



## Three-Dimensionally Knit Spacer Fabrics: A Review of Production Techniques and Applications

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### ABSTRACT

*As the textile complex is faced with increasing competition, innovation and specialization have been employed by many machinery and product manufacturers to create a niche in the marketplace. In an effort to compete and appeal to the end-use market, products that go beyond the current range of performance and style have been developed. This paper will focus on the development of such specialized production through the use of knitted spacer fabrics. Basic knitting concepts will first be introduced followed by a review of literature on the history, technologies, advantages, disadvantages and potential end uses of knitted spacer fabrics.*

*Keywords: Spacer fabrics, knitting, automotive textiles, technical textiles*

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### 1.0 INTRODUCTION

As control of the textile complex has shifted further downstream to the consumer, manufacturers have been faced with greater and more specialized demands. In order to compete and appeal to the end-use market, it is therefore important to offer products that go above and beyond the current range of performance and style offerings. One industry striving to meet such demands is the manufacturers of knitting machinery and knitted fabrics.

This paper will first introduce some necessary knitting concepts and then discuss the topic of spacer fabrics. Literature on the

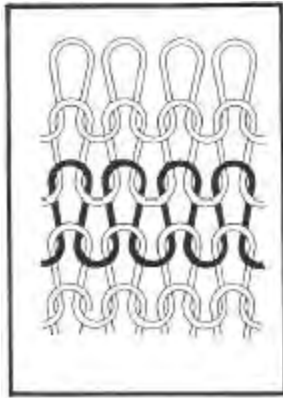
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history, technologies, advantages, disadvantages and potential end uses of knitted spacer fabrics will then be presented to create a complete understanding of spacer fabric's purpose and means of production.

### 2.0 KNITTING FUNDAMENTALS

Simply stated, knitting is the interlooping of yarns to form a textile structure. There are two classifications of knits – weft and warp. Weft formations have yarns which are knit across the width of the fabric while warp formations have yarns being knitted along the length of the fabric (Spencer, 2001) (see Figures 2.0a and 2.0b).

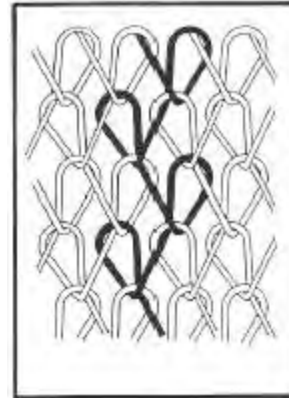
**Figure 2.0a: Weft Knit Structure**



Source: Raz, 1987. Page 17

There are three primary loops, each having their own characteristics used to produce knit fabrics – the knit loop, the float loop and the tuck loop (Brown, 1973). In addition to having three primary loops there are three needles used in the production of knitted fabrics – the spring-bearded needle, the latch needle and the compound needle. The latch and compound needles, however, are more prevalent because of their efficiency and ability to increase productivity (Spencer, 1983).

**Figure 2.0b: Warp Knit Structure**



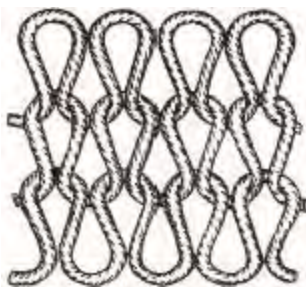
Source: Raz, 1987. Page 17

## 2.1 Variations of Weft Knit Fabric Structures

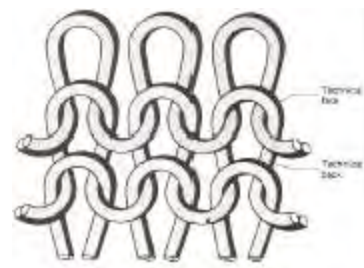
The three primary classifications of weft knit structures are the jersey (plain) structure and derivatives, rib fabric and derivatives and purl fabric and derivatives (Shinn, 1957; Smith, 1984; Smith, 2004). Jersey fabrics and their derivatives are single-sided structures and include fabrics such as plain jersey, feed stripe, pique, flat jacquard, fleece and plated jersey (Spencer, 2001; Smith, 2004). The two structures important for reference in this paper are the plain jersey fabric which is a single layer fabric in which the same yarn is being knit on the front and back of the fabric and a variation of the plain jersey called plated jersey (see Figures 2.1a and 2.1b).

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**Figure 2.1a: Technical Face of Plain Jersey Fabric**      **Figure 2.1b: Plated Jersey Fabric**



Source: Shinn, 1957. p. 10



Source: Spencer, 2001. Pg. 57

Plated jersey has the same basic structure as single jersey, but it uses two yarns which are knitted at the same time under controlled tension so that one yarn is always on the designated side of the fabric (Spencer, 2001; Smith, 2004). It is still a single jersey fabric, but with two layers of yarns which may be used to manipulate the characteristics of the fabric to control such

qualities as moisture transfer, comfort, hand and stretch.

Rib fabrics and derivatives include 1x1 rib, cardigan, interlock, flat jacquard and double-faced fabrics (Spencer, 2004). The three structures important for later discussion of spacer fabrics are the 1x1 rib, interlock and double-faced fabrics (see Figure 2.1c and 2.1d).

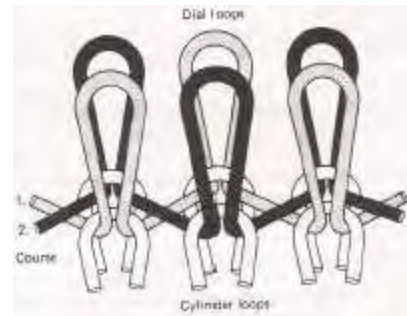
**Figure 2.1c: 1x1 Rib Fabric**



Source: Shinn, 1975. Pg. 12.

1x1 rib is a single layer fabric that has the same yarn knitting loops on both sides of the fabric. Interlock fabrics are a form of rib that use two sets of needles that knit back-to-back in an alternate sequence to create two sides of the fabric that are exactly in line with each other and hide the back of the loops on the inside of the structure and show identical face loops on both the front and the back of the fabric. The final product has the appearance of a plain jersey fabric on the front and back with the two yarns alternating sides of the fabric (Spencer, 2001; Smith, 2004). It should be noted that interlock fabric (like 1x1 rib and other stated fabrics) cannot be called spacer fabric because there is no separation of fabric layers.

**Figure 2.1d: Interlock Fabric**



Source: Spencer, 2001. Pg. 73

Purl fabric is the final classification in which there is also the possibility of making double-faced fabrics using the same idea presented with the rib fabrics. However, due to slow machine speed and low productivity they are not typically used for such production.

