23
The Heat Shield™ product, 168, 326
Hegde, R.R., 73
Heggs, P.J., 53
Helmholtz’s principle, 53
hemp, 105, 132, 136, 142, 144
hemp fiber, 141
handsheet properties, 141
HEPA, 85, 86, 102, 334, 348
HEPA filter, 27, 348, 349
mini-pleat, 350
rectangular, 349
round, 351
separator-less filter panels, 350
traditional, 349
HEPA media, 239
Hercules, Inc., 227
Hersh, S.P., 2
Herty Foundation, Savannah, Georgia, 225
high bulk pulps, 122
high efficiency air filtration, 347
high loft, 71
high loft filter media, 17, 73, 334
High Volume Instrument (HVI), 133
Hildyard, M.L., 53
Hills, Inc., 218
hogs hair, 104, 143, 145
Hollingsworth & Vose Air Filtration Ltd., 93
Hollingsworth & Vose Company, Inc., 8, 177, 194, 347, 348, 365, 369, 382
hollow islands, 172
Homonoff, Ed., 26, 116, 195
hot melt bonding, 18
Hsieh, K.-C., 365
Huang, Hsu-Yeh, 73
Hurlbut Paper Company, 348
HVAC (Heat Ventilation and Air Conditioning), 334
Hycoknit®, 206
hydraulic diameter and radius, 40, 67, 69, 70
hydroentangled felts, 329
hydroentanglement, 11, 14, 16, 71, 73, 204
drying, 204
entanglement, 204
formation, 204
recirculation, 204
vacuum system, 204
wet laid, 73
wind-up, 204
Hydroformer®, 23, 223
hydrogen bonding, 120, 227
I.G. Farben, 153
IEST (Institute of Environmental Science and Technology), 287, 352, 353
IEST recommended practices (RPs), 349, 353
IEST RP-CC-001.3, 353
IEST RP-CC-007.1, 353
IEST RP-CC-034.1, 353
IEST-RP-CC001.4, 287
Im, Seung Soon, 220
image analysis, 258
inclined wire, 222, 224
Index

Incone1601®, 167
INDA, 1, 3, 4, 5, 22, 409
INDA IST 110.1-.4, 267
INDA IST 120.1-2, 247
Industrial Ceramic Solutions LLC, 165
industrial filter papers, 294
Industrial Filters Company (IFC), 299
industrial fumes, 330
dry smoke, 330
wet smoke, 330
industrial mist eliminators, 96
Ingham, D.B., 53
inhomogeneity factor, 51
inorganic fibers, 5, 112, 159
properties, 159
Inspec Fibres, 120, 156, 157
Institute of Environmental Science and Technology, see IEST
Institute of Petroleum (IP), 386n
Intelligensys Ltd., 176
internal bond strength, 277
internal bond test, 277
International Nickel Co., Inc., 167n
Intersept®, 102
Invista, 145
Irish, L., 195
Irgaguard®, 194
Irish, L., 195
ISO 14644-1, 354
ISO 16889-99, 286, 316, 318, 319
ISO 1924-2:1995, 267
ISO 2493, 275
ISO 2758, 272
ISO 4405, 322, 323
ISO 4406-1999, 322, 324
ISO 4572, 384
ISO 4572-81, 316, 318, 319
ISO 5011, 379
ISO 5635:1878, 280
ISO 9073-1:1989, 245
ISO 9073:1995, Part 2, 247
ISO 9092:1988, 4, 5
ISO 9865, 280
ISO Medium Test Dust (ISO MTD), 318
ISO test dusts, 319
Israel, J., 204, 329
IST 30.1, 272
Jacob Holm industries GmbH, Germany, 234
Japanese Ministerial Ordinance #112, 246
Jaroszczyk, T., 378
JCEM GmbH, Fulenbach, Switzerland, 236
Jena, A., 41, 258, 263, 265
jet cleaning
normal, 326
reverse, 326
Jirsák, O., 209
Johns Mansville Corp., 348
Johns Manville, 159, 162, 164
Johnson, R.A., 363
Joo, Y.L., 220
Jaroff, S.A., 193
Kahn, A.M., 52
Kalets, J., 381
Kamath, M.E., 73
Karl Raboﬁsky GmbH, Germany, 239
Kaufman, 44
Kaustinen, H.M., 124, 125, 128, 136, 143
