INTRODUCTION

Fabrics are items of commerce used in clothing, furnishing, and industrial utility applications. To the untrained hand or eye, any two fabrics of comparable weight, thickness, and openness which are devoid of coloration, patterning, or finish are not easily distinguishable. This circumstance is not all bad, for in reality if two different fabrics perform equally well in any given application, it really matters little if they are not exactly the same or if they were made by different methods. It does matter, however, if one of the fabrics costs more than the other and the more expensive fabric is put to use in an application that does not fully utilize its properties. A fundamental truth about fabrics is that they are engineered structures with properties dependent primarily on their basic components and the manner by which they were constructed. Basic fabric components are fibers, and fabric construction methods are the technologies used to assemble fibers into fabrics. Fabric properties may be envisioned as the primary responses of the engineered structure to physical forces and chemical environments.

Fundamentally, a fabric can be defined as a planar textile structure made by interlooping one or more yarns, interlacing two or more yarn sets, or interlocking networks of fibers, filaments, or yarns. A yarn is a continuous and relatively thin strand of fibers or filaments held together by twist, entanglement, or an external adhesive. Knitting is a yarn interlooping process. Weaving is a yarn interlacing process. Nonwoven processes involve interlocking fiber, filament, or yarn networks. Now, since a filament can be considered to be a fiber of continuous length and yarns are composed of fibers, it can be reasoned that fibers are the common component of all fabrics.

Essentially then, making fabrics (fabric formation processes) can be equated to transforming fibers which are relatively long, thin items and for all practical purposes one dimensional into two dimensional (planar) structures. Further, if the same fibers were used to make fabrics of the same width and weight, then any differences in the fabrics should be due to the manner by which the fibers are assembled. These differences will be reflected in specific properties and characteristics of the fabrics such as uniformity, thickness, porosity, flexibility, and integrity.

This paper is intended to provide a general description of the basic technologies used to make fabrics and an overview of some basic characteristics of the fabrics produced by each technology.

WEAVING

Since the vast majority of fabrics made in the world contain yarn and the predominate method of manufacturing fabric from yarn is weaving, an examination of the weaving process and its extensive diversity merits first consideration. Traditional weaving is the process of mechanically interlacing two sets of yarns at right angles to one another in a
designated order. In a woven fabric, the longitudinal or warp yarns are called ends and the transverse or weft yarns are called picks. The order or pattern of interlacement of ends and picks is called the weave or fabric design. The most basic and extensively used woven fabric is the plain weave in which the warp and weft (filling) yarns are interlaced in alternate order is shown in Figure 1.

![Figure 1. Interlacing of Warp (vertical) and Filling (horizontal) Yarns in a Plain Woven Fabric.](image)

The process of forming a plain fabric by interlacing yarns on a loom is illustrated in Figure 2.

![Figure 2. Fabric Formation by Interlacing Two Yarn Sets on a Loom.](image)

Warp yarns are supplied as parallel strands on a beam. Individual ends of yarn are first threaded alternatively through openings in rows of thin wires called heddles, grouped in frames called harnesses, and then between a second set of wires in a closed comb called the reed. The weaving process consists of three basic operations carried out sequentially: (1) shedding or lifting the harnesses to separate the warp yarns and form a
space for a weft yarn (2) picking or inserting a weft yarn through the shed, and (3) beating-up or moving the reed to the fell point where the "filled-in" yarn is packed next to the previously inserted pick and the cloth is formed. Following the let-off of sufficient warp yarn for the next pick and the take-up of cloth formed, subsequent interlacings are accomplished by alternating harnesses positions during shedding. All looms perform the three primary motions of shedding, picking, and beating-up. Looms made by various machinery manufacturers differ in the manner in which these motions are carried out. Woven fabrics differ according to interlacing pattern and yarn structure and composition.

Fabric Weaves

Interlacing patterns or fabric weaves are determined by the shedding motion, which may be thought of as the brain center of a weaving machine. According to the method of shedding, looms may be grouped into three basic categories: cams, dobbies, and jacquards. Cam looms form sheds by raising and lowering harnesses through the employment of a series of individual cams on a common shaft located across the width of the loom. Cam looms control interlacing patterns by distributing warp yarns into as few as two and as many as 14 harnesses and alternating harness lifting sequences. The plain woven structure can be made by distributing the warp yarns alternatively into two harnesses and alternatively raising and lowering the two harnesses. Placing two warp yarns in each heddle can yield a batiste structure. The same warp arrangement coupled with two pick insertions per shedding motion can yield a basket weave (Figure 3a). The addition of a third harness can yield batiste, basket, 2/1, or 1/2 twill patterns. The addition of a fourth harness can expand loom versatility to include 2/2 (Figure 3b), 3/1, and 1/3 twills, while a fifth harness expands loom capabilities to include warp (Figure 3c) and filling faced satins.