## 2.2 Weft Knitting Machines

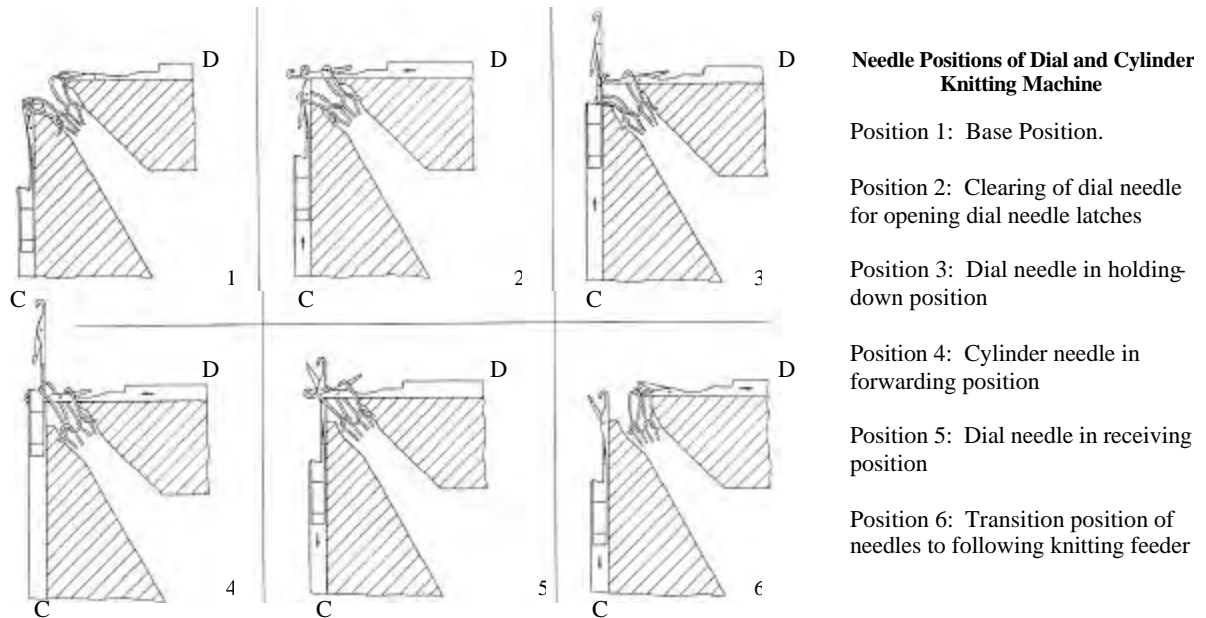
There are two types of weft knitting machines – circular and flat. Circular machines can be classified in one of three categories – 1) single jersey machines which have one set of needles and make only jersey fabrics, 2) dial and cylinder machines which have two sets of needles and are capable of making jersey and rib fabrics, and 3) double cylinder purl machines which use double-ended latch needles and make purl fabrics (Iyer, et al, 1995; Spencer, 2001; Smith, 2004). The two primary forms of flat knitting machines are the V-bed machine, which is useful in the production of spacer fabrics and the flat purl machine which is nearly non-existent in today's applications (Raz, 1993; Smith, 2004). The V-bed has the potential for making both jersey and rib

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fabrics, as well as their derivatives including double-faced fabrics. Figures 2.2a and 2.2b show and explain the knitting action

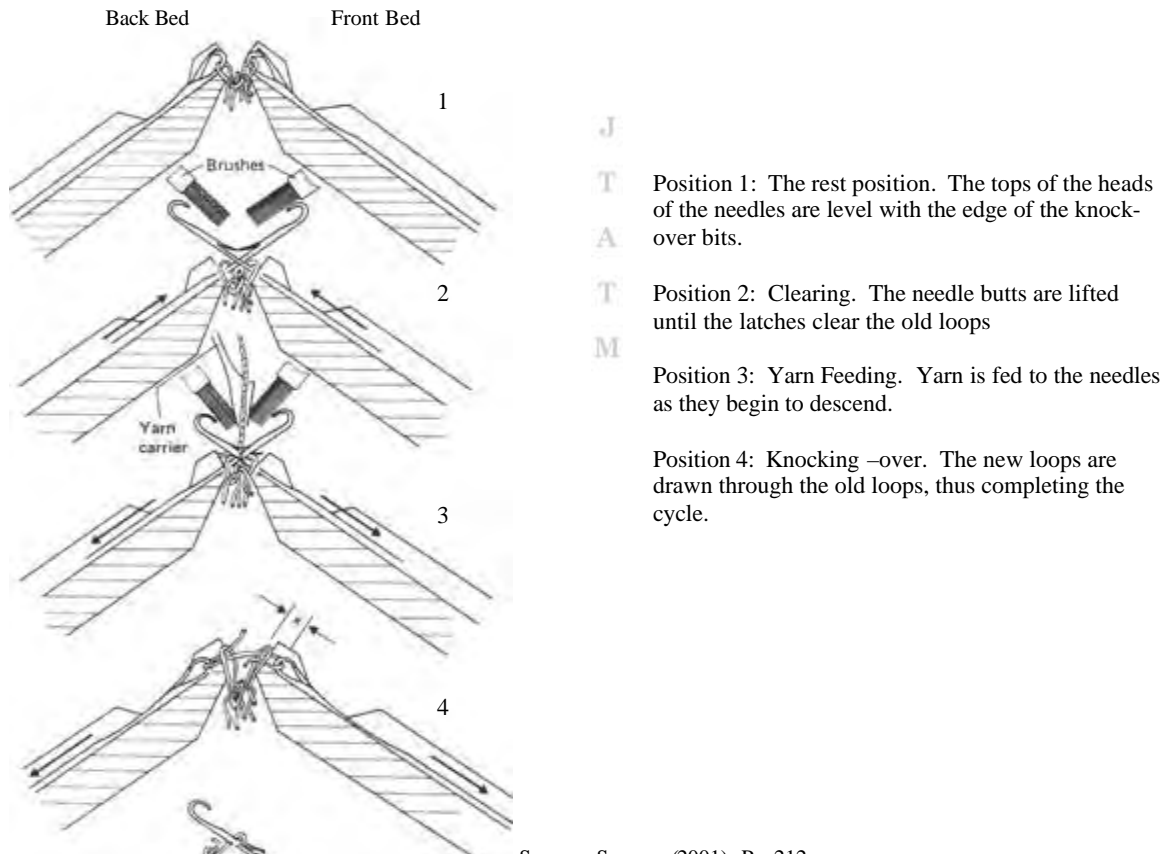
associated with the dial and cylinder and v-bed knitting machines.

