NONWOVEN FABRICS, SPUNBONDED

1. Introduction

In 2001, the global production of spunbonded fabrics reached a record 1,400,000 metric tons with an annual growth rate of between 6 and 8% (1). There are ~260 individual production lines in operation throughout the world. Spunbonded fabrics are distinguished from other nonwoven fabrics in their one-step manufacturing process which provides either a complete chemical-to-fabric or polymer-to-fabric process. Although the use of monomers as part of the in-line process is no longer in commercial use, in either instance the manufacturing process integrates the spinning, laydown, consolidation, and bonding of continuous filaments to form a fabric. Commercialization of this process dates to the early 1960s in the United States and Western Europe (2,3) and in the early 1970s in Japan (4). Many of the first plants constructed are still in operation attesting to the usefulness of the method. New production plants continue to be built (1,5) to supply the growing demand (Table 1).

The large investment required for a turnkey spunbonded plant ($15–50 million, 2002 U.S. dollars) is offset by their high productivity. Spunbonded production was originally limited to western Europe, the United States, and Japan, but has since spread to virtually all areas of the world. Production lines, mainly nonproprietary, have been installed throughout Asia, South America, and the Middle East, areas and countries that previously did not participate in the technology. Considerable ownership changes occurred in the United States and Europe, as the strategies of companies committed to the technology evolved (6).

Early marketing efforts for spunbonded fabrics centered on their substitution for existing, ie, woven, textile fabrics. Generally, success was achieved in areas where only functionality was important. Extremely slow progress has occurred in areas where textile-like aesthetics are required. Only in the area of disposable protective clothing has success been achieved for the garment market. Nevertheless, spunbonded fabrics are recognized as a unique class of materials within the general category of nonwoven fabrics (see NONWOVEN FABRICS, STAPLE FIBERS).

The area of largest growth for spunbonded fabrics continues to be disposable diaper coverstock that accounts for ~70% of the U.S. coverstock market. Forecasts for the future growth of spunbonded fabrics continue to be favorable as consumption in both durable and disposable areas continues to grow. Growth is forecast to generally exceed the growth of all nonwovens, which itself is expected to grow at 3–6% per annum (1,6). In addition to diaper coverstock and hygiene, growth is anticipated in geotextiles, roofing, carpet backing, medical wrap, and durable paper applications such as envelopes (6).

New plant construction will bring increased capacity to levels of regional overcapacity that will force producers to export large quantities of product to keep supply and demand in balance. Considerable consolidation of ownership has occurred during the last 5 years and the investment and output for each new line has grown enormously. New production lines can produce up to 1 billion square meters of coverstock per year more than doubling the annual output of lines built only 5 years ago. Environmental issues have had relatively little effect on either production or products. Consumers prefer the convenience of disposable diapers and studies have shown that diapers are still a relatively small contributor to landfill space.

Although producers have benefited from the generally stable prices for crude oil, a sudden increase in these prices or decrease in availability of resin feedstocks would adversely impact both profitability and growth. Producers who have not upgraded to newer, faster, and more efficient lines have experienced low or negative profitability. There appear to be no new fiber technologies that would radically change the manner in which spunbonded structures are produced. Any serious challenges to existing markets will likely come from film, airlay, or advances in alternative technologies within a specific market segment.

2. General Characteristics

Spunbonded fabrics are filament sheets made through an integrated process of spinning, attenuation, deposition, bonding, and winding into roll goods. The fabrics are made up to 5.2 m wide and usually not < 3.0 m in order to facilitate productivity. Fiber sizes range from 0.1 to 50 dtex although a range of 2–20 dtex is most common. A combination of thickness, fiber fineness (denier), and number of fibers per unit area determines the fabric basis weight that ranges from 8 to 800 g/m^2; 13–180 g/m^2 is typical. Average basis weights in hygiene have fallen by 20% or more due to improvements in process technology.

Most spunbonded processes yield a sheet having planar–isotropic properties owing to the random laydown of the fibers (Table 2). Unlike woven fabrics, spunbonded sheets are generally nondirectional and can be cut and used without concern for higher stretching in the bias direction or unraveling at the edges. It is possible to produce nonisotropic properties by controlling the orientation of the fibers in the web during laydown. Although it is not readily apparent, most sheets are layered or shingled structures with the number of layers increasing with higher basis weights for a given product. Fabric thickness varies from 0.1 to 4.0 mm; the range 0.15–1.5 mm represents the majority of fabrics in demand. The method of bonding greatly affects the thickness of the sheets, as well as other characteristics. Fiber webs bonded by thermal calendering are thinner than the same web that has been needle-punched, because calendering compresses the structure through pressure whereas needle-punching moves fibers from the x–y plane of the fabric into the z (thickness) direction.

The structure of traditional woven and knit fabrics permits the fibers to readily move within the fabric when in-plane shear forces are applied, resulting in a fabric that readily conforms in three dimensions. Because calender bonding of a spun web causes some of the fibers to fuse together, thus giving the sheet integrity, the structure has a relatively stiff hand or drape compared to traditional textile fabrics. This is a result of the immobilization of fibers in the areas of fiber-to-fiber fusion. The immobilization may be moderated by limiting the bonds to very small areas (points) or by entangling the fibers mechanically or hydraulically. Saturation bonding of spun webs with chemical binders such as acrylic emulsions can bond the structure throughout and result in very stiff sheets. This technique is used to provide thermal and mechanical dimensional stability to certain structures whereby the emulsion binder functions as a nonthermoplastic component within the thermoplastic matrix.

Other approaches include powder bonding, although this method may be more suitable for bonding nonwoven fabrics made from staple fibers (7,8) (see NONWOVEN FABRICS, STAPLE FIBERS).

The method of fabric manufacture dictates many of the characteristics of the sheet, but intrinsic properties are firmly established by the base polymer selected. Properties such as fiber density, temperature resistance, chemical and light stability, ease of coloration, surface energies, and others are a function of the base polymer. Thus, because nylon absorbs more moisture than polypropylene, spunbonded fabrics made from nylon are more water absorbent than fabrics of polypropylene.

The majority of spunbonded fabrics are based on either isotactic polypropylene or polyester (Table 1). Small quantities are made from nylon-6,6 and an increasing tonnage from (flash spun) high density polyethylene. Table 3 illustrates the basic characteristics of fibers made from different base polymers. Although some interest has been seen in the use of linear-low-density polyethylene (LLDPE) as a base polymer, largely because of potential increases in the softness of the final fabric (9), economic factors continue to favor polypropylene (see OLEFIN POLYMERS, POLYPROPYLENE). Bicomponent technology will allow polyethylene to be used in a more economical way by directing it only to the surfaces where it brings a useful property.

Isotactic polypropylene is the most widely used polymer in spunbonded production because it is the least expensive fiber-forming polymer that provides the highest yield (fiber per weight) and covering power owing to its low density. Isotactic polypropylene is only $\sim$70% the density of most types of polyesters and thus equivalent yields of fiber require a greater weight of more expensive polyester. Large advances have been made in the manufacture of polypropylene resins and additives since the first spunbonded polypropylene fabrics were commercialized in the 1960s. Unstabilized polypropylene fibers are readily degraded by ultraviolet (uv) light, but dramatic improvements in additives permit years of outdoor exposure to occur before fiber properties are significantly affected. Metallocene polypropylene resins are the latest major resin improvement available for spunbonding.

Polypropylene fibers are neither dyeable by conventional methods nor readily stained because dye receptor sites do not naturally exist along the molecular backbone. However, some spunbonded polypropylene fabrics are colored by the addition of a pigment to the polymer melt wherein the pigment becomes encased within the fiber interior. Advantages to this method include higher resistance to fading and bleeding and ease of reproducibility of color shades from lot to lot. A key disadvantage is the generation of small to large quantities of off-quality production during the transitions into and out of a particular color and coloration normally only occurs on low output lines. A delustering pigment, eg, TiO_2, is often added to polypropylene as it almost always is with the manufacture of nylon fibers.

Most off-quality or scrap polypropylene fibers may be repelletized and blended in small percentages with virgin polymer to produce first-grade spunbonded fabrics. The economics are of great importance in a process where high yields are required in order to be competitive. Some manufacturing equipment directly recycles edge-trim back into an extruder where it is blended back into the polymer melt (see FIBERS, OLEFIN).

Polyester fiber has several performance advantages versus polypropylene, although it is less economical. Polyester can produce higher tensile strength and modulus fabrics that are dimensionally stable at higher temperatures than polypropylene. This is of importance in selected applications such as roofing, automotive carpet backing, and dryer sheets. Polyester fabrics are easily dyed and printed with conventional equipment which is of extreme importance in apparel and face fabrics although of lesser importance in most spunbonded applications (see FIBERS, POLYESTER).

Spunbonded fabrics have been made from both nylon-6 and nylon-6,6 polymers. Because nylon is more costly and highly energy intensive, it is less economical than either polyethylene or polypropylene. Although a considerable body of knowledge exists in the preparation of nylon polymers, such as end-group control, it has been of little advantage in spunbonded fabric production. Historically, nylon-6,6 spunbonded fabrics have been commercially produced at weights as low as 10 g/m^2 with excellent cover and strength, but recently this has also been achieved with polypropylene as well. Unlike the olefins and polyesters, fabrics made from nylon absorb water quite readily through hydrogen bonding between the amide group and water molecules (see POLYAMIDES).

Traditional melt spun methods have not utilized polyethylene as the base polymer because the resin is more expensive and the physical properties obtained have been lower compared to those obtained with polypropylene. Advances in polyethylene technology have resulted in the commercialization of new spunbonded structures having characteristics, such as softness, not attainable with polypropylene. Although fiber-grade polyethylene resin was announced in late 1986, it has seen limited acceptance because of higher costs and continuing improvements in polypropylene resin technology (see OLEFIN POLYMERS, POLYETHYLENE).

Flashspun high density polyethylene fabrics have been commercial since the early 1960s; however, this is a proprietary and radically different process of manufacturing a spunbonded fabric, more technically challenging to produce, and highly capital intensive. Today, there is only one manufacturer of flash spun fabrics although they are produced in both Europe and the United States.