![Figure 3. Basic Weave Patterns.](image)

Practical weft repeat patterns are limited to eight on cam looms; however, this limitation in combination with the number of different harness lifting sequences possible through the use of 14 harnesses can yield a considerable range of fabric constructions. Dobby looms also distribute warp yarns into harness groupings, but individual harnesses in this loom category are controlled by lifting arms or levers located along the length of the loom. Practical weft repeat patterns up to 5000 are possible, expanding fabric interlacing capabilities to hundreds of powers of ten. In jacquard weaving, up to 1344 individual heddles are attached via hooks to a control station called a jacquard head wherein preprogrammed patterns are transformed into warp lifting sequences. As in
Dobby weaving weft repeat patterns up to 5000 are practical, expanding fabric interlacing capabilities even higher. Jacquard design options can be increased to yet another dimension by the addition of multiple heads. Comparative summary of information on shedding is given in Table I.

Table I. Information Summary on Shedding.

<table>
<thead>
<tr>
<th>Primary Function</th>
<th>Controls Woven Fabric Interlacing Patterns (Fabric Design)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Considered by some to be</td>
<td>&quot;The Brain Center of the Weaving Machine&quot;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Method</th>
<th>CAMS</th>
<th>DOBBY HEAD</th>
<th>JACQUARD HEAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heddles</td>
<td>Heddles</td>
<td>Heddles</td>
<td>Heddles</td>
</tr>
<tr>
<td>Control</td>
<td>2-14 Harnesses</td>
<td>up to 32 Harnesses</td>
<td>1344 Individual Hooks</td>
</tr>
<tr>
<td>Practical Weft</td>
<td>8 picks</td>
<td>5000 picks</td>
<td>5000 picks</td>
</tr>
</tbody>
</table>

Using the same warp and filling yarns, fabrics with different weights, strengths, elongations, and porosities can be made by altering the number of picks per unit length, yarn let-off, and fabric take-up. A change in filling yarn size and structure (twist for example) will yield yet another set of fabric properties. Changes in warp yarn size or structure and the number of warp yarns per unit width will also yield fabrics with different properties, as will changes in fiber type and blends of various fibers. This degree of versatility on even the simplest loom is one reason that more fabric is made by weaving than any other fabric formation technology.

Weaving Productivity
Over the past forty years, weaving productivity has been boosted by innovations in weft insertion and the construction of wider looms. On conventional looms, weft insertion is accomplished by placing a filling supply package (quill) in a shuttle and propelling the shuttle through the warp shed from one side of the loom to the other. Two bottlenecks are inherent in this method: accelerating and stopping a 30 cm shuttle weighing about 1.5 kg for each pick and replenishing the filling yarn supply at frequent intervals. Shuttleless looms overcome these bottlenecks by replacing the shuttle with small gripper projectiles, yarn grippers mounted on extending and retracting rapiers, or jets of water or air which withdraw the filling yarn from large packages placed on the side of the loom. The Sulzer weaving machine is an example of a gripper projectile loom. This machine uses a series of 10 cm, 50 gram gripper-shuttles. Individual gripper-shuttles grip and propel the filling yarn through the shed, release the yarn, and attach to a conveying chain located underneath the warp yarns for return to the filling package. The filling yarn is cut after each weft insertion and positioned for pick up by the next gripper-shuttle. Most rapier looms use two rigid, telescoping, or flexible gripper support
arms which meet at the center of the loom and transfer the filling yarn from one gripper head to the other. In jet weaving, a stream of fluid is used to carry the filling yarn through the warp shed. Water jet looms were the first of this type of insertion system to achieve widespread commercial success and are still used extensively to weave fabrics from hydrophobic continuous filament yarns such as polyester and nylon. Over the past several years, however, air jet looms have become the weft insertion system of choice, due to their ability to weave wider fabrics and both spun and filament yarns. A comparison of moderately efficient productivity levels as measured by the rate of weft yarn insertion in picks per minute and meters per minute is provided in Table II.