**Figure 2.2a: Knitting Action of Dial and Cylinder Knitting Machines**



Source: Iyer, Mammel & Schach (1995). Pg. 149

**Figure 2.2b: Knitting Action of V-Bed Machine**



Source: Spencer (2001). Pg. 212

### 2.3 Weft Knitting Notation

In order to fully understand the structures to be discussed, it is necessary to introduce the concept of notation. The two methods of notating weft stitches used in this paper are the graphic and diagrammatic techniques. The graphic method uses pictures or photographs to illustrate the fabric structure and is used in Figures 2.1a-c to depict basic weft knit structures. Figure 2.3 shows the diagrammatic method which is often more useful. The dots represent needles, while the lines represent the path of the yarns. The type of machine being used can be identified by the number of needles (i.e. dots) per course (one set per course being jersey while two sets per course indicate rib or interlock fabric created on dial and cylinder or v-bed machines), the way the needles are arranged and the notation used.

### 2.4 Warp Knitting Classifications and Machines

Warp knit structures have yarns that knit parallel to the length of the fabric and can be classified in three ways (Raz, 1987; Reisfeld, 1966; Smith, 2001). The first method of classification is the machine used in production – Tricot or Raschel. The Tricot machine makes fabrics that are less complicated, finer in gauge and more rapidly produced, while the Raschel

machine has the ability to make more complex structures, but is considerably slower in production speed (Reisfeld, 1966; Spencer, 2001; Smith, 2001). It is important to mention that as gauge is increased, finer yarn is used and it is more likely that production flaws will occur (Smith, 2001).

The second means of classification is the number of bars or sets of yarns used in production. With the addition of bars, fabrics become more expensive, more stable, denser and more versatile (Smith, 1984). Typically a Tricot machine uses 2-6 bars (i.e., making a 2-bar fabric, 3-bar fabric, 4-bar fabric, etc.). Sub-categories of Tricot fabrics include traditional solid fabrics (also called standard full set fabrics) such as Locknit or Full Tricot, Openwork fabrics or Laid-in fabrics (Raz, 1987; Spencer, 2001). Raschel machines found in industry vary significantly, but for spacer fabrics discussed in this paper will range from 5-8 bars (Smith, 2001). Further sub-classification of Raschel fabrics can be broken down into solids, lace, open-work, mesh, laid-in and spacer fabrics (Raz, 1987; Spencer, 2001; Smith, 2001). It will be noted that even though production of one bar fabrics is possible, it is not common because they are weak and unstable, but such structures can be used to produce fabric structures that are components of warp knit spacer fabrics.

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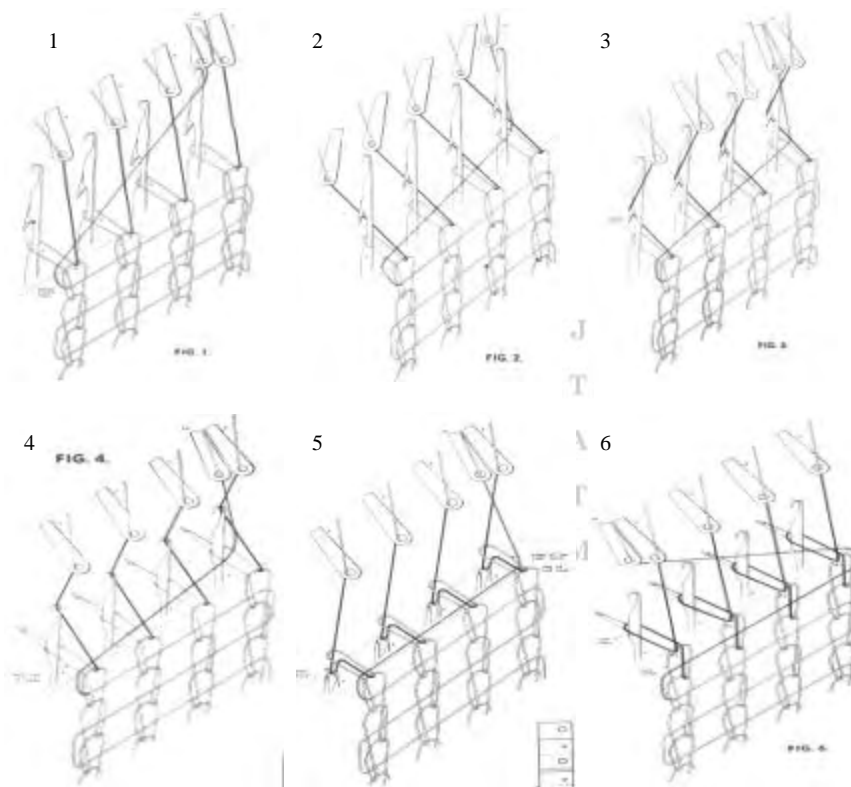
Table 2.3: Weft Knitting Notation

Loop Notation	Term	Loop Notation	Term	Loop Notation	Term
	Knit Loop (Face)		Knit Loop (Rear)		1x1 Rib
	Tuck Loop (Face)		Tuck Loop (Rear)		Half Cardigan
	Float Loop (Face)		Float Loop (Rear)		Interlock
	Single Jersey Machines		Plain Single Jersey		Plated (2 Yarns)
<p>a) </p> <p>b) </p>	<p>Interlock Gaiting</p> <p>a) V-Bed Machine</p> <p>b) Dial &amp; Cylinder Machine</p>	<p></p> <p></p>	Feed Stripe		Double Face
<p>a) </p> <p>b) </p>	<p>Rib Gaiting</p> <p>a) V-Bed Machine</p> <p>b) Dial &amp; Cylinder Machine</p>	<p></p>	1x1 Cross Tuck (Pique)		
		<p></p> <p></p>	2x2 Cross Tuck (Pique)		

The final means of classifying warp structures is by the number of needle bars used under each machine classification. Traditional tricot machines have one set of needles that move simultaneously and create fabrics that look different on each side (Paling, 1965; Spencer, 2001; Smith, 2001). The front and back of the fabric can be easily identified by the diagonals or underlaps being observed on the back-side of the fabric. Simplex Tricot machines have two sets of needles that are arranged similarly to a V-bed machine and knit alternately. The fabric created on this machine has only one layer with one set of yarns going from front to back while another set of yarns goes from back to front to make

a fabric similar to interlock (Brown, 1973; Spencer, 2001; Smith, 2001). Raschel machines may also have one or two sets of needles. Single needle bar fabrics look different on both sides and do not have two distinct layers. Double needle bar fabrics differ from the Simplex fabrics introduced with the Tricot machine in that the two sets of needles are parallel and have an alternate knitting action so that the front and back sets of needles knit separate layers of fabric while yarn travels back and forth to join them together (Thomas, 1976; Spencer, 2001; Smith, 2001). Figure 2.4 shows the knitting action associated with Raschel machines.

**Figure 2.4: Knitting Action of Raschel Machine**



Position 1: Starting point. Needles are extended fully upward and the front guide bar swings to the back of the machine.