Some fabrics are composed of combinations of polymers where a lower melting polymer functions as the binder element. The binder element may be a separate fiber interspersed with higher melting fibers (10), or the two polymers may be combined in one fiber type (11). In the latter case, the so-called bicomponent fiber may have the lower melting portion as a sheath covering a core of the higher melting polymer (Fig. 1). Bicomponent fibers can also be spun whereby the two polymers are extruded side by side. The polymer composition of the binder element in such structures may be either polyethylene, nylon-6, and polyester copolymers typically modified by lowering the terephthalic acid content by substitution with isophthalic acid. Great advances have been made in bicomponent spinning and a large variety of intrafiber structures can be easily produced from turnkey spinbeams (Fig. 2) (12). Bicomponent webs can be subjected to mechanical stresses such as water jet impact which causes the individual filament to fracture into its components yielding a new number of filaments equal to the number of components or segments created in the filament during spinning. Thus, a single filament containing sixteen pie segments will fracture into sixteen smaller wedge-shaped filaments.

Spunbonded fabrics with elastomeric properties are now commercial. One type of structure has been commercialized in Japan based on thermoplastic polyurethanes but the process is more similar to melt blowing than spunbonding (13). This represented the first commercial production of such fabrics, although spunbonded urethane fabrics have been previously discussed (14). A more economical approach using polypropylene has recently become commercial and is used in medical and hygienic applications (15). High costs and inferior performance versus woven fabrics continue to exclude these fabrics from the huge apparel markets. Elastomeric fabrics may also be created using the meltblown process for specialty applications.

There is an almost unlimited number of ways to characterize spunbonded fabrics. Many tests in use were originally developed for the characterization of textiles and paper products. When taken together, properties such as tensile, tear and burst strength, toughness, elongation to break, basis weight, thickness, air porosity, dimensional stability, and resistance to heat and chemicals are often sufficient to uniquely describe one product. The reason is that these properties reflect both the fabric composition and its structure, the latter being defined by a manufacturing process unique to that fabric. Compare, eg, the differing shapes of the generic stress–strain curves of thermally bonded and needle-punch bonded fabrics (Fig. 3). The shape of each curve is largely a function of the freedom of the filaments to move when the fabric is placed under stress and is thus a function of fabric structure.

Diverse applications for the fabric sometimes demand specialized tests such as for moisture vapor, liquid transport barrier to fluids, coefficient of friction, seam strength, resistance to sunlight, oxidation and burning, and/or comparative aesthetic properties. Most properties can be determined using standardized test procedures that have been published as nonwoven standards. Test methods adopted in the United States are published by INDA, while those adopted in Europe are published by EDANA. A comparison of typical physical properties for selected spunbonded products is shown in Table 2.

3. Spinning and Web Formation

Spunbonded fabric production couples the fiber spinning operation with the formation and consolidation of the web in order to maximize productivity. It is the coupling of these processes that distinguishes the spunbonded process from traditional methods of fabric formation where fiber is first spun and collected, then formed into a fabric by a separate process such as weaving or carded into a web. If the bonding device is placed in line with spinning and web formation, the web is converted into bonded fabric in one step (Fig. 4). In some arrangements, the web is bonded off-line in a separate step that appears at first to be less efficient; however, this offers the advantage of being more flexible if more than one type of bonding is to be performed on the web being produced. Some specialty processes also separate the spinning and the laydown steps which adds cost but provides high control on the fiber properties and ensures few breaks in laydown.

The basic spinning process is similar to the production of continuous filament yarns and utilizes similar extruder conditions for a given polymer (16). Fibers are formed as the molten polymer exits the 500 or more tiny holes (~0.2 mm) of each spinnerette where it is immediately quenched by chilled air. Since a key objective of the process is to produce a relatively wide (eg, 3–4 m) web, individual spinnerettes are placed side by side in order that sufficient fibers be generated across the width. This entire grouping of spinnerettes is often called a block or bank, and in commercial production it is common for between two and four blocks, but as many as eight, to be used in tandem in order to increase the coverage and uniformity of laydown of the fibers in the web.

Most spunbond machinery producers now utilize large rectilinear spinplates in lieu of multiple small individual spinnerettes. In effect, the spinning plate is slightly wider than the desired web and a continuous curtain of filaments is formed providing uniformity from point to point relative to multiple side by side spinnerettes in a block. Each spinbeam can contain up to 30,000 holes and it is common for multiple spinbeams to be used in tandem to further improve uniformity and increase throughput.

Prior to deposition on a moving belt or screen, the molten polymer threads from a spinnerette must be attenuated to orient the molecular chains of the fibers in order to increase fiber strength and decrease extendibility. This is accomplished by hauling the plastic fibers off immediately after they have exited the spinnerette. In practice, this is done by accelerating the fibers either mechanically (17) or pneumatically (17–19). In older processes, the fibers are pneumatically accelerated in multiple filament bundles; however most new installations accelerate an entire beam or curtain of filaments (20–22).

In traditional textile spinning, some orientation of fibers is achieved by winding up the filaments at a rate of 3000–5000 m/min to produce the so-called partially oriented yarns (POYs) (23). The POYs can then be mechanically drawn in a separate step to achieve maximum strength. In spunbonded production filament bundles are partially oriented by being pneumatically accelerated at speeds of 6000 m/min or greater (19,24). Accelerating the filaments at such great speeds not only achieves a partial orientation but results in extremely high rates for web formation, particularly for lightweight structures (eg, 15 g/m^2). The formation of wide webs at high speeds results in a high efficiency of manufacture. Newer processes have been commercialized that can accelerate filaments at speeds up to 8000 m/min and simultaneously create very small fiber deniers with high throughput (25).

For many applications this partial degree of orientation imparts a sufficient increase in strength and decrease in extendibility to make the final bonded fabric perfectly functional, eg, diaper coverstock. However, some applications, such as geotextiles (qv) and primary carpet backing, demand that the filaments achieve a very high tensile strength and low degree of extension. This requires subsequent additional attenuation, such as the mechanical drawing of filaments, a process usually accomplished over heated rolls with a typical draw ratio of ~3.5:1 (17). After drawing, the filaments are pneumatically deposited onto a moving belt or screen. Because drawing rolls cannot normally dispatch filaments as fast as pneumatic jets, the web-forming process is usually less rapid, although the resulting web has greater physical strength.

The pneumatic deposition of the filament bundles onto the moving belt results in formation of the web. A pneumatic gun uses high pressure air to move the filaments through a constricted area of lower pressure but higher velocity, as in a venturi tube. Pneumatic jets used in spunbonded production have been described (17,24). Unfortunately, the excellent filament uniformity coming out of the spinnerette is lost when the filaments are consolidated going through a gun.

In order for the web to achieve maximum uniformity and cover, it is imperative that the individual filaments be separate from each other prior to reaching the belt. Failure to sufficiently separate individual filaments results in the appearance of “ropes” in the web. One method used to effect this state of separation is to induce an electrostatic charge onto the bundle while still under tension and prior to pneumatic deposition. The charge may be induced either triboelectrically or more typically by applying a high voltage charge to the filaments (26). The level of electrostatic charge on the filaments must be at least 30,000 esu/m^2 of filament surface area (16) to be effective. After deposition onto the moving belt it is necessary to discharge the filaments; this is usually accomplished by bringing the filaments in contact with a conductive grounded surface. In some cases, the deposition belt is made of conductive wire and connected to ground. The electrostatic repulsion method has the advantage of being relatively simple and reliable. Producing webs by spinning rectilinearly arranged filaments through a so-called slot jet reduces or eliminates the need for such bundle-separating devices (20,21), because the filament bundles are not collapsed en route to the belt as they are in a pneumatic gun.

Other routes to reachieving filament separation have been described and rely on mechanical or aerodynamic forces to affect separation. Figure 5 illustrates one method that utilizes a rotating deflector plane to force the filaments apart while depositing the opened filaments in overlapping loops (27). After the splayed filaments fall to the deposition surface or forming screen, a suction from below the disposition surface holds the fiber mass in place.

For many applications, it is acceptable or desirable to lay down the filaments in a random fashion without orienting the filament bundles with respect to the direction of the laydown belt (24). However, it is sometimes desirable to control the directionality of the splayed filaments on the laydown belt in order to achieve a particular characteristic in the final fabric. Directionality can be controlled by traversing the filament bundles either mechanically (19,27) or aerodynamically (17,28) as they travel downward toward the collecting belt. The aerodynamic method consists of supplying alternating pulses of air on either side of the filaments as they emerge from the pneumatic jet. By properly arranging the spinnerette blocks and the directing jets, laydown can be achieved predominately in the desired direction. Figure 6 illustrates the production of a web with predominately machine and cross-machine direction filament laydown (17). It is possible to generate highly ordered laydown patterns by oscillating filament bundles between closely spaced plates to achieve a high degree of parallelism.

If the laydown belt is moving and filaments are rapidly traversed across this direction of motion, the filaments are deposited in a zigzag or sine wave pattern on the surface of the moving belt. The effect of the traverse motion on the coverage and uniformity of the web have been described mathematically (29). The relationships between the collecting belt speed, period of traverse, and the width of filament curtain being traversed determine the appearance of the formed web upon the laydown belt. Figure 7 illustrates the laydown for a process where the collecting belt travels a distance equal to the width of the filament curtain x, during one complete period of traverse across a belt width y. If the belt speed is v_b and the traverse speed is v_t, the number of layers deposited, z, is calculated by the formula, $z = (x \cdot v_t)(y \cdot v_b)$. It can be seen that if the traverse speed is twice the belt speed and if x and y are equal, then a double coverage will occur over all areas of the belt.

The alternative to the use of multiple spinnerettes per bank, and now the most widely utilized process, is the so-called curtain spin process that utilizes a single plate the width of the desired web which has been drilled with holes for fiber formation. The advantage to this approach is that it results in a uniform distribution of filaments within the curtain of continuous fibers produced from the spinning plate. The use of the single uniform distribution of filaments within the curtain of continuous fibers is produced from the spinning plate. The use of the single spinning plate automatically places the fibers in a uniformly distributed array and thereby presents a curtain of high uniformity filaments to the fiber attenuation mechanism. Care must be taken to keep individual filaments from sticking while they are still plastic which is normally in the quench or cooling area between the spin plate and the laydown jet.

By comparison, the multiple spinnerette per bank process requires additional effort prior to laydown in order to compensate for the gaps between the individual spinnerettes. Failure to present a uniformly distributed filament array to the laydown screen will result in spot-to-spot variations in fiber density and a web that has the appearance of blotch.