### Table II. Weaving Weft Insertion Rate Comparison.

<table>
<thead>
<tr>
<th>Machine Type</th>
<th>Picks/min.</th>
<th>Meters/min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic Shuttle Loom</td>
<td>220</td>
<td>530</td>
</tr>
<tr>
<td>Gripper Projectile</td>
<td>450</td>
<td>1200</td>
</tr>
<tr>
<td>Double Rigid Rapier</td>
<td>400</td>
<td>850</td>
</tr>
<tr>
<td>Double Flexible Rapier</td>
<td>415</td>
<td>1000</td>
</tr>
<tr>
<td>Water Jet</td>
<td>925</td>
<td>1600</td>
</tr>
<tr>
<td>Air Jet</td>
<td>800</td>
<td>1625</td>
</tr>
</tbody>
</table>

As an index of woven fabric production rate, a contemporary air jet loom three meters wide can produce a 60 end by 60 pick fabric in the range of 2.0 to 6.0 oz/yd² (65 to 200 g/m²) at a rate of 55 m²/hr. The same loom can produce 20 x 12 gauze or scrim fabric at a rate of 275 m²/hr. Again, the properties of woven fabric can be changed by changing fibers, yarn structure, yarn size, the number of yarn interlacings, and the yarn interlacing pattern. The number of unique fabrics attainable by the weaving process defies computation. Weaving is a simple, yet sophisticated fabric formation process with a history extending several thousand years and a development heritage that spawned the industrial revolution.

**KNITTING**

Knitting may be considered to be the most direct method of converting yarn to fabric, since a planar structure can be made by intermeshing loops from a single yarn strand into a two dimensional array. In a knitted fabric, the longitudinal loops are called wales and the horizontal loops are called courses. The loop configuration or interlooping pattern is called the stitch. The actual loop formation operation may be envisioned by examining knitting as a craft or the familiar domestic avocation of hand knitting. In hand knitting a yarn is progressively transformed into a series of loops as a course on one long pin or needle and then transferred to a second needle concurrent with the formation of individual loops in a new course. In machine knitting, each loop is formed as a wale in the hook of a separate needle. The loop becomes a stitch upon being transferred or cast from the needle and pulled through a previously formed loop.
Knitted Fabric Types
Knitted fabric can be classed into two general categories according to the type of
machine used to make the fabric, namely, weft and warp. An abbreviated summary of
knitted fabric production methods is outlined in Table III. All knitting machines have four
common components: yarn supply, knitting elements, fabric take-down, and fabric
collection. In weft knitting, yarn is supplied on individual packages. The yarn supply in
warp knitting is provided on beams similar to those used in weaving. The knitting
elements are (1) a yarn carrier, (2) a needle, (3) a needle bed, and (4) a sinker; their
function is to carry out the knitting cycle as follows: the yarn carrier guides an individual
yarn to the needle which forms the stitch which in turn is removed downwardly or sunk
from the needle with the assistance of the sinker. Fabric take-down is a mechanism
which tensions the fabric and pulls it downward form the knitting elements. Fabric
collection is a roll take-up device. Two needle types are common: latch needles and
beard needles. Latch needles are used on weft knitting machines; both latch and beard
needles are used on warp knitting machines. In weft knitting, a single yarn passes
through each needle and each needle is housed in an individual slot (trick) where it
moves independently of every other needle to form loops in a sequential manner and
produce either tubular or flat fabric across the courses (weft direction) with one yarn in
each course. In warp knitting, the needles are affixed to movable bars and each needle
is provided with its own yarn; all needles in a bar knit at the same time to form loops in a
parallel manner and produce flat fabric along the wales (warp direction) with multiple
yarns in each course. Weft knitted fabrics include jersey, rib, and interlock (double knit)
structures. Tricot and raschel are warp knits.

Weft Knitting
The cycle for making a plain weft (jersey) structure is illustrated in Figure 4.