Position 2: Movement left. Guide bars move to the front of the needles and to the left.

Position 3: Swing between needles. Guide bars are swinging between the needles and back to the front side of the machine.

Position 4: New loop formation. Needles are taken down causing the loops to slide from the latches into the hook.

Position 5: Knocking over. The new loops are drawn through the last row of loops.

Position 6: Completion. The needles rise and the new loops slide down from the hook, open the latch and slip over its edge onto the stem.


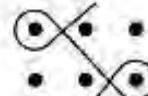



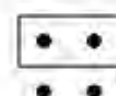

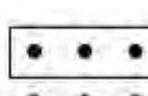
Source: Reissfeld, et. al, 1953. Pgs. 8-18.

## 2.5 Warp Knitting Notation

Similar to the concept of notation introduced in weft knitting, warp knitting requires a means of communicating how a structure should be knitted. The three methods of notating warp stitches used in this paper are graphic, diagrammatic representation and numbers (Reisfeld, et al, 1953; Reisfeld, 1966; Spencer, 2001; Smith, 2001). The graphic method uses pictures or photographs to illustrate the fabric structure and examples can be seen in Figures 2.6 a-c. Figures 2.5 a-c show the diagrammatic method which is more useful as the warp structures become increasingly complex. The dots represent needles, while the lines represent the path of the yarns as the guide

bars move between and around the needles. The type of machine being used (Tricot or Raschel) can be identified by the numbers between the wales at the bottom of the diagram. Sequential numbers (i.e., 0, 1, 2, 3, etc.) indicate that the structure being knitted is on a Tricot machine while even numbers (i.e., 0, 2, 4, 6, etc.) indicate a Raschel machine is being used. Additionally, each row of needles is labeled as either the front bar (FB) or the back bar (BB). As will be noted later, when spacer fabrics are produced, it is necessary to identify front and back needle bed knitting actions. Tables 2.5a and 2.5b show notation for single guide bar fabrics while Table 2.5c shows notation for fabrics that are produced on machines with two guide bars.

**Table 2.5a: Single Guide Bar Warp Structures**

Term	Notation	Needle Spacing	Term	Notation	Needle Spacing
Open Chain/ Open Pillar Stitch		Tricot 0-1 / 1-0 / Raschel 0-2 / 2-0 /	Modified Half-Tricot With Closed Loops		T 1-0 / 2-3 / R 2-0 / 4-6 /
Closed Chain/ Closed Pillar Stitch		T 0-1 / 0-1 / R 0-2 / 0-2 /	Modified Half-Tricot With Open Loops		T 0-1 / 3-2 / R 0-2 / 6-4 /
Closed Half-Tricot		T 1-0 / 1-2 / R 2-0 / 2-4 /	Laid-In		T 0-0 / 2-2 / R 0-0 / 4-4 /
Open Half-Tricot		T 0-1 / 2-1 / R 0-2 / 4-2 /	Laid-In		T 0-0 / 4-4 / R 0-0 / 8-8 /



**Table 2.5b: Single Guide Bar Atlas Fabrics**

Term	Notation	Needle Spacing
Conventional Van Dyke / Atlas Movement		T: 1-0 / 1-2 / 2-3 / 3-4 / 4-5 / 4-3 / 3-2 / 2-1 / R: 2-0 / 2-4 / 4-6 / 6-8 / 8-10 / 8-6 / 6-4 / 4-2 /
Fancy Van Dyke / Atlas Movement		T: 4-5 / 4-3 / 4-5 / 3-2 / 1-0 / 1-2 / 1-0 / 2-3 / R: 8-10 / 8-6 / 8-10 / 6-4 / 2-0 / 2-4 / 2-0 / 4-6 /
Fancy Van Dyke / Atlas Movement		T: 1-0 / 2-3 / 1-0 / 2-3 / 4-5 / 3-2 / 4-5 / 3-2 / R: 2-0 / 4-6 / 2-0 / 4-6 / 8-10 / 6-4 / 8-10 / 6-4 /

**Table 2.5c: Two Guide Bar Structure Representations**

Term	Notation	Needle Spacing	Term	Notation	Needle Spacing
Half-Closed Tricot		Tricot FB - 1-0 / 1-2 / BB - 1-2 / 1-0 / Raschel FB - 2-0 / 2-4 / BB - 2-4 / 2-0 /	Queenscord		Tricot FB - 1-0 / 0-1 / BB - 3-4 / 1-0 / Raschel FB - 2-0 / 0-2 / BB - 6-8 / 2-0 /
Modified Half-Tricot on FB, Half-Tricot BB		Tricot FB - 1-0 / 1-2 / BB - 1-2 / 1-0 / Raschel FB - 2-0 / 4-6 / BB - 2-4 / 2-0 /	Laid-in Fabric / Open Work FB - Chain BB - Laying-in		Tricot FB - 1-0 / 0-1 / BB - 0-0 / 3-3 / Raschel FB - 2-0 / 0-2 / BB - 0-0 / 6-6 /
Half-Tricot on FB, Modified Half-Tricot BB		Tricot FB - 1-0 / 1-2 / BB - 2-3 / 1-0 / Raschel FB - 2-0 / 2-4 / BB - 4-6 / 2-0 /	Laid-in Fabric / FB - Half-Tricot BB - Laying-in		Tricot FB - 1-0 / 1-2 / BB - 0-0 / 2-2 / Raschel FB - 2-0 / 2-4 / BB - 0-0 / 4-4 /

## 2.6 Variations in Warp Knit Fabric Structures

Warp structures can be composed of stitches containing both open and closed loops as can be seen in Figures 2.6a and 2.6b.

**Figure 2.6a: Open Loop**



**Figure 2.6b: Closed Loop**



Source: Smith, 2001.

Figures 2.5 a-c show fabric notations, some of which contain what are referred to as open loops (two examples include the open chain stitch, and open half tricot stitch) which tend to be flimsy, and lack stability because the yarns do not cross at the bottom, however, they are easier to knit (Raz, 1987; Spencer, 2001; Smith, 2001). Closed loops are those that do cross at the bottom and create a more fixed fabric. It should be noted that the chain stitch is used to lock fabrics in place and is successful at adding

length stability, but if used alone cannot make a fabric (Raz, 1987; Smith, 2001).

Warp knit fabrics can be classified in many ways. For example they can be solid/full-set fabrics or open-work fabrics (Reisfeld, 1966; Smith, 2001). Examples of solid fabrics include Locknit, Full Tricot and Queenscord (see Figures 2.6 c-e). In order to have a two bar solid fabric both guide bars must be full set meaning that each wale will have two yarns (Reisfeld, 1966; Smith, 2001).