Kaydon Custom Filtration Corporation, USA, 239, 240, 242, 311
Kelmanson, M.A., 53
Kelvin’s Law, 265
Kevlar®, 22, 72, 107, 154, 155
Khan, A.M., 55
Kim, Seong Hun, 220
Kimberly-Clark Corporation, 24, 234, 303, 312
Kinzer, K.E., 334, 335
Kiolbasa, J., 204, 329
Kirsch, A.A., 50, 51, 65
Kirschner beater, 201
Klein, G.-M., 369, 372, 376
Knauf, P., 21, 379
Knize, R.W., 372
Knudsen number, 51, 60, 87
Kodel®, 151
Kohle and Mineralotechnik GmbH, 18
Kowalski, W.J., 60, 61n
Kozeny-Carman equation, 39, 41, 42, 44, 252
Kozeny constant, 39, 41, 42
Kozeny, J., 39
kraft process, 126
cooking conditions, 126
KX Industries, 2
Kuralon®, 24, 227
Kuraray Co. Ltd., 24, 227n
Kuwabara, S., 47, 48, 50, 54, 115
Kuwabara equation, 50
Kuwabara flow model, 59, 60, 63
Kuwabara hydrodynamic factor, 51, 62
KX Industries, LP, of Orange, Connecticut., 99, 384

laboratory filter papers, 295
  qualitative, 295
  quantitative, 295
Lamb, H., 54
Lamb equation, 54
LaMer, V.K., 348
laminating, 234
Langmuir, I., 31, 44, 45, 46, 47, 54, 115, 347
latex binders, 18
latex resins, 82, 178
  additives, 178
  crosslinking agents, 179
  other properties, 180
  polymer structure, 180
  saturation and impregnation, 179
  shelf life and pot life, 181
  thermoplastic, 179
  viscosity control, 179
Latimer, J.J., 178
Lauscha Fiber International, 159, 161, 162, 163
Lee, K.W., 63
Lee, Sung Goo, 220
lenticular filters, 297, 298
Lenzing, 146
Lenzing AG, 120n
Lifshutz, N.L., 87, 93, 318, 319, 384
Lightfoot, E.N., 36, 38, 44, 61n
Lim, L., 56
Lindsay, J.D., 41, 252
linear density, 119
liquid bag filters, 291
liquid extrusion porometry, 261
liquid extrusion porosimetry, 261
liquid filtration, 7, 27, 28
  applications, 291
  intrusion porosimetry, 263
Lisakovsky, A.N., 168
Liu, B.Y.H., 53, 63
Liu, J., 378
Lo, L., 56
loss on ignition, 85
lube oil filtration, 372
  concerns, 375
  filter media, 374
  filter module, 374
  filter types, 372
  general operation, 373
  lubricating oil, 372
  particle size, 372
  spin on filter, 374
Ludwig, E., 115
Lurgi Kohle & Mineralotechnik GmbH, 214
Lydair®, 85, 86
Lydall, 81, 85, 86, 98, 99
Lyocell®, 215
LyPore® MB, 81

Madelaine, G., 64
Malkan, S.R., 18, 74, 79, 209n
Mango, P.A., 282, 283
Manilla hemp, 116, 131, 136, 141;
  see also abaca
Man-Made Fiber and Textile Dictionary, 3, 121
Manufacturing Machine Corp., USA, 240, 243
Marin, R., 294
Marshall, L., 294
Martin, S.B., 358
Martinez, J.M., 138
MASTERCHUTE®, 202
maximum pore size, 254
Mayer, E., 294, 303
McCulloch, J.G., 116
McDonald, B., 21, 87, 168, 379
McGowan, J., 151
mean flow pore size, 256, 258
  apparatus, 256
  mean pore orientation, 259
  mechanisms of particle capture, 30
  diffusion, 30
  electrostatic attraction, 30
  inertial impaction, 30, 31
  interception, 30
  media migration, 33
Medvedyev, A.A., 168
Meitner, G.H., 97
melamine formaldehyde, 178
melt-blown, 10, 19, 73, 79, 80, 81, 87, 90, 97, 116, 293
process, 215, 218
properties and characteristics, 79
membrane
  liquid filtration, 35