Figure 4. Weft Needle Movement.
With reference to Figure 4, latch needles are located in slots (tricks) at fixed spacings, x, (the gauge) around a rotating cylinder. At position 1, the top of the needle is parallel with the verge, v, and has begun its upward movement; the loop from the previous course is contained between the hook and the closed latch. At position 2, the needle has risen through the loop forcing the latch to open. At position 3, the needle has completed its upward movement, the loop rests in the throat of the needle, and a new yarn is positioned for looping. At position 4, the needle has begun its downward movement, the new yarn has been grasped in the hook of the needle, and the old loop has forced the latch to close. At position 5, the needle has completed its downward movement, the new loop has been pulled through the old loop by an amount equivalent to the stitch length, s.

As illustrated in Figure 5, the jersey knit structure has two distinct surfaces, the technical face and the technical back.

![Figure 5. Technical Face (a) and Technical Back (b).](image)

The technical face surface is relatively smooth and the side legs of the loops provide an appearance of columns of Vs along the wales. On the technical back, the tops of the loops provide an appearance of columns of intermeshed semi-circles along the wales. This fabric construction is the most basic weft knit structure, provides a maximum covering power, and is the most economical to produce. When stretched in the width direction, plain weft fabrics will recover up to 40 percent, but tend to curl when cut. Also, if a yarn is snagged or broken, the fabric will unravel or ladder from the face at the course knitted first, or from the back from the course knitted last.

Referring again to Figure 4, two additional interlooping geometries can be envisioned by examining the height to which a needle is raised during the cycle. Should the needle be raised to a level intermediate between positions 1 and 2 (the rest position), the previous loop would not leave the hook area and the feed yarn would not enter the hook; consequently, the old loop would not be cast off and the new yarn would form a float rather than a loop. The resulting structure, illustrated in Figure 6a, is appropriately called the float stitch. Should the needle be raised to a level intermediate between positions 2 and 3 (the tuck position), the previous loop would not pass over the latch and the feed yarn would enter the hook; consequently, both the new yarn and the old loop would form a new loop consisting of two yarns. The resulting structure, illustrated in Figure 6b, is called the tuck stitch. A fourth interlooping arrangement, called the purl or reverse plain...
stitch, has identical face and back surfaces. These four stitches-the plain, miss, tuck, and purl-or combinations thereof are fundamental elements of weft knitted fabrics.

![Figure 6. Float Stitch (a) and Tuck Stitch (b).](image)

Basic double-sided, double-thickness weft knits are rib and interlock. Both require two sets of needles and are made on either circular or V-bed machines. The needle beds are oriented at 90 degrees with the individual needles arranged (gated) in an aligned or staggered configuration. An illustration of needle gating and a simple 1x1 rib fabric is provided in Figure 7.

![Figure 7. Needle Gating for a 1x1 Rib Fabric.](image)

A characteristic of this structure is that wales of face stitches and wales of reverse (back) stitches are knitted on each side of the fabric resulting in a vertical cord appearance. The 1x1 rib has twice the width-wise recoverable stretch as the plain weft, relaxes by about 30 percent of its machine width and does not curl when cut. An illustration of needle gating and a simple interlock fabric is provided in Figure 8.
Figure 8. Needle Gating for Interlock (double knit) Fabric.

A characteristic of the interlock structure is that wales of face loops appear on both sides of the fabric and are aligned so that the reverse stitches are hidden. Compared to plains and ribs, interlock fabrics are more dimensionally stable and less recoverable.

**Warp Knitting**

Warp knitted fabrics are somewhat comparable to woven fabrics in the respect that both make flat fabric from beams of yarn and each yarn is individually guided into the fabric formation zone. Individual yarn guides in a weft knitting machine are mounted on bars that function like harnesses in a weaving machine to provide design capabilities. As outlined in Table III, each yarn has its own needle and all needles in a needle bar knit in unison to interloop yarns along the length of the fabric (wale direction).