**Figure 2.6c: Full Tricot**



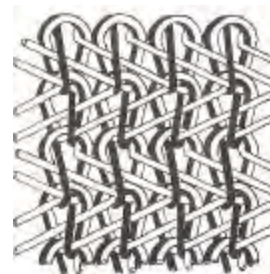
Source: Reichman, et al, 1967. Pg. 36

**Figure 2.6d: Locknit**



Source: Reichman, et al, 1967. Pg. 36

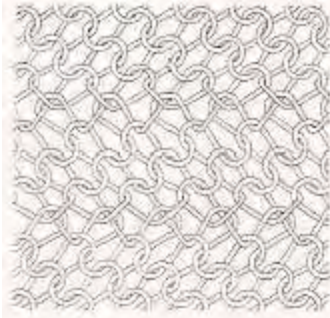
**Figure 2.6e: Queenscord**



Source: Reichman, et al, 1967. Pg. 36

Open-work or mesh fabrics are often created using either the Van Dyke/Atlas or laid-in approach (see Figures 2.6f and 2.6g for illustrations).

**Figure 2.6f: Single Atlas Fabric**



Source: Paling, 1965. Pg. 76

An Atlas lapping is a movement where the guide bar laps progressively in the same direction for a minimum of two consecutive courses, normally followed by an identical lapping movement in the opposite direction (Spencer, 2001). Used alone, atlas lapping makes poor fabrics, but can generate desired effects such as interesting design and open-work fabrics. The concept of laid in yarns allows for a fancy or special yarn to be incorporated into the fabric. Laid-in yarns are typically locked in place by a knitting yarn and must therefore be placed on a back guide bar (Spencer, 2001; Smith, 2001).

Yet another way an openwork fabric may be created is through the use of ‘partial set threading’ or if the number of guides left empty equals the number of guides threaded, ‘half set threading’ (e.g. with a threading of 1 in 1 out or 2 in 2 out) (Wheatley, 1972). By having full set threading the weight of the fabric is increased. Additional means of increasing fabric weight include heavier yarn (lower cotton count or higher denier), using full set threading as opposed to partial

**Figure 2.6g: 2-Bar, Full-Set, Laid-In Fabric**



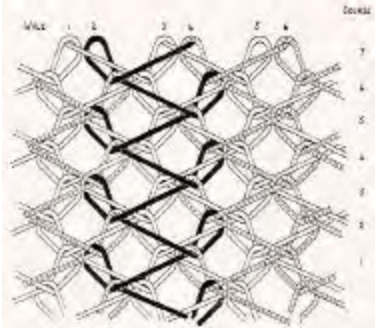
Source: Paling, 1965. Pg. 175

set, adding pile bars, and moving needle beds further apart (Smith, 2001).

Figures 2.6h and 2.6i show openwork or mesh fabrics and Figures 2.6j and 2.6k show laid-in, open work fabrics and their notations. The fabric depicted in both Figures 2.6j and 2.6k are full set and can be modified by changing the way in which the yarns are laid-in, ultimately changing the size and shape of the openings. Figure 2.6k is more rigid and has greater vertical stability because it has three sets of yarns being knitted rather than the two seen in 2.6h. It is important to note that the variety of fabrics that can be created is many and significant in the production of spacer fabrics. Because solid or open-work fabrics can be used independently or as a basis for both sets of fabric in a warp knit spacer fabric, meaning that each side of the spacer fabric can have a different construction (i.e. the front may have the construction of Figure 2.6h and the back could have the construction of 2.6i).

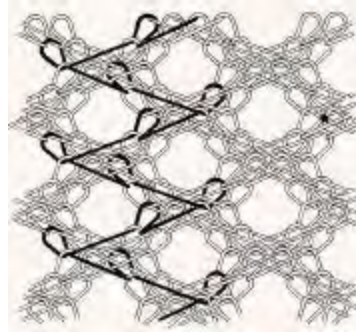
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**Figure 2.6h: 2-Bar, Half-Set Net**



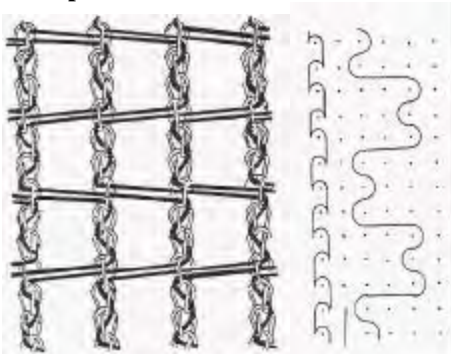
Source: Paling, 1965. Pg. 110

**Figure 2.6i: 2-Bar, 2-in, 2-out Net**



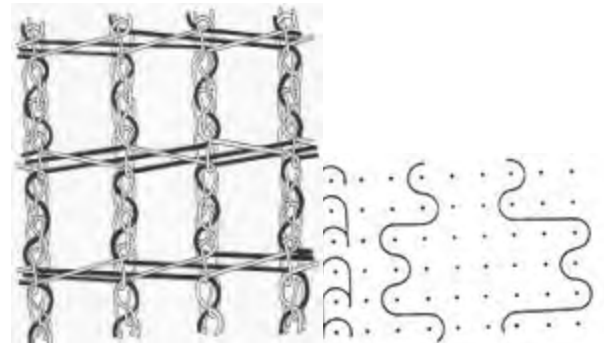
Source: Paling, 1965. Pg. 118

**Figure 2.6j: 2-Bar, Full Set Open-Work Fabric**



Source: Smith, 2001.

**Figure 2.6k: 2-Bar, Full Set Open Work Fabric with 3 Sets of Yarns**



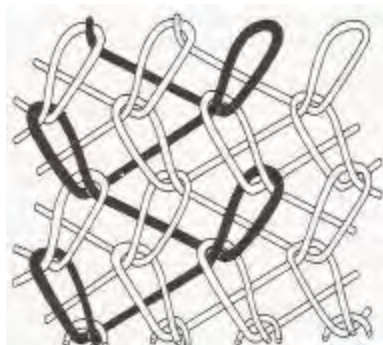
Source: Smith, 2001.

Identified as the second way of classifying warp knits, the number of guide bars on Tricot and Raschel machines can vary. Fabrics knitted using only a single guide bar use only one set of yarns and tend to be less stable and more distorted leading manufacturers and consumers to demand

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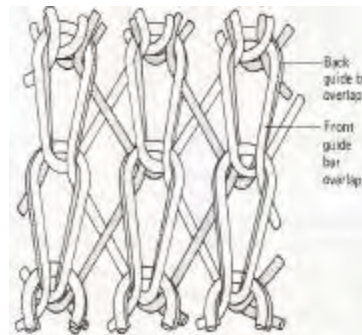
fabrics made with 2 or more guide bars (Reisfeld, 1953; Raz, 1987; Smith, 2001). By adding guide bars, the fabric becomes more balanced and stable. Figures 2.6l and 2.6m show fabrics made with one and two guide bars.