  mechanisms, 33
membrane filters, 8, 10
Mercedes Benz, 382
mercerized pulps, 122
mercury intrusion, 263
MERV rating, 339, 341
metal fiber, 167
metal fiber media, 168
metallic clothing, 15, 196
metallic coated rolls, 197
  condensing rolls, 198
  doffer rolls, 198
  likerin roll, 197
  mister cylinder, 197
  randomizing rolls, 198
  stripper rolls, 197
  worker rolls, 197
Microban®, 76, 102
micro-fibrils, 127
microfiltration, 33
microglass fiber, 22
micron rating, 285
  absolute micron ratings, 285
  nominal micron ratings, 285
micronaire, 119, 133
microorganisms, 102
microscopy, 259
Micro-Tuft Opener, 201
Microwave-Cleaned Particulate Filter System, 165
Middlebrooks, M., 98
MIL-STD-282, 351
Miles, R.E., 67
MIL-F-51068, 348
Miller, D., 381
MIL-M-36954C, 290
MINIFIBERS, Inc., 114, 117
Mitsubishi Rayon, 146
Mlynar, M., 181
Mohamed, M.H., 2
moisture content, 246
  hysteresis, 246
  moisture resistance, 278
Monte Carlo technique, 66, 67
Moreno, R.C., 334, 335
Moser, N., 369, 372, 376, 378, 380
most penetrating particle size (MPPS), 31, 32, 287
Mott Corporation, 168
Moyer, E., 358
MTS air laid pilot plant, 14
MTS pilot process, 195
MTS Testing Laboratories, 13
Mullen burst, 364
multi-component fibers, 218
multi-pass test stand, 316
multi-ply forming, 97, 234
Murphey, R.W., 8, 177
Myagi, 51
Myers, D.L., 87, 89
Myman, A., 26
diameter, 116
nanofiber coated filter media, 378
nanofiber coating, 378
nanofiber webs, 219
nanofiltration, 33
Nanoval Gmbh & Co. KG, Germany, 214
Nanoval®, 214
Nanoval® process, 214
NAS 1638, 322, 323
National Defense Research Council (NDRC), 347
National Institute of Standards and Technology (NIST), 316
National Nonwovens, 144, 156
National Starch, 183
natural fibers, 73, 104, 112, 116, 122
  coconut fiber-coir, 73
  hogs hair, 73
natural filters, 143
Navier–Stokes Equation, 37, 53, 56, 64
needle loom, 203
  bed plate, 203
  draw rolls, 203
  feed apron, 203
  needle beam, 203
  stripper, 203
needle punch, 16, 71, 72
  properties and characteristics, 71
negative pressure particulate respirators (NPAPPRS), 360
NIOSH efficiency ranges, 360
Nixdorf, R.D., 165
Nomex®, 22, 107, 154, 155, 168
non-cylindrical filter cartridges, 303
non-mercury intrusion, 264
nonwoven
  classification, 10
  classification by process, 195
definition, 2, 3, 4
differentiation from paper, 5
  process, 5, 10
nonwoven filter media, 1, 9, 103, 122, 130, 141, 178
  applications, 11
  bonding, 9
  challenges, 26
  definition, 9
  fiber properties, 113
  marketing segments, 26
  raw materials, 103
  sources, 11
nonwoven filter media properties
  air permeability, 114
  bulk, 114
  pore size, 114
Nonwovens: Theory, Process, Performance, and Testing, 3
Norafin®, 234
novolaks, 176
nylon, 106, 112, 117, 118, 150, 153, 154
  nylon 6, 153
  nylon 6, 6, 119, 121, 146, 153, 154
nylon fiber, 153
  applications, 153
  properties, 153
Oberlin Filter Company, 299
offset screen model, 55
Omnova Solutions, Inc., 179
Optiflo® WFE 150P, 331
Optiflo® WFE 300P, 331
OPTIMIX® bale opener, 200