<table>
<thead>
<tr>
<th>WARP KNITTING</th>
<th>WEFT KNITTING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yarn is supplied from a beam</td>
<td>Yarn is supplied from individual packages</td>
</tr>
<tr>
<td>Beard needles and latch needles are used</td>
<td>Latch needles are used</td>
</tr>
<tr>
<td>Each needle has its own yarn</td>
<td>A single yarn passes through each needle</td>
</tr>
<tr>
<td>Needles are fixed in a moveable bar</td>
<td>Needles are housed in individual slots (tricks)</td>
</tr>
<tr>
<td>All needles knit at the same time (parallel knitting cycle)</td>
<td>Each needle knits independently (sequential knitting cycle)</td>
</tr>
<tr>
<td>Many individual yarns in each course</td>
<td>One yarn in each course</td>
</tr>
<tr>
<td>Fabric is formed along the wales</td>
<td>Fabric is formed across the courses</td>
</tr>
<tr>
<td>Fabric is made in a flat form</td>
<td>Fabric is made in either tubular or flat form</td>
</tr>
<tr>
<td>Each machine revolution produces one course (row) of stitches</td>
<td>Each machine revolution produces one course (row) of stitches for each yarn feed</td>
</tr>
<tr>
<td>Production rate=machine rpm</td>
<td>Production rate=machine rpm x # of feeds</td>
</tr>
<tr>
<td>Fabric is relatively stable dimensionally)</td>
<td>Fabric stretches, but unravels</td>
</tr>
<tr>
<td>Tricot and Raschel are examples</td>
<td>Jersey, rib, and Interlock (double knit)</td>
</tr>
</tbody>
</table>

The warp knit stitch is formed as a result of a yarn being wrapped around a needle and pulled through a previously formed stitch. The stitch geometry consists of two parts,
a loop portion (called the lap) and an extended leg portion (called the underlap) and may take an open or closed form as illustrated in Figure 9.

Figure 9. Warp Knit Stitch Geometry.

Warp knitted fabric has distinct face and back surfaces. The face surface can be described as a series of slightly angled stitches alternating along the vertical direction of the fabric; the back surface can be described as a series of floats slightly alternating across the width of the fabric. The face stitches are the result of the yarn looping around the needle; the floats (laps or underlaps) are the result of the yarn alternating from needle to needle.

A plain warp (tricot) structure and the cycle for making it are illustrated in Figure 10.

Figure 10. Plain Warp (tricot) Structure and Warp Knitting Cycle.

With reference to Figure 10, the elements are a warp yarn, yarn guide, beard needles, presser bar, and sinker. At position 1, the needles are shown at their highest point, the previous loops are on the stems of the needles, and the sinker is holding the fabric. At position 2, the guide has carried yarn from the left wale to the right needle. At position 3, the needles have begun their downward movement, the guide has carried yarn to the far side of the right needle, yarns are between the needle beards and hooks, the sinker has released the fabric, and the presser bar has begun its movement toward
the needle beards. At position 4, the presser bar has closed the beards, new yarns are in the needle hooks, the needles pull the new yarns through the previous loops. At position 5, the needles have reached their lowest point, previous loops have been cast (knocked) off, the sinker holds the fabric, the guide has begun its movement to carry yarn from the right wale to the left needle. The cycle is completed when the needles are moved to their highest point.

Tricot fabrics exhibit uniform porosity and dimensional stability, do not unravel, and most always are made from continuous filament yarns knitted with beard needles. Fabric weight and thickness are determined by the size of yarn used and the number and type of stitches per unit area. Tricot machines employ up to four guide bars and range in gauge (needles per inch) from 14 to 36. As a index of tricot fabric production rate, a machine five meters wide operating at 1500 rpm and knitting a stitch 0.25 cm in length can produce fabric at a rate of some 1200 m² per hour.

Raschel fabrics are produced in flat form using machinery that operates on the same knitting principle as tricot. Major differences between raschel and tricot machines are that raschel machines uses latch needles and are fitted with up to 48 guide bars. Distinguishing features of raschel fabrics include the use of spun yarns, open constructions, intricate designs, and surface effects.

NONWOVENS

Nonwoven fabrics are flat, flexible, porous sheet structures which are produced by interlocking layers or networks of fibers or filaments, or by perforating films. Processes for manufacturing nonwoven fabric can be grouped into general technology bases: textile, paper, extrusion, or hybrid. The textile technology base includes garnetting, carding, and aerodynamic forming of textile fibers into selectively-oriented webs. Fabrics produced by these systems are referred to as dry laid nonwovens and carry terms such as "garnetted", "carded", and "air laid." Textile based nonwoven fabrics or fiber network structures are manufactured with machinery designed to manipulate textile fibers in the dry state. Also included in this category are bonded yarn structures, structures formed from filament bundles (tow), and fabrics composed of staple fibers and stitching threads.