In general, once the curtain of filaments has been produced, it is necessary to attenuate the filaments in order to provide strength and resistance to deformation. The most commonly practiced approach is to utilize a single slot, which is at least the width of the curtain, at a point below the spinning plate and above the laydown screen. There are three practical approaches taken. The first utilizes the injection of low pressure air at a point above the slot so that the fibers attain sufficient acceleration in the slot to provide adequate draw (21) (Fig. 8). The second utilizes a low pressure vacuum below a venturi to provide the pressure differential required for sufficient acceleration and resulting attenuation (30). The third utilizes an acceleration slot immediately below the spin plate with little or no quench or cooling of the filaments (25).

One of the limitations of the curtain–slot draw process has been that the amount of fiber attenuation is constrained due to the short distance generally allowed between the spinnerette and the venturi slot and the use of relatively low pressure air for drawing so as not to induce high turbulence in the area of the laydown. In order to adapt this concept for the production of polyester fabrics that inherently require much higher fiber acceleration to attain the desired polyester fiber properties a new process has been commercialized (25).

4. Bonding

Many methods can be used to bind the fibers in the spun web. Although most procedures were originally developed for use with nonwoven staple fibers, three were adapted for use with continuous filaments: mechanical needling, thermal, and chemical/binder. Thermal and chemical–binder methods may bond the web by fusion or adhesion of fibers using either large or small regions, generally referred to as area bonding and point bonding, respectively. Point bonding results in the fusion of fibers at discrete points with fibers remaining relatively free in between the point bonds. Other methods that are used with staple fiber webs but which are not routinely used with continuous filament webs are stitch-bonding (29,31), ultrasonic fusing (8,32), and hydraulic entanglement (33). Hydraulic entanglement is currently being developed as a high speed bonding process for spunlaid webs as a way to achieve superior softness. It has the potential to produce the most radically different continuous filament structures, however, it has the disadvantage of being a more costly and complex bonding process.

Of the three standard bonding methods used in spunbonded manufacturing, mechanical needling, also called needle-punching or needle-bonding, is the simplest and least expensive. Although it is the oldest process, it continues to be widely used. Significant improvements in throughput and flexibility have resulted in the sales growth of needle-bonded fabrics, particularly for geotextiles (qv) and roofing. An excellent review of mechanical needling technology has been published (29).

In the needle-punching process, a continuous filament web is subjected to barbed needles that are rapidly passed through the plane of the moving spun web (see NONWOVEN FABRICS, STAPLE FIBERS). The needles pass in and out of the web at frequencies exceeding 3,000 strokes/min that can result in as many as 500 penetrations/cm^2 depending on the needle density and the line speed, which can be as high as 150 m/min (34). The effect of this operation is to interlace the fibers and thus bond the structure together, relying only on the mechanical entanglement and fiber-to-fiber friction. The fabric produced tends to be more conformable and bulky than fabrics bonded by thermal or chemical/binder methods. Because the fibers have freedom to move over each other, the fabric is easily deformed and exhibits a low initial modulus (Fig. 2).

The principal variables in needle-punching are the needle design, punch density, and depth of punch. Considerable research has been conducted on the shape and design of the needles and how this affects the interlacing of the fibers (29). Needling produces a fabric that is 100% fiber with no points or areas of fusion or melting, thus it is easily adapted to most fiber webs and requires less precise control than thermal bonding. In addition it is the only bonding method suitable for the production of spunbonded fabrics of very high basis weights, eg, 800 g/m^2. It is, however, only suitable for the production of uniform fabrics greater than $\sim$80 g/m^2 because needling tends to concentrate fibers in areas resulting in loss of visual uniformity at lower weights.

Unlike mechanical needling, both thermal and chemical/binder bonding depend on fiber-to-fiber attachment as the means of establishing fabric integrity. It is the degree and extent of attachment that determines many of the fabric qualities, most notably the hand or softness. Because point bonding can be accomplished using as little as 10% bonding area, ie, 90% unbonded area, such fabrics are considerably softer than area-bonded structures. Fiber mobility is retained, in part or in total, outside the areas of the point bonds. Thermal bonding is far more common than chemical–binder bonding and is generally more economical because the latter method adds the cost of resin and still requires a thermal curing treatment as the final step. Both area and point thermal bonding are rapid processes having line speeds in excess of 300 m/min and up to 800 m/min during production of lightweight fabrics.

Area thermal bonding can be accomplished by passing the spun web through a source of heat, usually steam or hot air. Prior to entering the bonding area the spun web may be consolidated by passing it under compressional restraint through a heated prebonding area which adds integrity to the web (10). While in the bonder the consolidated web is exposed to hot air or pressurized steam that causes fusion to occur between some, but not all, of the fiber crossover points. Complete fusion leads to a paper-like structure with low resistance to tearing. The spun web may contain small percentages, typically 5–30%, of a lower melting fiber (10), or the filaments may contain undrawn segments that are lower melting than the drawn or matrix segment (28). Heterofilament structures utilize a lower melting covering (sheath) on the outside of the filaments to effect fusion. Both polyethylene and nylon-6 have been used as the lower melting sheath in commercial spunbonded products.

The use of steam is generally limited to polypropylene and polyethylene fusion because impractical pressures are required to reach the temperature levels, eg, >200°C, required for bonding polyesters. In general, greater temperature control is required for area bonding polypropylene than for other polymers because the temperature difference between the matrix and binder fibers can be only 3°C (28).

Whereas thermal area bonding uses temperature as the variable to a great degree and relies on sophisticated web structures containing binder fibers, thermal point bonding utilizes both temperature and pressure to affect fiber-to-fiber fusion. Thus it is a simpler approach to bonding because it does not require the web to contain lower melting fibers or segments and is less demanding of the technology required to produce the web. Point bonding is usually accomplished by passing a web, previously consolidated or compacted with either heated or unheated press rolls, through heated nip rolls, one of which contains a raised pattern on its surface (Fig. 9). When bonding, polypropylene roll temperatures generally do not exceed 170°C; however, pressures on the raised points are quite high, preferably 138–310 MPa (20,000–45,000 psi) (35). The degree of bonding between the points can be controlled by varying the ratio of heights of the raised points to the depth of the web (36). Typically only 10–25% of the surface available for bonding is converted to fused, compacted areas of bonding.

Optimum conditions of pressure and temperature are dependent on many variables including but not limited to the nature of the web, line speed, and engraved pattern. Optimized conditions are best obtained through detailed investigations and much experience. Even subtle changes in any of these variables can result in significant changes in the properties of the finished fabric (7,8). New designs for bonding calenders continue to refine the process (37).

Because engraved point bonding rolls can be as wide as 5 m, the problem of maintaining uniform pressure across the width must be addressed. Small differences in pressure across the width can produce an unacceptably variable product. Hydraulic pressure is applied at the ends to the roll causing a slight deflection that results in less pressure being applied in the center compared to the ends. A number of solutions to this problem have been devised (37), including cambering wherein the roll diameter decreases slightly from the center to the ends and mechanical means such as pressurizing the external shell of one of the two nip rollers.

Chemical–binder bonding is used less frequently than thermal bonding in the production of spunbonded fabrics, and in a shift over the past decade, the same is also true for staple fiber nonwovens. Resin binders are occasionally used with spunbonded webs to achieve special characteristics that are unattainable thermally (38). In a typical case, acrylic resin(s) are applied to saturate the web, excess resin is removed by nip rolls, and the wet web is passed through a drying oven to remove excess water and cure the resin which tends to concentrate at fiber–fiber junctions. By curing the resin, a thermoset binder conveys high thermal dimensional stability to the web for applications such as roofing.

Resin binders may alternatively be applied in discreet points in a pattern so as to immobilize fewer fibers and produce a softer fabric; however, it is difficult to accurately control the diffusion of the resin, and the drying step requirements make it less attractive than thermal bonding.

Chemical bonding with hydrogen chloride gas has been used with spun webs of nylon-6,6 to commercially produce spunbonded nylon fabrics (39). In this bonding process, the activating hydrogen chloride gas is passed over web fibers held in close contact by tension. The hydrogen chloride disrupts hydrogen bonds between the polymer chains and forms a complex with the amide group. When the gas is desorbed the process reverses, this time with new hydrogen bonds formed between polymer chains in different fibers. This basic method has been further refined to permit only the formation of pattern bonds, whereby fiber mobility is retained between the bonded areas yielding a softer hand to the bonded fabric (40).

Bonding a web by any means allows for certain generalizations. If the web is highly bonded, most of the fibers are bonded to another fiber. The resulting structure is relatively stiff, paper-like, and has higher tensile and modulus but lower resistance to tear propagation. On the other hand, if the web is only slightly bonded fewer fiber-to-fiber bonds are present and the structure is more conformable with lower tensile and modulus but higher resistance to tear propagation due to bunching of filaments. Additionally, webs that are only slightly bonded exhibit low surface abrasion resistance. In comparing area to point bonding, greater varieties of structures are achievable through point bonding because of the various bonding roll patterns available. The expense associated with the manufacture of the pattern roll generally dictates the careful selection of the pattern, however.

5. Meltblown Fabrics

Meltblown fabrics differ from the traditional spunbonded fabrics by having lower fiber denier (fineness) and by usually being composed of discontinuous filaments. Although meltblown fabrics are not generally referred to as spunbonded, the integration of spinning, attenuation (although slight), laydown, and bonding during the production of meltblown webs describes a process traditionally defined as spunbonding. The inherent fiber entanglement often makes additional bonding unnecessary, however. Fibers produced by melt blowing are very fine, having typical diameters of 3 μm (41,42), smaller by nearly an order of magnitude than traditional spunbonded fibers. The fibers are extremely fine and largely unoriented, causing the webs to be quite weak and easily distorted. Most thermoplastic polymers have been meltblown, but the majority of commercial products are produced from high melt flow grade polypropylene.

In the manufacture of meltblown fabrics, a special die is used in which heated, pressurized air attenuates the molten polymer filament as it exits the orifice of the dye or nozzle (Fig. 10). Air temperatures range from 260–480°C with sonic velocity flow rates (43).

The rapidly moving hot air greatly attenuates the fibers as they exit from the orifices to create their small diameters. The fibers are relatively weak and deposited on the forming screen as a random entangled web that may be thermally point bonded to improve strength and appearance. The web may also be deposited onto a conventional spun web, then thermally bonded. Sandwich structures, called SMS, are routinely created with the meltblown web in the middle between two conventional spunbonded webs (44). Other materials, eg, cellulosics, have been blended into the meltblown filament stream to yield a meltblown structure with a unique combination of properties (45). Mixtures of meltblown and crimped bulking fibers have been sold as thin thermal insulation for use in outdoor clothing and gear (46). Meltblown technology has also been adapted to produce nontraditional spunbonded fabrics, such as elastomeric webs (47).