**Figure 2.6l Single Guide Bar Fabric (Technical Face)**



Source: Spencer, 2001. Page 296

**Figure 2.6m: Two Guide Bar Fabric (Technical Face)**



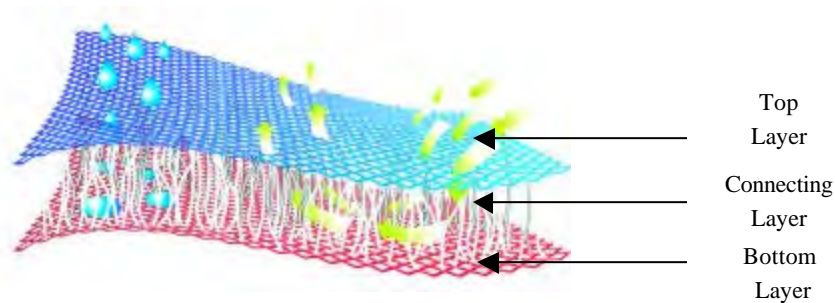
Source: Spencer, 2001. Page 316

### 3.0 Introduction to Spacer Fabrics

According to Cass (2000), spacer fabrics are much like a sandwich and feature “two complementary slabs of fabric with a third layer tucked in between. The inner layer can take a variety of shapes, including tubes,

pleat or other engineered forms, which gives the entire three-layer fabric a wide and ever-expanding range of potential applications” (pg. 20) (see Figure 3.0a for illustration).

**Figure 3.0 a: Spacer Fabric**

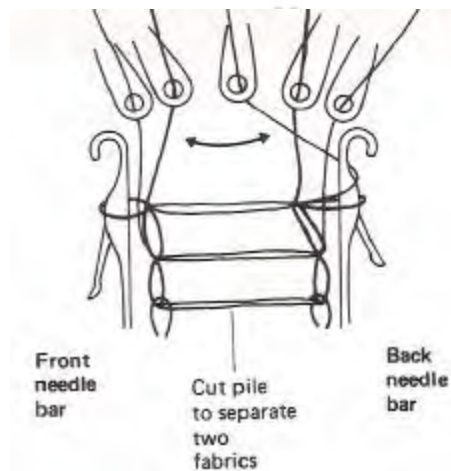


Source: Knitting International. (2002, February 2002). Breathing Room. Knit Americas. <http://www.inteletex.com/FeatureDetail.asp?PubID=27&NewsId=191>. [2005, January 17].

Although increasing in popularity and exposure, the innovation of spacer fabrics is not new, commercial developer Matthew Townsend of Leicester took out an initial patent for spacer fabrics in 1868. The patent was for knitting mattresses on a two needle-bed hand frame with interconnecting “threads” (Bremner, 2004; Knitting International, 2002). More prevalent in the marketplace, spacer fabrics are essentially

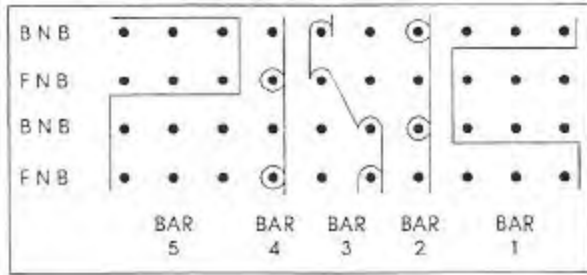
pile fabrics that have not been cut consisting of two layers of fabric separated by yarns at a 90 degree angle. Typically, double plush or “plush” fabrics are created by knitting two separate layers of fabric that are connected by pile yarns then sliced down the middle to create two separate fabrics (Smith, 2001). Figure 3.0b illustrates a side view of a two needle-bed Raschel machine using one pile bar.

**Figure 3.0b: Cut Plush Fabric Made on Five Guide Bar Raschel Machine**



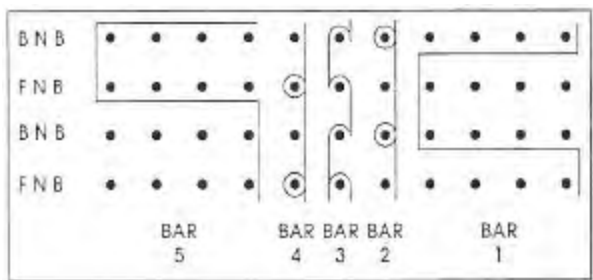
Source: Spencer, 2001. Page 368

Three examples of different notation and structures used to produce double plush fabrics on Raschel machines having 5 guide bars are given in Figures 3.0c – 3.0e.



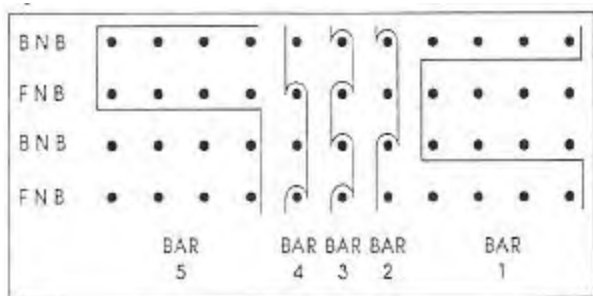
Source: Smith, 2001

**Figure 3.0c:** Here a pile fabric is made with one pile bar (3). Bar 3 is moving between wales in order to make a design effect. Bar 3 is lapping over both needle bars and is alternating courses which results in a fabric with less overall weight.



Source: Smith, 2001

**Figure 3.0d:** Here is a variation on Figure 3.0c, however, Bar 3 is moving straight up and down in a single wale. Bars 1 and 5 are making longer movements creating a heavier, more stable fabric than seen in Figure 3.0c.



Source: Smith, 2001

**Figure 3.0e:** Here a variation of the pile fabric shown in 3.0d is made. Here we have a fabric with more movement and less stability because Bars 2 and 4 are making open chain stitches as opposed to closed chain stitches seen in Figures 3.0c and 3.0d.

More recently these uncut pile fabrics have attracted new attention with one use established in 1982 when A.W. Fischer of Germany applied for a patent for the production of fabric for padded bras. The innovation offered great opportunity to the market since it would allow for the elimination of foam or other layering options traditionally found in such undergarments that were subject to deformation, deterioration and difficulty in disposal (Reisfeld, 2002).

As a result of unique attributes, applications to various industries such as automotives, medical textiles, technical textiles, geotextiles, sportswear and other apparel products, environmental protection

and safety exist and will be noted later in the paper.

### 3.1 Spacer Fabric Production on Weft Knitting Machines

Spacer fabrics are two distinctive layers of fabric joined together by a connecting layer. Weft knitting machines with two sets of needles have the ability to create two individual layers of fabric that are held together by tucks. Such a fabric was referred to as a double-faced fabric in Section 2.1, but can also be called a spacer fabric. Double-face fabrics can be produced on dial and cylinder, v-bed and purl machines.