The paper technology base includes dry laid pulp and wet laid (modified paper) systems designed to accommodate synthetic fibers as well as wood pulps. Fabric produced by these systems are referred to as "dry laid pulp" and "wet laid" nonwovens. Paper based nonwoven fabrics are manufactured with machinery designed to manipulate short fibers suspended in a fluid.

The extrusion technology base includes spunbond, meltblown, and porous film systems. Fabrics produced by these systems are referred to individually as "spunbonded," "meltblown," and "textured or "apertured film" nonwovens; or, generically, as "polymer laid" nonwovens. Extrusion based nonwoven fabrics are manufactured with machinery associated with polymer extrusion. In polymer laid systems fiber structures are simultaneously formed and manipulated.

The hybrid technology base includes (1) fabric/sheet combining systems, (2) combination systems, and (3) composite systems. Combining systems employ lamination technology or at least one basic nonwoven web formation or consolidation technology to join two or more fabric substrates. Combination systems utilize at least
one basic nonwoven web formation element to enhance at least one fabric substrate. Composite systems integrate two or more basic nonwoven web formation technologies to produce web structures.

As outlined in Figure 11, the basic nonwoven manufacturing systems have four principal elements or phases of manufacturing: fiber selection and preparation, web formation, web consolidation, and finishing.

Figure 11. Basic Nonwoven Manufacturing Systems.

From the manufacturing flow matrix provided in Figure 11, the routes for producing most nonwovens can be traced and additional fundamental points regarding the general nature of nonwovens can be inferred, namely:

1. nonwovens are fiber material dependent;
2. individual fibers or fibrous materials are arranged in two or three dimensional networks;
3. fiber networks are interlocked to yield flat, flexible, porous sheet structures in the form of rolls; and
4. rolls can be provided engineered properties and are prepared for conversion to end-use items.

These elements are interrelated further in that optimum product performance and maximum processing efficiency are a function of their mutual compatibility. From a practical standpoint, the fiber or polymer must interact or "process" freely with the dynamics of web formation, and the resulting fiber network must be in register with the interlocking arrangement or media in order for the fabric structure to transmit the maximum potential inherent in the properties of the fiber.

A key factor in the evolution of the various nonwoven manufacturing technologies has been the development of means to utilize commodity fibers and polymers and control individual fiber placement, fiber-to-fiber bonding, and fabric surface energy while
employing basic principles known to textile, paper, and plastic scientists, technologists, and practitioners. From a practical standpoint, the fiber or polymer must interact or "process" freely with the dynamics of web formation, and the resulting fiber network must be in register with the interlocking arrangement or media in order for the fabric structure to transmit the maximum potential inherent in the properties of the fiber. Ultimately, in order for a nonwoven to be totally effective and fully efficient the fabric roll must be transformed to an end-use shape whose performance reflects the position characteristics of the fiber.

**General Characteristics of Nonwovens**
Each nonwoven process, like each nonwoven product, at some phase has special, if not unique, fiber requirements. Also, because the range of fabric properties which can be engineered from each technology employed and the physical and chemical environments of each system are different, all nonwoven processes can not accommodate all available fiber types. In general, textile-technology based processes provide maximum product versatility, since most textile fibers and bonding systems can be utilized and conventional textile fiber processing equipment can be readily adapted with minimal capitalization. Extrusion-technology based processes provide somewhat less versatility in product properties, but yield fabric structures with exceptional strength to weight ratios (spunbonds), high surface area to weight characteristics (melt blown), or high property uniformities per unit weight (textured films) at modest capitalization levels. Paper-technology based nonwoven processes provide the least product versatility and require extensive capitalization, but yield outstandingly uniform products at exceptional speeds.

**Nonwoven Manufacturing Methods**
In the manufacture of textile-technology based nonwovens, discontinuous fibers are formed into parallel, two-dimensional layered, two-dimensional isotropic, or three-dimensional random orientations by mechanical or aerodynamic means and are subsequently consolidated (bonded) mechanically, chemically, or thermally. Mechanical web formation involves the utilization of textile carding or garnetting machinery or components to transform tufts of fibers or fiber blends into fibrous webs in which individual fibers are held by cohesion. For optimum processability, fibers must have crimp in addition to flexibility, length uniformity, cross-sectional consistency, and a finish which provides lubricity and anti-static properties.