The great quantity of very fine fibers in a meltblown web creates several unique properties such as large surface areas and small (<1 μm) pore sizes. These have been used in creating new structures for hospital gowns, sterile wrap, incontinence devices, oil spill absorbers, battery separators, and special requirement filters. During the last decade meltblown technology has experienced large growth mainly in the form of SMS or SMMS sandwich structures in hygiene (6).

6. Flash Spun Fabrics

The process of producing spunbonded webs by flash spinning is a radical departure from the conventional melt spinning approach. In melt spinning, a molten polymer is typically extruded through a spin plate containing ~20,000 tiny holes. This produces a fiber curtain containing ~20,000 fibers, each typically 15–50 μm in diameter. The fibers are kept separate from each other until the bonding operation connects some or all of them.

By contrast, flash spinning begins with a 10–15% polymer solution prepared by dissolving a solid polymer, such as high density polyethylene, with a suitable solvent, such as pentane, trichlorofluoromethane or methylene chloride (48). The solution is heated to $\sim$200°C, pressurized to $\sim$4.5 MPa (653 psi), and the pressurized vessel is connected to a spinnerette containing a single hole. When the pressurized solution is permitted to expand rapidly through the hole, the low boiling solvent is instantaneously flashed off leaving behind a three-dimensional film–fibril network referred to as a plexifilament. The three-dimensionality results from the cross-linking interconnection of the fine fibers which produces a film thickness of 4 μm or less (48). Thus many individual but interconnected fibers are created from a single-hole spinnerette.

It is believed that bubbles form rapidly as the pressurized solution undergoes depressurization during spinning and the bubbles may grow and rupture thus forming the plexifilamental network (48). Gases that are effectively insoluble in the solvent may be added to the pressurized solution in order to facilitate high rates of bubble nucleation.

When a multiplicity of single-hole spinnerettes are assembled across a width, the plexifilaments produced can form a wide web that can be thermally bonded to produce a flat sheet structure (49). The web-forming procedure is ameliorated by use of a baffle that deflects the stream of plexifilaments after exiting the spinnerette.

Unlike fine fibers prepared by melt blowing, the plexifilaments from flash spinning are substantially oriented and possess relatively high tenacities [0.08 N/tex (>1g˙f/den)]. The plexifilaments scatter light effectively as a result of high surface areas ($\sim$2 m^2/g) and thus form opaque webs. In addition, the fineness of the plexifilament fibrils also results in a web structure of exceptional softness. Webs are either area or point bonded to yield paper- or cloth-like aesthetics, respectively. The paper-like sheets are used as durable papers and may be printed using conventional inks (qv) and printing equipment, whereas the point-bonded structures are very soft and find use in disposable protective clothing.

Flash spinning is the most complex and sophisticated method for manufacturing spunbonded fabrics. A single production line can require an investment of nearly $200 million and serious safety issues must be addressed in the plant's design and operation. Although the process has been in use since 1962, the need to spin heated and pressurized solutions under precise conditions has resulted in only one company (Du Pont) practicing the technology as a route to these unique spunbonded products. A second producer (Asahi) stopped producing some years ago in Japan after forming a marketing joint venture with Du Pont. Hydrocarbon solvents are now being used for the process since chlorofluorocarbons, the traditional solvents, are restricted due to environmental regulations (50).

The physical properties of flash spun fabrics are unique and not attainable via the melt-spun spunbond process. Even bicomponent melt spinning cannot produce similar structures. As a result the profitability of a flash spun operation is very high when the capacity of a line is fully utilized.

7. Test Methods

Spunbonded fabrics are characterized by standardized test procedures originally developed for textile fabrics and paper products. The Association of the Nonwoven Fabrics Industry (INDA) has published a list of test procedures (Table 4) (51) that are routinely used in determining specific physical characteristics of spunbonded and other nonwoven fabrics. Analogous test methods are published in Europe by EDANA, the European Association of Nonwoven Fabrics. INDA and EDANA are working together to develop and publish harmonized international test procedures. Many tests are established for the evaluation of nonstrength related properties such as washability, stiffness, and softness. Great strides have been made in the test methodology used to evaluate the hand of materials for textile applications such as clothing. A methodology and equipment, permitting quantitative evaluation of fabric hand, have been developed (52).

As applications are developed, the need for new end use specific test methods grows. Geotextile uses are a good example of how a large new application requires the design of new test methods (54). In addition to break, stretch, tear, and burst resistances described in Table 4, geotextile fabrics are tested for puncture, maximum opening size, permittivity, and asphalt retention, according to IST 180.1–9. The puncture test notes the resistance to being punctured by a probe with either a flat or spherical tip. Maximum opening measures the largest size glass beads that can pass through a fabric, thereby reflecting the size of soil particles that can be stopped by a geotextile. Permittivity is how fast water, at a given pressure, passes through a geotextile. Asphalt retention is judged by how much asphalt cement is left in a geotextile after it is dipped in the cement and allowed to drain, and what change in area the geotextile undergoes.

Long-term applications also demand test methodology on the aging characteristics of spunbonded fabrics. Roofing applications, eg, require that the saturated fabrics retain their strength for many years despite a hostile environment. By heating the fabric at several different temperatures higher than the expected nominal conditions, and measuring the time it takes to observe a significant property change, for instance loss of 50% tensile strength, effects can be plotted to permit some extrapolation back to expected nominal conditions (55). The importance of aging tests will increase as more long-term applications are developed for synthetic fabrics. The Swedish Building Institute has developed heat aging tests and standards for films and fabrics used in building construction. Canada has established a number of longevity and performance test procedures for construction fabrics, such as housewrap.

In medical applications, many test procedures have been developed for screening the efficiency of fabrics to block the passage of viruses, blood-borne pathogens, etc. Spunbonded SMS sandwich fabrics are widely used as protective gowns in hospital operating rooms due to their combination of barrier and comfort.

Overall, the test methods published by INDA (Table 4) continue to be the general tests used to characterize fabrics; however, specific market applications often generate special test procedures to fulfill unique needs.

8. Applications for Spunbonded Fabrics

Uses for spunbonded fabrics have traditionally been segmented into durable and disposable categories. In the early 1970s, consumption of spunbondeds was predominately for durable uses such as carpet backing, furniture, bedding, and geotextiles. By 1980, however, disposable applications accounted for an increasingly large percentage due to the acceptance of lightweight (eg, 17 g/m^2) spunbonded polypropylene fabrics as a coverstock for diapers and incontinence devices (6). In the 1990s, the use of new diaper and training pants designs have increased the demand for lightweight fabrics far beyond earlier predictions.

Both the durable and disposable markets for spunbondeds have experienced dramatic growth (~6%/year). Disposable applications utilize the vast majority of the yardage produced although only ~50% on a tonnage basis (56). Significant areas of durable growth have been in the building and construction industries where spunbondeds are used in geotextiles, roofing membranes and Housewrap (see BUILDING MATERIALS). Growth has also been achieved in primary carpet backing in automotive carpets and carpet tiles, where moldability and high dimensional stability, respectively, were achieved through the use of polyester spunbonds.

With the possible exception of Housewrap, however, there have been virtually no new markets established as a result of the special characteristics of spunbonded fabrics. Growth has come about in an evolutionary fashion where spunbonded fabrics were substituted for woven fabrics, other nonwoven fabrics (including knits), paper or film in previously existing applications, or where the cost–property relationship has permitted an extension of an existing application, such as the redesign of diapers. The principal contributions that spunbondeds have made in these markets generally have been attractive economics, or improved processibility and performance in the final product. This combination has greatly accelerated the use of the products within an application and consequently contributed to the growth of specific markets. General market opportunities for nonwovens have been reviewed (6,7,56).

Of the four basic polymer types available in spunbonded form, ie, polypropylene, polyethylene, polyester, and nylon, both polyester and nylon are more costly polymer forms than either of the olefins. It is possible for this cost advantage to be offset by other factors, such as production of the fabric in lighter unit weight, but in general olefin-based products have an economic advantage for an equivalent weight fabric. In addition, the lower density of olefinic polymers provides a greater “yield” of more fibers per unit area that provides better cover and performance. In some applications, however, this advantage is moot if the olefin-based product cannot perform properly. An example of this is in roofing membranes where a key requirement is dimensional stability to hot bitumen at temperatures approaching 200°C, which is above the melting point of both polypropylene and polyethylene but well within the performance limits of polyester. To a great extent this one property, ie, higher temperature resistance, largely differentiates the opportunities for polyester spunbondeds versus olefinic counterparts. Although polyester fibers exhibit higher modulus and more flexible dyeing, these properties seem to be of little advantage in the markets for spunbonded fabrics.

8.1. Spunbonded Markets: Durable Applications. A summary of late 1990s markets for nonwoven fabrics in the United States and western Europe is shown in Figures 11–13. Approximately 37% of total global nonwoven production for 2001 was estimated as being spunbonded (1). In North America this represents 550,000 metric tons of spunbonded production with volume growth of 8.5%/year for the period 1996–2001 (1). The principal durable applications center around construction and automotive applications although there are other smaller areas.

One of the first durable applications was the use of spunbonded polypropylene in primary carpet backing. First introduced in the mid-1960s as a replacement for woven jute, it is still used in specialty carpets and holds a unique position in applications that require isotropic planar properties for dimensional stability such as printed or patterned carpets. The finer fiber versus woven ribbons or jute also allows tufting needles to penetrate with little deflection where fine-gauge tufting is desired. Finally, because the spunbonded backing is bonded at many fiber junctions, it offers the advantage of maintaining clean edges after cutting or trimming, making it attractive for use in small rugs where the unraveling feature of woven ribbon backings can be a concern. Although the first spunbonded primary carpet backing was made from polypropylene, other spunbonded products based on polyester and polyester–nylon were later commercialized as tuftable carpet backing products, mainly for automotive uses.

An extremely successful application for spunbonded fabrics is in the area of furniture, bedding, and home furnishings. In furniture construction the use of lower cost spunbonded fabrics has become routine, whereas in the 1970s woven sheeting dominated the market. Spunbondeds are used in hidden areas requiring high strength and support in chairs, sofas, and other seating. The bottoms of chairs are often covered with dust covers made of spunbonded fabrics because of the nonfraying characteristics, high porosity, excellent cover, and low cost. An inherent resistance to rot and mildew versus natural fabrics also adds to the popularity of spunbonded fabrics in home uses.