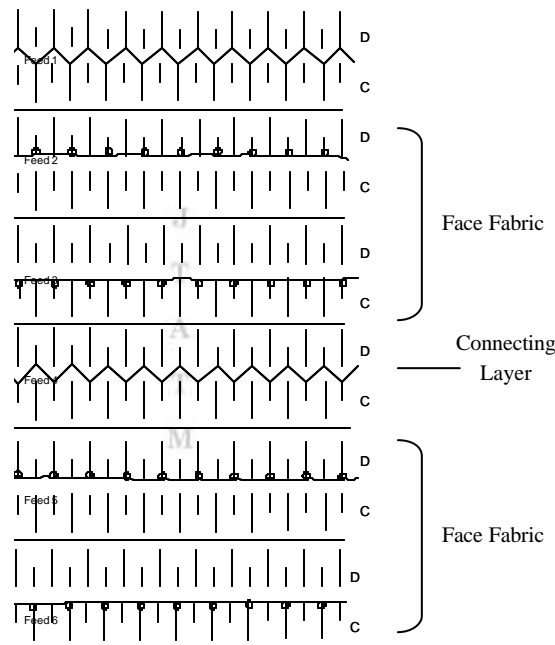
### 3.1.1 Dial and Cylinder Spacer Fabrics

Producing knitted spacer fabrics on dial and cylinder machines can be done using a variety of combinations of stitches that ultimately connect two independent layers of fabric together. All techniques require the use of at least three different yarns for each course of visual fabric: 1) yarn for the cylinder needles; 2) yarn for the dial needles; and 3) a spacer yarn, normally monofilament yarn connecting the two layers (Anand, 2003b). The distance between the two fabrics can be manipulated by the dial height adjustment, ultimately determining the amount of pile yarn being put between the two ground fabrics. Anand (2003a, pp. 10), describes two techniques of producing spacer fabrics that are explained and depicted below. It should be noted that using high and low butt needles refers to the

different types of needles in the cylinder and dial. In the following notation, long lines represent high butt needles and short lines represent low butt needles. Interlock needle gating is shown.

1. Tucking on dial and cylinder needles at the same feeder (see Figure 3.1.1a):
  - a) tucking on the dial and cylinder needles on feeders 1 and 4 on low and high butt needles alternately (this connects the two layers together);
  - b) knitting dial needles with dial yarn at feeders 2 and 5 on low and high butt needles alternately; and
  - c) knitting cylinder needles with cylinder yarn at feeders 3 and 6 on low and high butt needles alternately

**Figure 3.1.1a: Circular Knitted Spacer Fabric Formed by Tucking on Dial and Cylinder Needles**



Source: Anand, S. (2003). Recent Advances in Knitting Technology and Knitted Structures for Technical Textiles Applications. Istek, 2003.

2. Knitting/plating on the dial needles and knitting on cylinder needles (see Figure 3.1.1b):
 

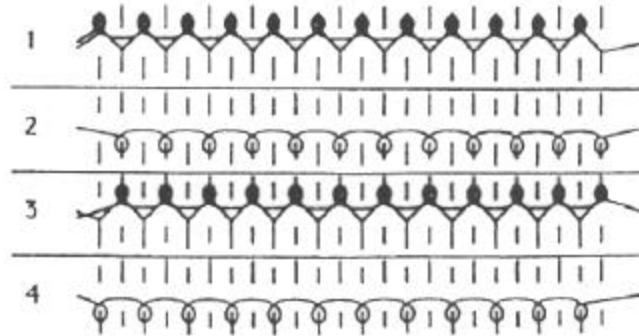
A special yarn feeder is required with two holes to enable two yarns to be knitted at the same feeder (feeders 1 and 3):

  - a. Face yarn knitted on the dial needles on low and high butt needles alternately; and spacer yarn knitted on

dial needles and tucked on cylinder needles, as shown in feeders 1 and 3;

b. cylinder yarn knitted on cylinder needles at feeders 2 and 4 on low and high butt needles alternately.

**Figure 3.1.1b: Circular Knitted Spacer Fabric Formed By Knit/Plating on Dial and Tuck on Cylinder**



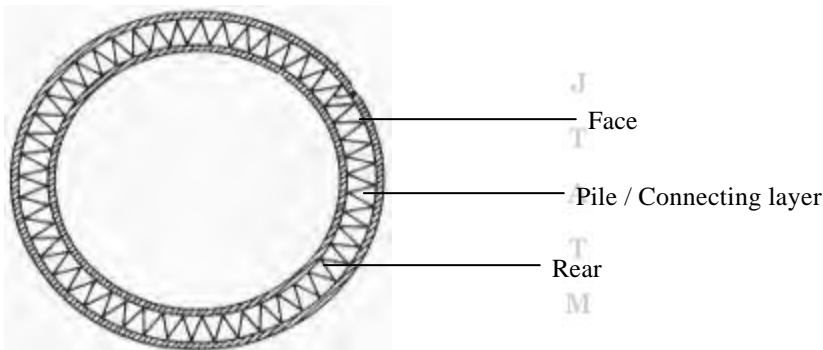
Source: Anand, S. (2003). Recent Advances in Knitting Technology and Knitted Structures for Technical Textiles Applications. Istek, 2003.

Note that the concept used in the second technique is similar to the concept of producing a plated single jersey fabric. It should also be noted that a single jersey fabric is not a spacer fabric because there is

no separation of fabric layers present.

Figure 3.1.1c depicts a circular knit spacer fabric before it has been cut to make an open-width fabric.