In contrast to carded or garnetted nonwovens, where multiple forming machines are employed to build uniform webs, air laid nonwoven webs are generally formed on single machines. Also, as air currents and vacuum boxes are used to transport, mix, and collect fibers, a wide variety of fiber geometries, properties, and fiber combinations can be handled. Air laid systems designed to handle textile-length fibers employ mechanical fiber opening apparatus to prepare a loose batt of fiber tufts. The batt is mechanically fed through a feed-roll/feed-plate arrangement onto a metal-toothed lickerin roll which separates the fiber tufts and combines the fibers into a controlled air suspension and onto a venturi zone where the fibers are tumbled while being transported to a collection screen. A basic fiber requirement for textile based nonwoven systems is thermal stability
sufficient to withstand the heat encountered by impact with machine parts to avoid fusion or melting together of individual fibers.

In these and other systems, web consolidation (the interlocking of fibers in adjacent horizontal layers or vertical zones) can be accomplished by mechanical, chemical, or thermal means. Mechanical consolidation methods include stitchbonding, needlefelting, and hydroentangling (i.e. spunlace); fiber-to-fiber bonding in this instance is friction dependent and consequently not recoverable upon appreciable deformation. Chemical bonding methods include air or airless spraying, saturation, printing, and stable or semi-stable foam bonding; fiber-to-fiber bonding in this instance is highly dependent on binder surface tension and fiber and surface energy compatibility. Further, binder properties often mask or override fiber properties. Thermal bonding methods employ radiant, convention, conductive, or sonic energy sources; fiber-to-fiber bonding in this instance is achieved through thermal fusion and (as in chemical bonding) is set or stabilized upon cooling.

As virtually all nonwoven fabrics are shipped in large rolls in widths narrower than the consolidated web, common finishing operations are slitting and winding. Other application dependent or surface treatment finishes commonly used include embossing, brushing, sanding, and topical coatings for static, moisture, and bacteria control.

In the wet lay or wet forming process, fibers are suspended in water, brought to a forming unit where the water is drained off through a screen and the fibers deposited on the wire, and then picked off the wire to be dried. Processing synthetic or inorganic fibers in slurry form creates interesting challenges. As a general rule, these fibers do not wetout readily, are difficult to disperse, and tend to tangle with one another. Consequently, very high water dilutions are necessary to keep the fibers apart in the water suspension. If not handled properly, the fibers will tangle and poor sheet formation will result.

Another basic difference between conventional papermaking and wet lay nonwoven technology is the mechanism of bonding employed. Most man-made fibers used in nonwovens do not selfbond as readily as natural cellulose. Thus, some external bonding method must be employed. A number of binder types and application methods are used, each engineered to yield specific fabric properties. Binders can be applied either before web formation or afterwards by saturation, spraying, printing, foaming, or a combination thereof.

Web drying and binder activation is usually accomplished with steam heated cans. High synthetic content webs frequently bag or stretch during drying on multiple steam cans. Ovens or other air drying devices, including the use of infrared, are employed for specialty nonwoven production. At the end of the processing line, calender or creeping rolls are often placed to densify, smooth, and soften the fabric.

Air laid systems designed to handle pulp-length fibers employ mechanical defibrators such as pin mills, disc refiners, and hammer mills housed in close proximity to a perforated screen to disperse the fibers. When the fibers have been sufficiently dispersed, they pass through the screen into a controlled air steam and onto a forming wire. For these systems, fiber rigidity is required to avoid fiber tangling by air currents.

Extrusion-technology based or polymer laid systems transform polymer solutions, melts, or sheets into fabric in one continuous operation. Manufacturing parameters include obtaining uniform polymer orientation, fabric formation, and consolidation.
Spunbond systems have been the most commercially successful, possibly due to their similarity to filament extrusion processes. Meltblown systems have been commercialized more recently and perform well in applications which require high surface area due to the very small cross-section of individual fibers. Oriented film systems are commercial realities and are used as biological barriers for healthcare, reinforcing scrims, adhesive networks, and personal absorbent product cover stock.

Spunbond nonwovens are composed of continuous filaments which have been extruded in web form onto a collection belt and subsequently consolidated by mechanical, chemical, or thermal means. Most spunbonded processes utilize melt extruders. Upon extrusion, individual filaments are separated and/or oriented aerodynamically, electrostatically, or mechanically and patterned into a web on an apron or collection conveyor. The web is then consolidated by one or a combination of the following methods: (a) mechanical entanglement using needle looms; (b) adhesive bonding using latexes; (c) inherent bonding using acids, solvents, or gases to etch the filament surfaces and calender rolls to interlock the structure; (d) thermal bonding using heated calender rolls. Following consolidation, further mechanical and/or chemical fabric finishing operations can be incorporated.