In bedding, spunbondeds are used as spring insulators, spring wrapping in mattress construction, dust covers under box springs, and facing cloth for quilting. Home furnishing uses include mattress pad covers where the spunbonded fabric serves as the top and bottom of a sandwich structure with a middle layer of fiberfill and fastened by ultrasonic quilting. Draperies also have used spunbonded fabrics wherein the lightweight fabric serves as a stitching medium for use with stitchbonding equipment. Spunbonded fabrics are also used in blinds, both vertical and horizontal, wherein the fabric, which must be extremely uniform, may be saturated with colored resins to form opaque and optionally pleatable blinds.

A high growth application for spunbonded fabrics is the air infiltration barrier whereby the penultimate vertical surfaces of old or newly constructed houses are covered with a layer of spunbonded fabric followed by the application of the ultimate external sheathing such as siding or masonry. The objective is to construct a barrier to the infiltration of air into the wall cavity and to the insides of homes, thus lowering the cost of heating and cooling. Tests conducted by the

National Bureau of Standards and the National Association of Homebuilders confirmed the effectiveness of the air infiltration barrier concept as a means of lowering the cost of heating a home (60). Certain spunbonded fabrics are well suited for this application because they possess a unique combination of properties required for functionality. These include resistance to the penetration of liquid water and low porosity to air currents, but with a simultaneously high transport of moisture vapor. In a winter climate, warm moist air from inside the house can penetrate through the wall cavity and to the outside. If the air barrier material is not sufficiently permeable to moisture vapor, condensation can occur inside the wall cavity where damage from moisture can occur. In addition, the effective R-value of the insulation (eg, fiber glass) inside the wall cavity is diminished by the presence of liquid and solid water. Trapped moisture in wall cavities provides an opportunity for the growth of molds, a growing concern in warm moist climates. The combination of water and air current resistance combined with breathability to moisture vapor and high tensile and tear strength is a difficult combination of properties to assemble. Spunbonded technology can provide these characteristics in economical form.

Uses for nonwovens in automobiles have grown from a rather modest beginning in the 1970s to a position of significance (58). Although needle-punched nonwoven fabrics have been used in large-area applications, such as backing for vinyl seats and landau tops, spunbonded fabrics have historically been utilized in lower volume applications such as labels for seat belts, spring insulators, listings in seats, and as coated fabrics for ducting. Spunbonded polyester has become accepted as a tuftable backing in molded carpets where the use of spunbonded backing allows for greater molding precision, improved dimensional stability, and resistance to puncture. Newer applications include headliners, which are often complex composites that can be molded into sophisticated shapes. Lightweight spunbonds are used as sound insulators in between dashboard components, and as the base fabric in interior door panels and sun visors.

Material acceptance in roofing applications has changed significantly since the mid-1970s, particularly for spunbonded fabrics. The market opportunity is extremely large and is thought to exceed $1.86 \times 10^8 m^2$ for commercial buildings (flat roofing) in the United States alone. Much of the development for roofing applications was done in Europe and slowly became accepted in the United States. Although fiber glass fabrics have been the largest volume nonwoven consumed in roofing, spunbonded polyester and polypropylene have made considerable penetration (61). A significant difference between glass and polyester is the ability of polyester to flex and stretch without damage to the filaments. Because rooftops are known to expand and contract with seasonal changes, fabrics of polyester are less susceptible to damage from sudden temperature fluctuations which induce rapid dimensional changes.

Spunbonded polyester is basically a carrier for bituminous waterproofing membrane. Here spunbonded fabric is saturated with bitumen and serves to provide integrity and dimensional stability to the bitumen. As bitumen coatings modified with elastomeric polymers, such as atatic polypropylene (APP) or sequenced butadiene–styrene (SBS), became accepted as improvements over unmodified bitumen, changes occurred in the installation and manufacture of membranes. Historically, built up roofs were made *in situ* by mopping hot bitumen into organic felts that had been placed on the roof decking. In the 1990s, the roof membrane is manufactured under tightly controlled conditions in a factory distant from the site of application. The spunbonded fabric is typically saturated with modified bitumen by dipping into tanks of hot bitumen that are heated up to 200°C. Excess bitumen is metered off and the cooled surfaces are coated with a release material such as talc to prevent blocking together on the roll. The composite is packaged into rolls approximately 1 m wide and 50 m long. The rolls are then shipped to the job site and applied to the flat roof surface by slowly unrolling while heating the underside to tackiness with a propane torch to enable it to adhere to the roof deck. Adjacent rolls are lap seamed to provide for watertightness across the roll-width of the roof. Spunbonded polyester is also used in the so-called cold roof method, typically used for roof maintenance. In this method, a cold mastic is applied over a fiber glass base sheet, followed by more mastic, another layer of polyester, more mastic, and a final topcoat.

In Europe, particularly France and Germany, bitumen-coated spunbonded polypropylene fabrics are widely accepted as rooflinings under concrete, clay, or ceramic tiles for pitched roof construction. In this use, the spunbonded fabric is a critical element of the membrane because the rooflining is draped between roof rafters and depends on the strength of the spunbonded for self-support during the life of the roof. The bitumen coating renders the spunbonded waterproof and allows it to shed any water that might leak between the tiles during snow and rainstorms. Spunbonded fabrics coated with nonbituminous materials such as acrylics have also been used in Europe. Rooflinings represent a considerable opportunity for spunbonded fabrics in Europe and in the sunbelt areas of the United States.

Nonwoven fabrics have played an important part in the development of geotextile applications. Needle-punch fabrics manufactured from either staple fibers or spunbonded continuous filaments have found worldwide acceptance based on field performance. In 2000, it is estimated that North America consumed ~300 million m^2 of geotextiles (62).

Many fabric manufacturers have dedicated considerable effort to the marketing of their products in order to participate in this growth area. Geotextile fabrics function by being porous to water but not to the fines of the soil, thereby permitting them to effectively separate or partition soil fines from other elements. The net effect is keeping the soil from eroding or moving position. For example, in the construction of a new road the geotextile can separate the subsoil from the gravel or aggregate. By maintaining this separation, the aggregate is not driven into the subsoil base by the weight of vehicles nor are soil fines pumped up into the aggregate since the geotextile filters out their passage. However, water is freely transported through the fabric enabling proper drainage without buildup of hydrostatic pressures. Thus the road resists rutting and sustains the weight of traffic more effectively while permitting proper drainage of water through the fabric. In drainage ditches, perforated drainage pipes are often wrapped with a geotextile prior to installation to prevent them from becoming clogged.

Spunbonded fabrics are effective filters in that they are layered structures of relatively fine fibers, the three-dimensional structure of which creates a torturous path. Even relatively thin spunbonded fabrics (eg, 0.2–0.25 mm) present a significant challenge to the passage of soil fines and are suitable for use in some filtration applications. The porosity of geotextile fabrics is classified by means of several procedures such as flux (volume flow/area per time) and equivalent opening size (EOS), which is a measure of the apparent pore size of the openings in the fabric. The flux measures the porosity to liquid water, and the EOS measures the porosity to solid particles of a known diameter. Literature is available on limitations of particular styles of fabrics within an application.

Growing university research ensures that users and specifiers will continue to become more sophisticated in their methodology and more demanding of manufacturers. Excellent textbooks are available for both students and practicing engineers (53,63).

A growing use for spunbond fabrics is in landscaping where lightweight (eg, 70–100 gsm) fabrics are sold as landscape fabrics for weed control. Typically these fabrics are placed in landscape beds over the soil and covered with stones or mulch where they resist the emergence of weeds from the soil while allowing water to drain through into the soil. They will not, however, prevent seed germination in the mulch and they should be viewed as only a partial solution for weed control.

Other durable applications such as interlinings and coating–laminating substrates do not appear to offer much near-term opportunity for growth for spunbonded fabrics. In interlinings, however, spunlaced nonwovens have received wider acceptance because of the outstanding drape and softness previously unavailable from any other fabric.

Spunbonded fabrics have a relatively small percentage of the coated fabric market which is dominated by other nonwovens. Needle-punched nonwovens offer more of the bulk and resiliency required for functionality in automotive and furniture seating.

Many filtration requirements are fulfilled by spunbonded structures and a growing but technically complex market has developed since the 1970s (64). Applications include pool and spa, air particulate, coolant, milk and sediment for household water.

A recent development is the automatic shaping of heavyweight spunbonded and needlepunched fabrics into three dimensional honeycomb-shaped structures that allows, for the first time, the use of spunbonded fabrics as a three dimensional solid object (65). This platform process opens up vast new applications previously unreachable by the two-dimensional nature of these fabrics. Spunbond fabrics can be automatically converted into products as diverse as matresses, sandwich panels, air flow straighteners, sand walls for temporary dikes and drainage containment blocks. There is high interest in third world areas for the very inexpensive mattresses that can be produced from spunbond lines already in place in these areas. This process holds promise to open up large new markets for existing spunbonded fabrics.

8.2. Spunbonded Markets: Disposable Applications. The outlook for spunbonded disposable applications indicates a 5–7% compounded annual growth forecast (66). Spunbonded plant capacity installed or announced since the 1980s has been aimed at satisfying increased demand largely for disposable applications. Key markets are components for baby diapers, training pants, and incontinence devices, surgical gowns and drapes, medical sterilization wrap, protective clothing, and envelopes [see Fig 13, (59)].

The use of spunbonded fabrics as coverstock for diapers and incontinence devices has grown dramatically since 1980 and by 1995 consumption exceeded 2 billion square meters in the United States and is forecast to reach 3.5 billion within 5 years (67). A coverstock functions as a one-way medium through which urine is transported into the absorbent core. The laminar structural feature of the coverstock helps keep the skin of the user dry and comfortable. Figure 14 shows the uses of nonwovens in a premium price diaper (68). Although 17 g/m^2 spunbonded polyester was originally used in diaper coverstock it has been supplanted entirely by 15–17 gsm weight spunbonded polypropylene.

Changes in diaper design have made disposable diapers among the most highly engineered disposable products in the world, and involve not only coverstock but the nature of the absorbent layer and design of the diaper itself. The use of form-fitting legs with leg cuffs for leak protection, as well as refastenable closures, has accelerated the acceptance of disposable diapers for both infants and adults. Spunbonded fabrics are used in several major components of the diaper, including coverstock, leg cuffs and backsheet (68). Spunbonded coverstock is also widely used in feminine napkins and to a limited extent in tampons. The conversion of eastern European countries to market economies has created increasing demand for disposable diapers and consequently spunbonded polypropylene coverstock. Other areas of the world showing higher penetration of disposable diapers are South America and China.