Other Techniques for Measuring Pore Size and Structure, 258
Ouyang, Ming, 21, 87, 168, 379
P-84®, 72, 157, 327
  properties, 157
packing density, 34, 36, 42, 51, 57, 250
Pall Corporation, 306, 319
  Pall Septa®, 306
  paper, 6
Para-Chem, 191
Paranol®, 191
Parhwem, R.A., 124, 125, 128, 136, 143
Parlier, J.M., 194
particle counting (APC), 315
particle filtration, 56, 59, 60
diffusion, 60, 63, 64
inertia, 60
interception, 60, 63
mechanisms, 60
Particle Filtration Efficiency (PFE), 288
particle mobility, 61
particle size analysis
dynamic light scattering, 315
electro-sensing zone technique, 315
laser diffraction, 315
light extinction, 315
microscopy, 315
sedimentation, 315
sieving, 316
Payet, S., 64
PBI, 158
PBN-II®, 75, 76
Peart, C., 115
Peclet number, 60
Pelz, A., 378, 380
penetration, 285
Petri, H.-R., 384
Pevrin, E, 261
phenol formaldehyde resins, see phenolic resin
phenolic resin, 83, 175, 177
  filter media, 177
  B-stage, 177
cure times, 176
environmental concerns, 177
pleating, 177
properties, 177
Phoenix Felt®, 144
Pich, J., 51
Pich equation, 51
Pickaar, H.W., 65, 66, 67
plate and frame filter press, 297
pleated filter element, 305
pleated filter media, 305
pleating, 82, 83, 235
  blade pleaters, 235, 237
gear pleater, 235
knife pleaters, 238, 239
pleating styles, 237
rotary pleaters, 239
pleating machines, 235
pleat-pack, 303
PLEKX® adsorption medium, 99
Ply Bond Strength, 277
PMI Capillary Flow Porometers, 255
pocket filters, 336
poly(vinyl acetate) PVAc latex, 183
poly(vinyl alcohol) (PVOH), 187
degree of hydrolosis, 187
poly(vinyl chloride) (PVC), 183
poly(vinylidene chloride) (PVDC), 183
polyacrylonitrile (PAN), 149, 167
polyamide-epichlorohydrin (PAE), 227
polyaramid, 107, 112, 154
meta-aramid, 154
para-aramid, 154
polyaramid fiber, 72
polybenzimidazole (PBI), 158
polybutylene terephthalate (PBT), 151, 152
properties, 152
polyester, 107, 112, 117, 118, 121, 151, 152
process, 151
properties, 151
polyethylene, 107, 112, 121, 147, 148
high density polyethylene HDPE, 147, 148
low density polyethylene LDPE, 147, 148
properties, 147
polyethylene terephthalate (PET), 151
polyimide fiber, 72
P-84®, 157
polymer feed distributor, 213
cloth hanger type, 213
Polymer Group International (PGI), 71, 73, 97
polymers, 103, 104, 105, 119, 121, 122, 134
atactic, 104
fibers, 103
isotactic, 104
properties, 104
steric chemical structures, 104
structure, 104
syndiotactic, 104
polyphenylene sulphide (PPS) fiber, 72, 108, 112, 156
properties, 156
TFI17®, 156
polypropylene, 109, 112, 117, 121, 148, 149
properties, 149
structure, 148
polytetrafluoroethylene (PTFE), 157
applications, 158
properties, 158
polyvinyl acetate
solvent-based, 83
pore, 29, 40, 41, 65, 68, 69, 70
area, 70
size, 114, 127, 130, 139, 254
size distribution, 259
structure, 254
porosity, 37, 39, 41, 57, 250
definitions, 252
Porous Materials, Inc., 258
porous structure, 41
portable air cleaners, 344
Powder Technology Incorporated, 318
powered air-purifying respirators (PAPR), 361
Powerloft®, 303