Meltblown nonwoven manufacturing processes are similar to spunbonds in that melt extrusion is used. However, upon passage through the extrusion orifice, the molten polymer is accelerated by high-velocity, hot-air jets which attenuate the filament streams to microdenier size and propel individual fibers to a collection surface. Because the fibers are in a tacky state upon collection, some bonding occurs at fiber crossover points.

Textured film nonwoven systems usually employ slit extrusion technology. Upon extrusion the molten sheets are cast onto engraved drums and may be subsequently stretched biaxially. As the structure is drawn, fibrillization occurs in the patterned areas and a net-like fabric results. Uniform-thickness, partially-oriented films can be heated on an apertured screen, vacuumed to create surface texture, set on chill rolls, and abraded to establish controlled porosity. Alternatively, molten polymer can be cast on an apertured vacuum drum.

**Hybrid** systems provide means of incorporating the advantages of two or more nonwoven manufacturing systems to produce specialized nonwoven structures with properties unattainable by any single nonwoven process. These systems also allow for the selective addition of non-fibrous materials, such as powders or granules, into the fiber matrix. Interesting combining examples are hydroentangling a tissue with carded rayon webs to manufacture wipes with large and small capillaries, thermoembossing a film to a highloft to yield a moisture-impermeable insulator, air-forming pulps and textile fibers to yield enhanced filter media, and spunbond-meltblown-spinbond laminates for enhanced strength/surface area fabrics. Successful coformed fabrics include meltblown/pulp fabrics for water and oil absorption, meltblown/polyester staple fabrics for apparel insulation, and meltblown/staple-fiber/charcoal granule fabrics for respiratory masks.

**PRODUCTION RATE COMPARISON**

Over the past several decades, considerable emphasis has been placed on applying technological innovations to increase fabric production. In the three general methods of
making fabric - weaving, knitting, and nonwovens - production rate increases of at least one order of magnitude have been achieved. A compilation of recent fabric formation production rate capabilities is presented in Table IV. These data are based on producing fabrics in the range of 2.0 to 4.0 ounces per square yard (65 to 130 grams per square meter) and should not be viewed as absolute. Production rate is an important, but deceiving, factor when viewing methods of making fabric. Other factors are equally, if not more, important. Product versatility, cost of materials, manufacturing efficiency, product consistency, and market acceptability are items which must not be overlooked.

Table IV. WOVEN, KNITTED, and NONWOVEN FABRIC PRODUCTION RATE COMPARISON.

<table>
<thead>
<tr>
<th>Method</th>
<th>System</th>
<th>Square Meters/Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weaving</td>
<td>Shuttle</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Rapier</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Water Jet</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Projectile</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Air Jet</td>
<td>55</td>
</tr>
<tr>
<td>Knitting</td>
<td>Double Knit</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>Single Jersey</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>Raschel</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>Tricot</td>
<td>1200</td>
</tr>
<tr>
<td>Nonwoven</td>
<td>Stitchbond</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>Needlepunch</td>
<td>7200</td>
</tr>
<tr>
<td></td>
<td>Card-Bond</td>
<td>15000</td>
</tr>
<tr>
<td></td>
<td>Wetlay</td>
<td>30000</td>
</tr>
<tr>
<td></td>
<td>Spunbond</td>
<td>48000</td>
</tr>
</tbody>
</table>

SUMMARY AND CONCLUSIONS

The principles of fabric formation are fundamental and well established. Each technology and product has some special or unique characteristic that provides differentiation in the marketplace. In general, weaving provides maximum versatility in fabric design and structures that are dimensionally stable and uniform in porosity. Knitting machinery is somewhat less versatile, and knitted fabrics are generally more extensible than wovens. Both woven and knitted fabrics generally require post treatment to remove processing additives. Nonwoven methods are the least versatile, but fastest of the three manufacturing technologies. Nonwoven fabrics can be engineered to provide characteristics both comparable to and unachievable by wovens and knits. Technological change has been rapid and dynamic in each of these fabric manufacturing industries and has set the stage for a future of continuing competition in applications to enhance and expand the quality of life.