The uses of spunbonded fabrics as fabrics in diapers and other personal absorbent devices will most likely remain unchallenged for the near term. Virtually any other nonwoven production method appears to be at a cost disadvantage opposite spunbonded polypropylene. Perforated films lack tactile feel and are largely limited to use in femine napkins. There have been composite products developed from meltblown and spunbonded combinations, generally where improved hydrophobicity is desired. These products can be produced on-line at relatively low additional cost and offer high value to diaper manufacturers.

In medical applications, great progress has been made in the substitution of traditional reuseable woven materials with higher performing spunbondeds (69). Historically, flash spunbonded polyethylene was the first 100% spunbonded to find limited acceptance in medical uses such as disposable operating room gowns, shoe covers, and sterilizable packaging. Other spunbonded fabrics of polypropylene or nylon found some acceptance as cellulosic composites with the lightweight spunbonded serving to add physical strength to the composite. Over the last decade composite structures of spunbond–meltblown–spunbond polypropylene (SMS) have gained wide acceptance in operating room gowns and sterilizable (CSR) wrap. Structures made of spunlaced polyester–cellulose are also widely used but have lost market share to SMS due to the higher barrier of SMS.

Operating room gowns worn by members of the surgical team place very high demands on fabric properties. Key requirements include breathability for comfort, low noise, absolute barrier to fluid penetration, low particle generation (linting), sterilizability, and impermeability to bacteria and viral particles. Woven cotton fabric gowns were worn for many years but had to be reused because of high cost. This required the added expense of laundering the garments and the need to decide when each garment was no longer suitable for use in the operating room. Several studies comparing disposable and reusable fabrics have been conducted in an attempt to correlate the effect of fabric linting with post-operative infections. Although no correlation has yet been established, some studies have demonstrated that single-use fabrics generate significantly fewer particles than cotton fabrics (70). Other studies have indicated that the rate of postoperative wound infection is reduced with the use of high barrier spunbonded olefin gowns and drapes. Concern for viral transmission [eg, acquired immune deficiency syndrome (AIDS)] has increased the demand for disposable, higher barrier fabrics without loss of comfort.

Medical devicesor trays of devices are often sterilized after the nonsterile device is sealed in a package. A part of this package, such as the lid, is made from flashspun or spunbonded–meltblown fabric because it possesses the unique property of permitting the sterilizing gas of ethylene oxide to pass through while remaining impenetrable to bacteria. These fabrics are manufactured to tightly controlled standards to ensure the highest resistance to bacterial–viral penetration. The superiority of a spunbonded fabric to the alternative coated papers has been reviewed (71).

Spunbonded fabrics have been utilized as shoe covers in the operating room. The covers are usually sewn with an elastic band at the top to allow them to be held snugly in place. The fabric requirements are toughness, some porosity for comfort, nonlinting, resistance to slippage, and a nonstatic characteristic. In order to achieve the last property, the fabric is usually treated with an antistatic coating. Failure to use a nonstatic fabric may cause sparks to be generated in the operating room environment which could damage sensitive electronic devices or lead to fire. Other medical applications for spunbonded fabrics include head covers, face masks, drapes, and other uses requiring breathable–barrier properties.

A large-volume area for spunbonded fabrics is the disposable protective clothing market (72). To a great extent the demand for high performance disposable protective clothing has tracked high technology manufacturing, environmental demands and more recently the concern from biological or chemical terrorism. The manufacture of particulate sensitive electronic components such as silicon chip integrated circuits resulted in the construction of clean rooms, where the generation of any particulate was in part controlled through the use of nonlinting yet comfortable clothing made from spunbonded fabrics. Because the spunbonded fabrics are made of continuous filaments, practically no linting results. At the same time the structure allows the passage of moisture and air, thus helping the wearer to remain comfortable. The spunbonded garment is worn over other clothing, therefore the maximum pore size must be sufficiently small to prevent the passage of lint and other particles through the garment and into the clean room.

The 1980s saw the beginning of the removal of large quantities of asbestos (qv) from schools and buildings, creating the need for clothing which could not be penetrated by small asbestos fibrils, yet inexpensive enough to permit daily disposal. Certain spunbonded and spunbond–meltblown laminate fabrics demonstrate excellent resistance to asbestos penetration from particles as small as 0.5 μm.

Similarly the handling of hazardous materials has prompted the need for affordable, disposable protective clothing. Once exposed to toxic waste, pesticides, or radioactive materials, the clothing itself is transformed into a hazardous material and must be disposed of to prevent spreading of contamination. Garments that demand the utmost in protection at the lowest price are often made by extrusion coating, laminating spunbonded fabrics with polyethylene, or laminating the fabric to poly(vinylidene chloride) film.

Packaging applications for spunbonded fabrics are for the most part a specialty area in which paper products or plastic films do not adequately perform. One of the largest packaging applications for spunbonded fabric is high performance envelopes. Although lightweight tear- and puncture-resistant envelopes are not in demand by individual consumers, both large and small businesses have found spunbonded envelopes to outperform those made from conventional paper products. The lighter weight of the spunbonded envelope allows for postal savings and some corporations specializing in overnight delivery have successfully used spunbonded envelopes with excellent results. Coated spunbonded fabrics are used as the outerwrap of coils of steel and aluminum where they outperform alternative materials such as films and papers.

A significant percentage of U.S. synthetic staple fiber production is packaged in bales of extrusion coated spunbonded fabrics, so treated to render the fabric impervious. Synthetic fibers have been shipped worldwide in this manner with great success.

Although other nonwoven processes such as spunlacing have experienced large growth in disposable wipes, spunbonded fabrics have not participated in this segment generally because some cellulosic fibers are required in the wipe and spunbonding cannot readily utilize such fibers.

A reverse-wipe application is seen in the clothes dryer fabric softener sheet wherein the spunbonded fabric is coated with a complex combination of wax, surfactants and perfumes which are released into the environment of a hot clothes dryer to soften and perfume the clothes, as well as provide an antistatic quality. The spunbonded sheet, which must be made of polyester or nylon for temperature resistance, provides a simple and cost-effective medium to store the chemical compounds prior to release in the dryer.

There are many other smaller specialty disposable applications for spunbonded fabrics which vary widely from country to country. These applications include candy wrapping, agricultural coverings, wall covering and packaging.

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Nonwoven Development Partners
LLCP Versacore Industrial Corp.

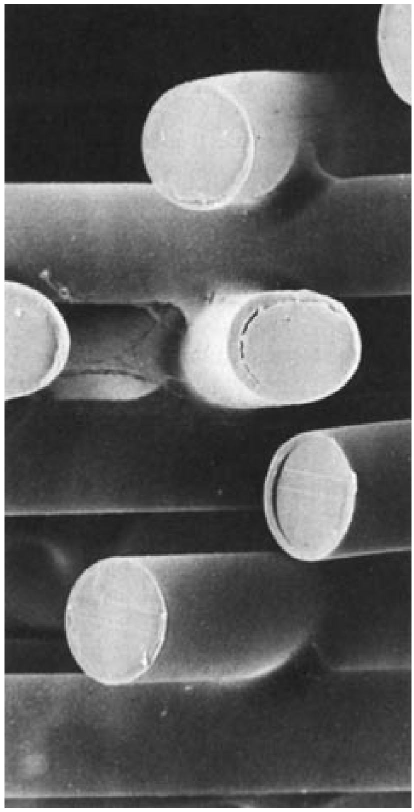

Fig. 1. Microstereo view of the cross-section of skin core filaments.

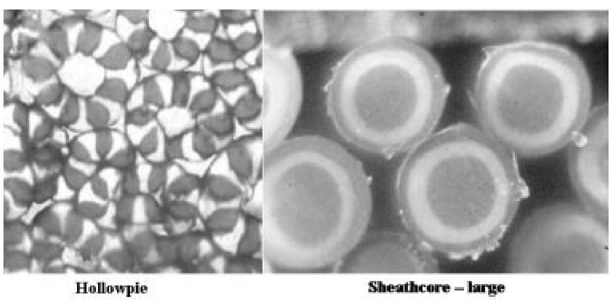

Fig. 2. Bicomponent filament structures (courtesy Hills Inc.).

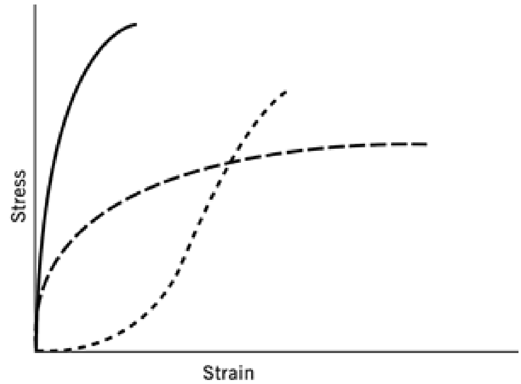

Fig. 3. Typical stress–strain curves of nonwoven fabrics, where (—) is woven; (– – –), thermally bonded nonwoven; and (- - -), needle-punched nonwoven.

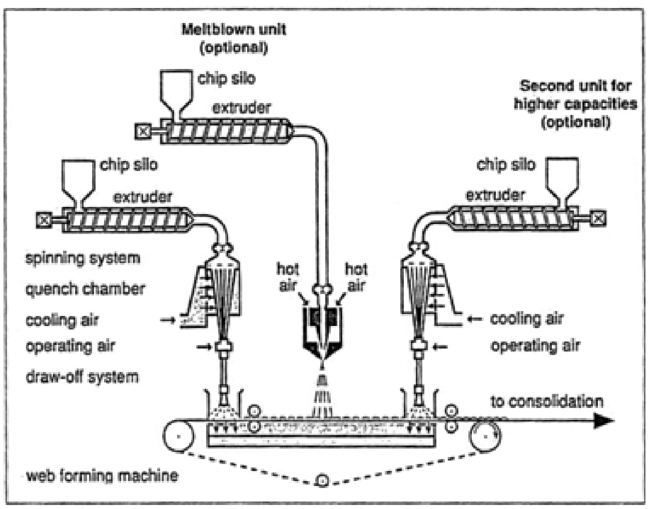

Fig. 4. Typical multibeam spunbonded process (3).