PPS, see polyphenylene sulphide fiber
Price, D.B., 102
protective apparel, 88
Ptak, T.J., 259
PTFE, see polytetrafluoroethylene
Pui, D.Y.H., 56
pulping, 126, 127, 138
bleaching process, 127
kraft process, 126
sulphite process, 126
pulse jet cleaning, 56
pulse-jet filter, 326
Purchas, D.B., 6, 29, 93, 252, 295, 303
Purolator, 145
Q127 penetrometer, 288
Raether, T., 21, 87, 379
Ramskill, E.A., 31
Rando Machine Corporation, 16, 200
Rando Webber®, 16, 195, 200
random fiber structure, 65, 66
line intersections, 68
Ravel, U., 177
raw stock, 81
rayon, 145, 146, 147, 166, 167
acetate, 146
application, 146
artificial silk, 145
cuprammonium, 145
cuprammonium process, 146
rayon (continued)
  high tenacity, 145
  high wet modulus, 145
  lyocell, 146
  polynosic, 146
  properties, 146
  saponified, 146
  viscose, 145
  viscose process, 146
ream size, 245
Reemay Advantage®, 102, 294
Reemay Elite®, 76
Reemay Freedom®, 76, 102, 294
Reemay®, 18, 75, 151
reentrainment, 33
refining, 127
  effects on a substrate, 127
Reicofil® system, 209, 214
Reifenhauer GmbH, 18, 209
Renoux, A., 60, 64
replaceable filter elements, 291, 303
resin, 73, 81, 82, 83, 95, 98, 99, 175
  definition, 207
  solvent-based, 82, 83
  thermoplastic, 175
  thermosetting, 175
  water based, 82
resin treated filter paper, 298, 311, 375
resins and binders, 175
  forms, 175
  purpose, 175
resoles, 175
respirators, 357
  air purifying respirators, 357
  air supplying respirators, 357
  filter media, 362
retting, 141, 143
reverse jet cleaner, 326
reverse osmosis, 34
rewinder, 231, 232
rewinding
  waste, 232
Reynolds number, 38, 39, 54, 64
Rio, J., 138
Ripol, R., 138
Ritchie, C.G., 151
Rodriguez, E, 212
Rohm and Haas Company, 181
roll filters, 299
  deep bed filters, 299
  pressure filtration systems, 299
Roman, C., 301
Ron Cox, 312
Rotoformer®, 23, 222, 224
Rotoformer® 2000, 224
Rubow, K.W., 63
Ryton®, 156
Sächsisches Textil Forschungs Institut (STFI), 206
SAE AS 4059, 322, 323, 324
SAE HS806, 285
Sangani, A.S., 52
Sawvell, R.W., 194
SCAN P-29, 275
Scheffel, N.B., 159
Schlack, P., 153
Schmalz, E., 206
Schreiber, J., 206
Schreuder-Gibson, H., 88, 220
Schroeder Industries LLC, 322
scope, 1, 2, 8, 9, 10
Scott bond, 278
Sell, W., 44
separation
  definition, 1
  types, 1
Sequabond® FGS, 179
sheet mold, 128, 129
short cut fibers, 117
silicon carbide fiber, 165
  process, 166
  properties, 165
silk, 145
Simmons, R.B., 102
Sinclair, D., 348
singing, 72
single fiber efficiency, 57, 58, 59, 60, 65
  model, 58
single fiber theory, 57
sisal, 105, 118, 131, 132, 138, 139
  grades, 139
  handsheet properties, 139
  plant, 138
  process, 138
  properties, 139
size press, 24, 228
  horizontal, 228
  vertical, 228
Skyt, A., 71
Slawski, J., 193
slip flow correction, 63
slitter, 232
slitting
waste, 232
Smith, W.C., 158
Smook, G.A., 119n, 222, 226
sodium bicarbonate, 99
softwoods, 116, 123
northern, 123
southern, 123
solidity, 36, 41, 42, 45, 47, 54, 57, 70n, 250
SoloFlo®, 19, 75, 214, 294, 301
solution polymers, 185