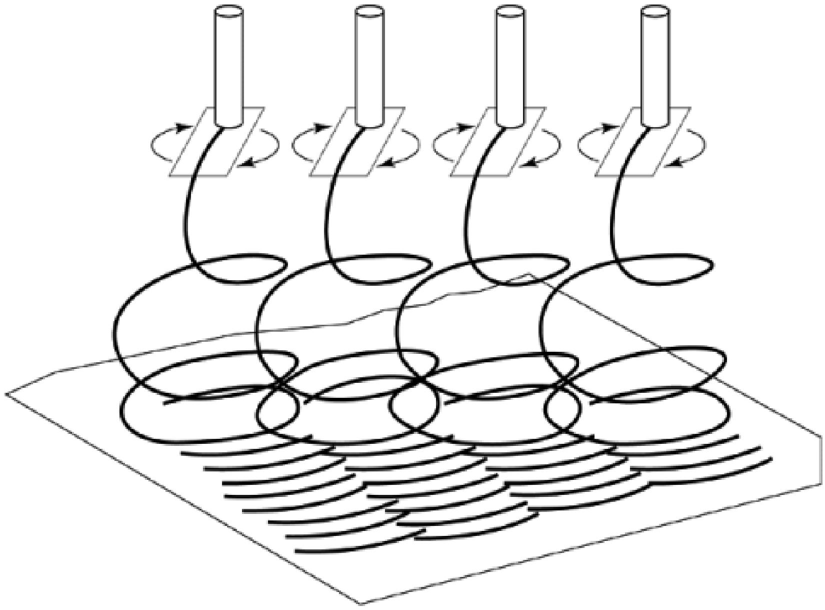

Fig. 5. Deflector plane for separation of filaments.

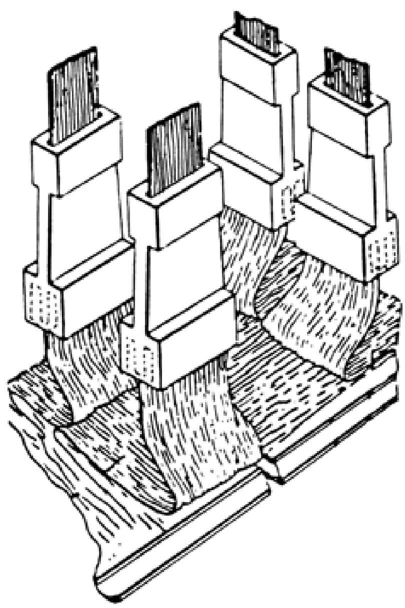

Fig. 6. Web production with predominantly machine and cross-machine direction.

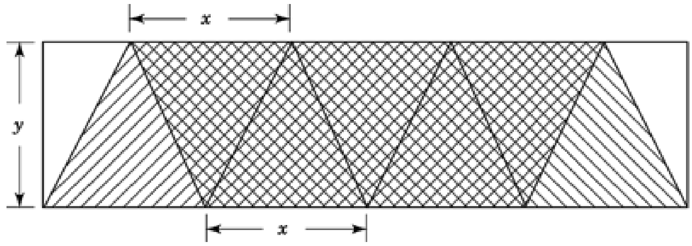

Fig. 7. Laydown pattern diagram.

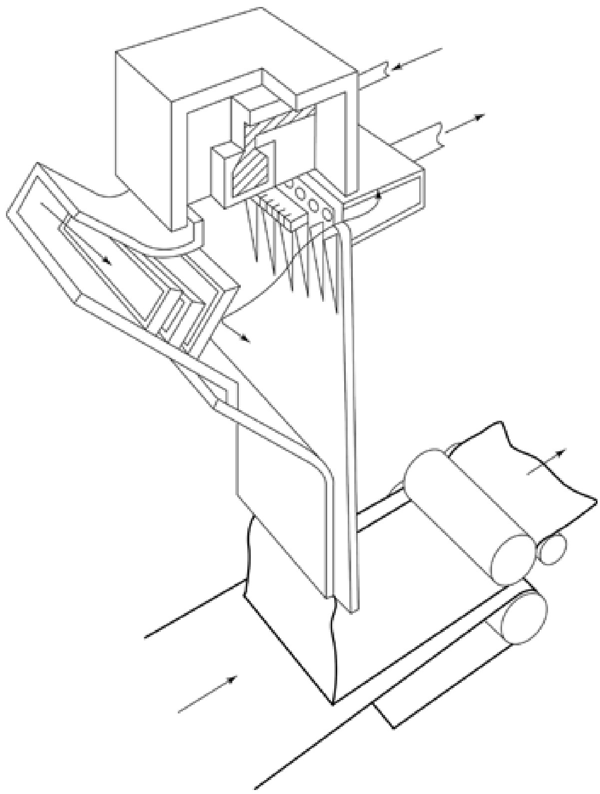

Fig. 8. Curtain spinning process (21).

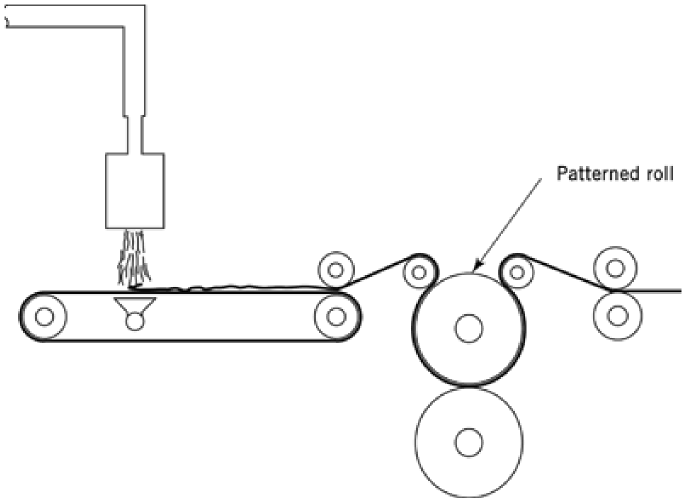

Fig. 9. Pattern bonding roll at the end of a spunbonding line.

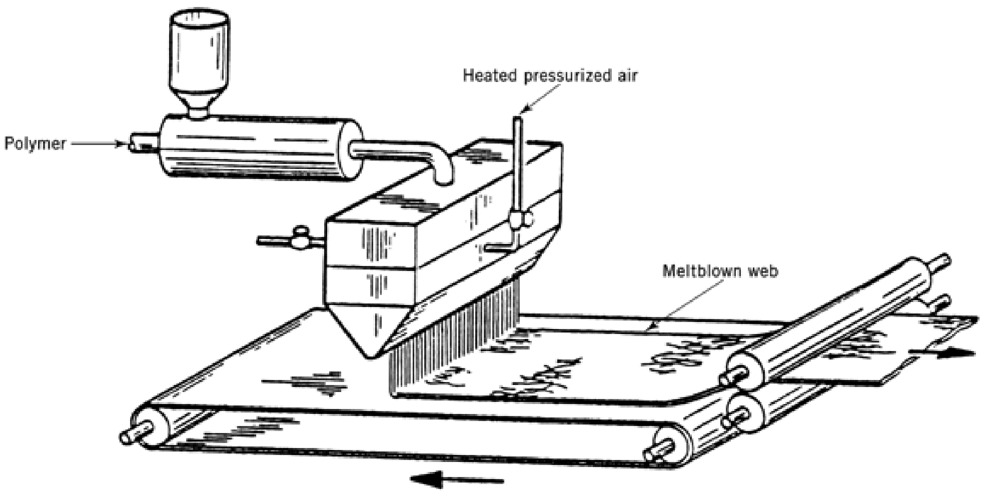

Fig. 10. Schematic of the meltdown process.

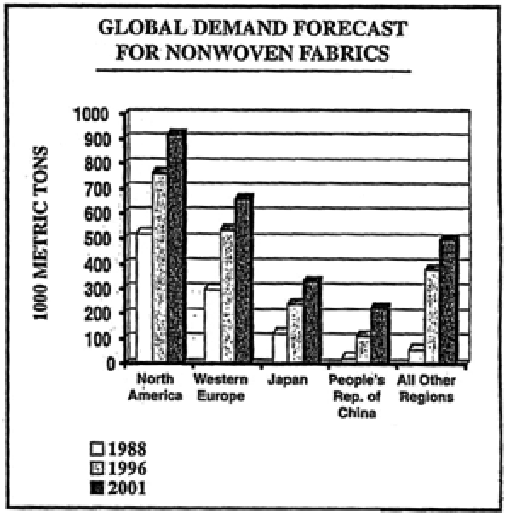

Fig. 11. Global demand for nonwoven fabrics (57).

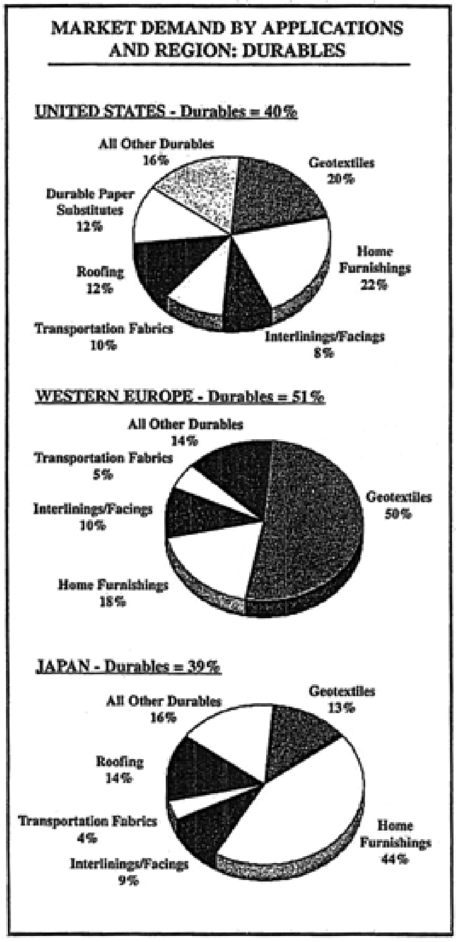

Fig. 12. Durable nonwovens market demand by applications and region (58).