Sontara®, 73, 204
Southwest Research Institute (SwRI), 386
SpecialChem S.A., 194
specific gravity, 118
specific surface areas (SSA), 253, 264, 163
Spider Web®, 220, 392
spinnerette, 5, 18, 213
splittable fiber, 116, 119
springwood (earlywood), 123
spunbond, 10, 11, 13, 18, 19, 75, 81, 88, 89, 97, 102
process, 18, 209, 215
properties and characteristics, 74
spunbonded, 294
spunlace, 11, 14, 16, 71, 73, 204
Spurney, K., 31
Staley, D.R., 372
Standard Test Methods for the Nonwovens Industry, 409
standards
nonwoven filter media, 397
standards organizations, 393
staple fibers, 72, 116
starch, 187
Stechkina, I.B., 51, 62, 65
Stephenson, P., 56
Stewart, W.E., 38
stiffness, 275
Gurley stiffness tester, 275
Taber stiffness tester, 275
Stille, J.K., 104, 175
stitch bonding, 16, 205
Stokes number, 62, 65
stream function, 48
strength properties, 267
Studio Technica, Italy, 159, 166
styrene butadiene (SBR), 184
summerwood, 123
Sunbond® FN, 180
Sunbond® FS, 180
Sunbond® FW, 180
super absorbent polymers (SAP), 10
Suter test, 279
Sutherland, K., 6, 29, 93, 252, 295, 303
Swicofil AG Textile Services, 151
swimming pool filtration, 76
Swoboda, P., 162n
swollen fiber, 41, 252
Synergex®, 76
synthetic fibers, 112
TANDEC, 209, 214, 216, 258
TAPPI, 15
TAPPI 1205-42, 133
TAPPI T494, 271
TAPPI T494 om-96, 267
TAPPI T234 cm-84, 119n
TAPPI T402, 246
TAPPI T403, 272
TAPPI T404, 267n
TAPPI T410, 245
TAPPI T411-76, 247
TAPPI T414, 273
TAPPI T489, 275
TAPPI T541, 277
TAPPI T550, 246
TAPPI T558, 278
TAPPI T833, 278
TAPPI TIP 1205-1, 149
TAPPI TIP 1205-02-1995, 119n
Tarleton, E.S., 34, 39, 294
TDC Filter Manufacturing, Inc., 388, 390
teabag, 2, 5
tear strength, 273
Elmendorf tear, 273
tongue tear, 273
trapezoid tear, 273
Technostat®, 94, 365
Teflın®, 157, 327
Teijin Limited, 154
Teijinconex®, 154
Tekton®, 18, 75, 76, 148
Tektron®, 301
tensile properties, 267, 268
breaking length, 271
elongation, 269
secant modulus, 270
strain, 269
stress, 268
tensile properties (continued)
  stretch, 269
  tensile energy absorption (TEA), 270
tensile ratio, 271
  tensile stiffness, 270
tensile strength, 179, 269
tensile strength, 179, 269
  dry, 179
  wet, 179
ter Kuile, W., 351
Terylene®, 151
test dust complication, 318
tex, 119
Textest AG, 248
thermal bonding, 17, 207
calendering, 207
embossing, 207
hot melt, 207
through air bonding, 207
ultrasonic, 207
thermobond, 259
Thibault, X., 261
thickness, 247
through air heating bonding, 17
Ticona Technical Polymers, 156
Toray, 157
tortuosity factor, 40
Toyoflon®, 157
traecheid, 123, 124, 126
structure, 124
Trautman, P., 378, 380
trees, 123, 130
  hardwoods, 123
  softwoods, 123
triboelectric charging, 92
triboelectric series, 92, 93
trilobal fiber, 119
Trinetex®, 382
Trinitex®, 97, 234
Tsai, P.P., 90
TSI Incorporated, 288
TSI Model 3160 filter tester, 288
TSI Model 8127 filter tester, 288
TSI Model 8130 filter tester, 288
Tsybula, Y.L., 168
Turbak, A.F., 209n
turbines, 369, 386
Twaron®, 154
Tyco Healthcare, 73
Typar®, 18, 75, 76, 148, 301
Tyvek®, 18, 19, 75, 214, 301
UK Atomic Energy Authority, 167
UL 900, 347
  Class 1 air filters, 347
  Class 2 air filters, 347
ULPA filters, 85, 334, 349, 354
ultimates, 139, 141
Ultra web®, 220
ultrafiltration, 33
ultrasonic bonding, 17
Ultra-Web®, 87
Underwriters Laboratories, 347
United States Army Chemical Warfare Service (CWS), 347
United States Department of Energy, 386
United States Environmental Protection Agency, 336
United States Federal Trade Commission, 153
United States Food and Drug Administration (FDA), 364
United States Naval Research Laboratory (NRL), 347
United States Patent 4,041,203, 234
University of Tennessee in Knoxville, Tennessee, 209
urea formaldehyde, 178
Uster Technologies, Switzerland, 133
Utipleat® filter, 306
vacuum cleaners, 364
Valley beater, 129
van Turnhout, 89, 90
variation method, 53
vegetable fibers, 130
  aspect ratio, 130
  chemical composition, 130
  diameter, 130
  length, 130
Velcon Filters, 385
venturi chamber, 213
VersaFilter®, 168
Vijayakumar, R., 288n
vinyl polymers, 104
Viral Filtration Efficiency (VFE), 288
viscose process, 145, 146
Voigt Dorries, Germany, 23, 223
volatile organic compounds, 83
volatile organic content, 246
volatiles, 246

test method, 246

W.L. Gore and Associates, 326
Wacker-Chemie GmbH, 183
Wadsworth, L.C., 18, 74, 79, 90, 209
Wakeman, R.J., 6, 34, 39, 294
Wang, W., 353
Warren, J., 294

water based resins, 82
water repellant, 83, 85, 193, 278
hydrostatic head method, 279
water repellent
coatings, 194
fibers, 194
water resistance, 278, 280
weld fume filters, 331
wet end binders, 227
wet laid, 4, 5, 6, 10, 12, 13, 22, 23, 81, 122
base sheet, 81
beater addition, 23
bonding, 23
chemical bonding, 23
converting processes, 24
forming, 22
machines, 10
process, 10
properties and characteristics, 81
thermal bonding, 24
wet lay bonding
dry end bonding, 227
wet end bonding, 227
wet lay converting processes, 229
bag making, 233
corrugation, 229, 230
creping, 230
pleating, 233
rewinding and slitting, 231
stamping and dye cutting, 233
wet lay process, 220
bonding, 227
consistency, 221
cyclic cleaning, 221
dry end, 220, 221
dryer felts, 226
forming, 221

headbox, 222
pond regulator, 224
radial distributor, 224
refining, 221
resin treatment, 228
thermal bonding, 227
water removal, 226
wet end, 220
wet press, 226
wet strength, 82
wet strength papers, 294
wet tensile strength, 271
Whatman International Ltd., 295
Whinfield, J.R., 151
White, C.M., 54
Whittam, T.S., 60, 61n
Wielema, T., 187
Williamson, J.E., 205
Winters, P., 353

wood pulp, 6, 14, 22, 104, 116, 119, 122, 123, 126, 127, 133, 134, 136, 140, 142
in air laid webs, 14
fiber length, 116
freeness, 127
hammer milled, 6
purity, 122
strength, 127
testing, 127
wall structure, 123, 124

Wood, C., 235n
wool, 104, 112, 144, 145
applications, 144
properties, 144
wound filter elements, 311

Xonics Corporation, 257
X-ray microtomography, 259

Yi, Y., 56
Yuan, S.W., 49
Yung, A., 381

Z-Direction Tensile Strength, 277
Zeta Plus®, 8, 298, 311
Zia, M., 52
Ziebold, S.A., 95n