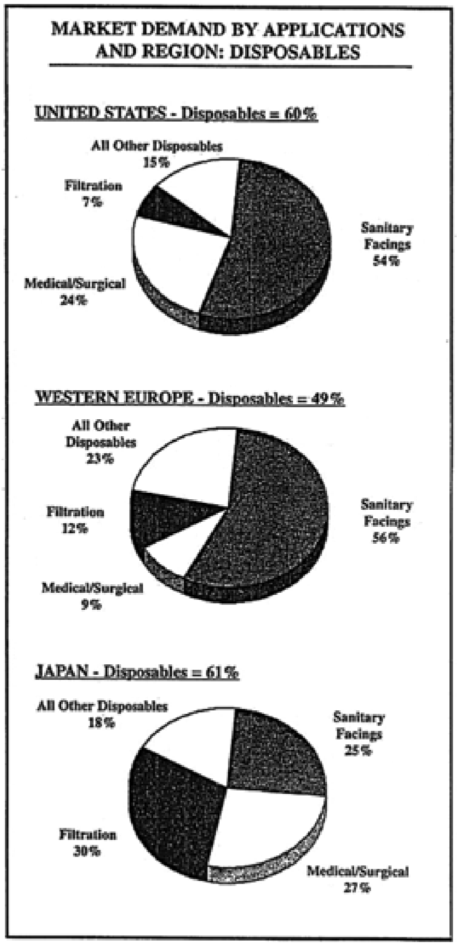

Fig. 13. Disposable nonwovens market demand by application and region (59).

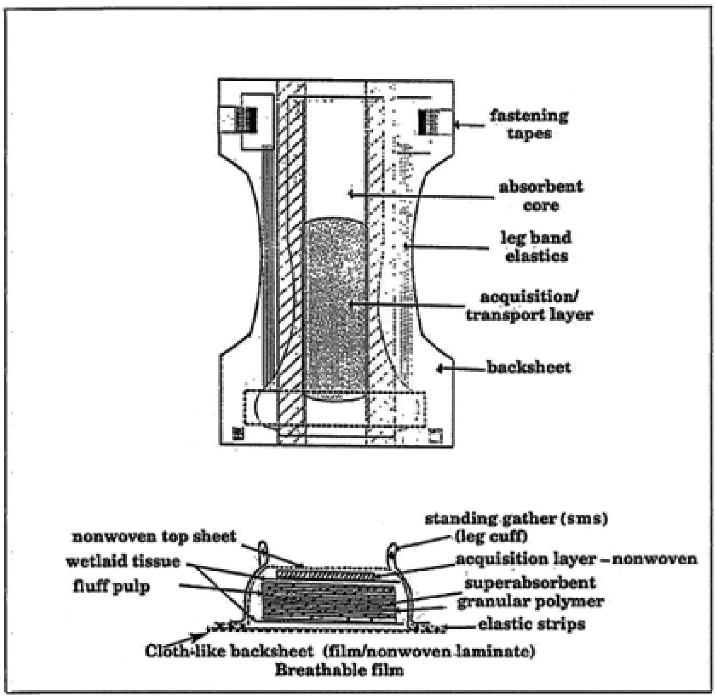

Fig. 14. Components of a modern disposable diaper (56).

Table 1. **Spunbond Producers by Region**

Company	Polymer base	Technology base
	North America	
Ahlstrom	PP	Nordson
American Nonwovens	PP	Ason Neumag
Avgol	PP	Reifenhauser
BBA Nonwovens	PET	via du Pont[a]
	PP	via du Pont[b]
		self-developed
		Reifenhauser
Colbond	PET/PA	via Akzo[c]
DuPont	HDPE, PET	self-developed[d]
First Quality	PP	Reifenhauser
Freudenberg	PET	self-developed[e]
Johns Manville	PET	via Hoechst[f]
Kimberly-Clark	PP	self-developed
PGI Nonwovens	PP	Reifenhauser
		STP Impianti
Texbond	PP	STP Impianti
Western Nonwovens	PA	via Monsanto[g]
	Europe	
BP	PP	Reifenhauser
BBA Nonwovens	PP	Reifenhauser
		Lurgi
		self-developed
NWI (Cartiere Mirano)	PP	NWT
Colbond	PET, PET/PA	via Akzo[h]
Don & Low	PP	Reifenhauser
DuPont	HDPE	self-developed[i]
	PP	self-developed[j]
Fibertex	PP	Reifenhauser
Freudenberg	PET	self-developed[k]
Johns Manville	PET	via Hoechst[l]
Pegas	PP	Reifenhauser
Politex-Freudenberg	PET	self-developed
Polyfelt	PP	Lurgi
Tenotex	PP	self-developed
Texbond	PP	STP Impianti
		self-developed
Terram BBA	PP/PE	via ICI
	South America	
Bidim BBA	PET	via Rhone Poulenc
Companhia Providencia	PP	Reifenhauser
Kami	PP	Reifenhauser
Fitesa	PP	STP Impianti
PGI	PP	Reifenhauser
	Japan	
Asahi	PP, PET, Cupra	self-developed
Chisso	PP, PP/PE	Reifenhauser
Idemitsu	PP	Reifenhauser
Futamura	Rayon	self-developed
Mitsui	PP	self-developed
		Reifenhauser
OJI Paper	PP	Reifenhauser
Teijin	PET,PP	self-developed
Toray	PET	self-developed

Toyobo	PET	self-developed
Unitika	PET, PA	self-developed
	Other Areas	
Avgol (Israel)	PP	Reifenhauser
Cheil (S.Korea)	PP	Reifenhauser
Freudenberg (Taiwan)	PET	self-developed[m]
Hanil (S. Korea)	PP/PET	Kobelco
IndoSyntec (Indonesia)	PET	NWT
Kaymac Industries	PET	via Rhone Poulenc
Kimberly-Clark (Australia)	PP	self-developed
Kolon (S. Korea)	PP/PET	self-developed
Nan Ya (Taiwan)	PP	Lurgi & Reifenhauser
PGI (China)	PP	Reifenhauser
SAAF (Saudi Arabia)	PP	Reifenhauser
Spuntec (S. Africa)	PP	Reifenhauser
Thai Tusco (Indonesia)	PP/PET	via Unitika
Yuhan-Kimberly (S. Korea)	PP	self-developed

[a]Reemay Process.
[b]Typar Process.
[c]Split process.
[d]Flashspun Tyvek Process (HDPE).
[e]Lutradur process.
[f]Began with RhonePoulenc license.
[g]Cerex process.
[h]Split process.
[i]Flashspun process Tyvek process (HDPE).
[j]Typar process.
[k]Lutradur process.
[l]Began with Rhone Poulenc license.
[m]Lutradur Process.

Table 2. **Physical Properties of Spunbonded Products**

Product	Basis weight, g/m^2	Thickness, mm	Tensile strength,[a]	Tear strength,[a] N[b]	Mullen burst, kPa[c]	Bonding method
Accord	69		144 MD 175 XD	36 MD 40 XD	323	point thermal
Bidim	150		495	280	1545	needle-punch
Cerex	34	0.14	135 MD 90 XD	40 MD 32 XD	240	chemically induced area
Colback	100	0.6	300[d]	120		area thermal (sheath-core)
Corovin	75		130	15		point thermal
Lutradur	84	0.44	225 MD 297 XD	85 MD 90 XD	598	copolymer area thermal
Polyfelt	137		585	225	1445	needle-punch
Reemay	68	0.29	225 MD 180 XD	45 MD 50 XD	330	copolymer area thermal
Terram	137	0.7	850	250	1100	area thermal (sheath-core)
Trevira	155		630 MD 495 XD	270 MD 248 XD	1512	needle-punch
Typar	103	0.305	540 MD 495 XD	207 MD 235 XD	825	undrawn segments area thermal
Tyvek	54	0.15	4.6[e] MD 5.1[e] XD	4.5 MD 4.5 XD		area and point thermal

[a]MD = Machine direction; XD = cross-direction.
[b]Unless otherwise noted. To convert *N* to pound-force, divide by 4.448.
[c]To convert kPa to psi, multiply by 0.145.
[d]300N/5 cm = 34.5 ppi.
[e]N/mm; to convert N/mm to ppi, divide by 0.175.

Table 3. **Fibers for Spunbonded Nonwoven Fabrics**

Fiber type	Breaking tenacity, N/tex[a]	Elongation, %	Specific gravity	Moisture regain,[b] %	Approximate melt point, °C
polyester	0.17–0.84	12–150	1.38	0.4	248–260
nylon-6,6	0.26–0.88	12–70	1.14	4.0	248–260
polypropylene	0.22–0.48	20–100	0.91	∼0.0	162–171

[a]To convert N/tex to gf/den, multiply by 11.3.
[b]At 21°C and 65% rh.

Table 4. **INDA Test Methods**[a]

Property	Description	IST Number
absorbency	amt of liquid absorbed and speed of absorption	10.1–3
abrasion	resistance of nonwovens to being worn away	20.1–5
bursting strength	force to rupture nonwoven under water pressure	30.1
electrostatic properties	amt of charge that can build up on a sample	40.1–2
optical properties	opacity: resistance to light being passed brightness: whiteness	60.1–2
permeability	ease of air or water vapor passage under pressure	70.1–2
repellency	resistance of nonwovens to wetting and penetration after exposure to water, salt solutions, alcohol, and hydrocarbon solvents and oils	80.1–9
bacterial	resistance of a nonwoven to penetratration by bacteria in a salt solution under water pressure	
stiffness		
cantilever	tendency for a nonlimp nonwoven to droop as it is pushed over the edge of a surface	90.1
curly	ability of a heavy, stiff nonwoven to push a pendulum aside as it is moved past it	90.2
Handle-O-Meter	ability of a soft, lightweight nonwoven to flex and not drag as it is pushed through an opening	90.3
tear	resistance of a nonwoven to continue to tear after being cut and pulled from both sides	100.1–3
breaking load and elongation	force to break a nonwoven when it is pulled from both ends; extent of stretching before breaking	110.1–4
seam breaking	force needed to break a seam holding two pieces of nonwoven together when the sample is pulled from both ends	
bond strength of laminates	force to separate a nonwoven from another material after they have been laminated together	
internal bond strength	force to pull a nonwoven fabric into two plies	
thickness	how thick a nonwoven is when it is held between a weight and a surface	120.1–2
coefficient of friction	drag when a nonwoven is slid over itself or over a polished surface	140.1
dry cleaning and laundering	shrinkage, loss of strength, ability to be peeled apart experienced by a single fabric or laminate	150.1
linting	extent of particles loosened from nonwoven as it is bent and flexed in air stream	160.1
extraction	amt of material leached out of nonwoven after exposure to hot solvents	190.1

[a]Ref. 53.