**Figure 3.1.1c: Cylindrically Shaped Double -Face Fabric**



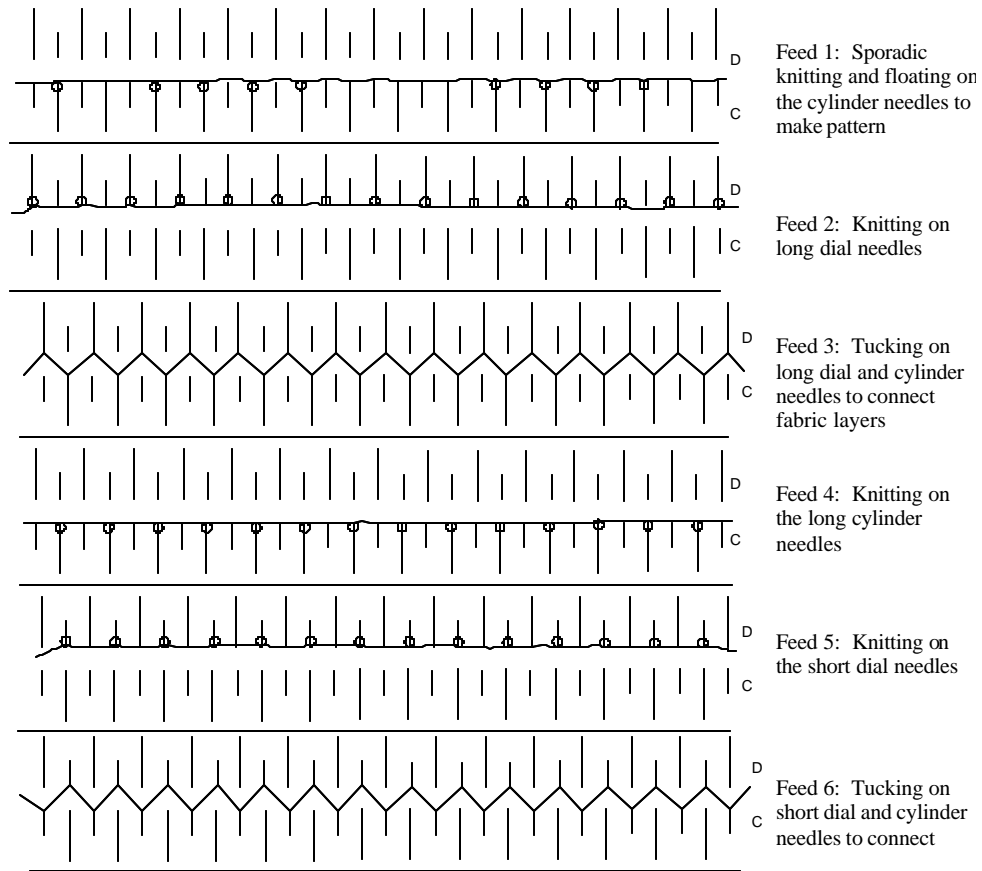
Source: USPTO (2004). Decorative Faced Multi-Layer Weft Knit Spacer Fabric, Method, and Articles Made Therefrom. US Patent Application. 0097151.

Another example of a spacer fabric produced on a dial and cylinder machine is created using jacquard patterning. In this case a jacquard pattern layer is weft knitted on the cylinder needles, a plain layer is weft knitted on the dial needles, and the two

layers are coupled together with spacer yarn connected in each layer on alternate needles of the cylinder or dial (USPTO, 2004) (see Figure 3.1.1d; Appendix 1 shows full figure).



**Figure 3.1.1d: Knitting Structure Diagram for Flat Pattern Jacquard Spacer Fabric**



Source: USPTO (2004). Weft Knitted Spacer Fabrics. US Patent No. 6,779,369.

Both of the examples given show fabrics having the same structure on the front and back and do not indicate what type of yarns are being used, however, it is possible to produce the two outer layers from different materials and with completely different structures.

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and absence in industrial production (it should be noted that purl machines have fewer feeds and knit slowly, making the production of spacer fabrics on purl machines economically unfeasible) (Raz, 1993; Spencer, 2001).

In addition to dial and cylinder machines, double cylinder purl machines fall under the classification of circular knitting (Raz, 1993). As mentioned in Section 2.2, double cylinder purl machines have only one set of needles. However, these needles are double-ended and thus have the ability to knit two separate fabrics with a connecting layer (i.e. double face or spacer fabrics) (Raz, 1993). These fabrics are not documented in recent literature on the production of spacer fabrics because of the inefficiency associated with the technology

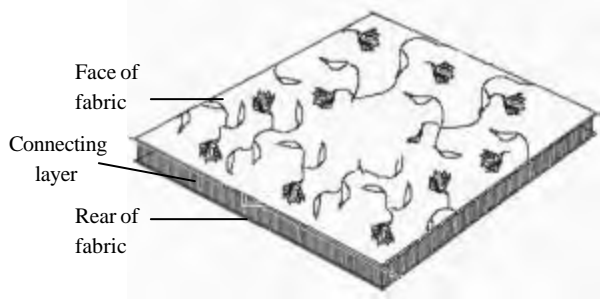
### 3.1.2 V-Bed Spacer Fabrics

When a flat-bed knitting machine is used in the production of three-dimensional spacer fabrics, two types of products can be created: 1) two independent structures connected by cross-threads, and 2) two independent fabric structures connected by fabric layers (de Araujo, et al, 2001). The method used in the first technique possible is the focus of this paper. Through the use of pile yarns to connect two independent layers of fabric on the front and back needle beds it is possible to form a double face fabric. This

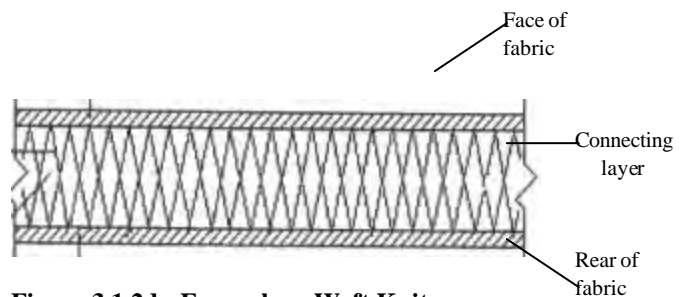
technique is extremely limited because when producing two separate fabric layers that are connected by connecting yarns the distance between the two needle beds dictates the space between the two fabric layers. Given that the two needle beds are a fixed distance apart, the user's ability to adjust the space between the two outer layers or the overall thickness of the spacer fabric is determined by the machine setting and is limited to a thickness between 2-10 mm (de Araujo, et al, 2001). Much creative potential still exists however because as was found with dial and cylinder machines, it is possible to use two different types of yarns and create two different structures on either side of the spacer fabric.

A specific example of the production and application of a spacer fabric knitted on a v-bed machine is shown in Figures 3.1.2 a-d. The product depicted is a decorative faced multi-layered fabric used in the production of brassieres. The knitting sequence shows two fabric layers being created through the use of varying stitches that are connected by tucks. Feed 1 has yarns being tucked on alternate needles of the back and front needle beds while Feeds 2 and 3 are knitting on alternate needles on the back needle bed. Feed 4 is sporadically knitting and tucking to create the decorative jacquard pattern seen on the front of the fabric.

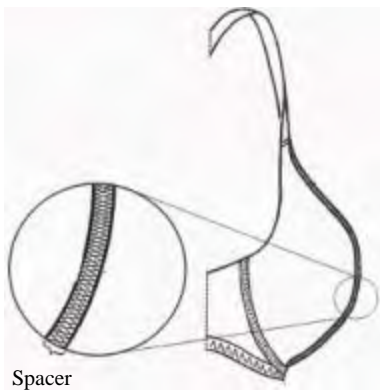
**Figure 3.1.2a: Perspective View of Jacquard Spacer Fabric**



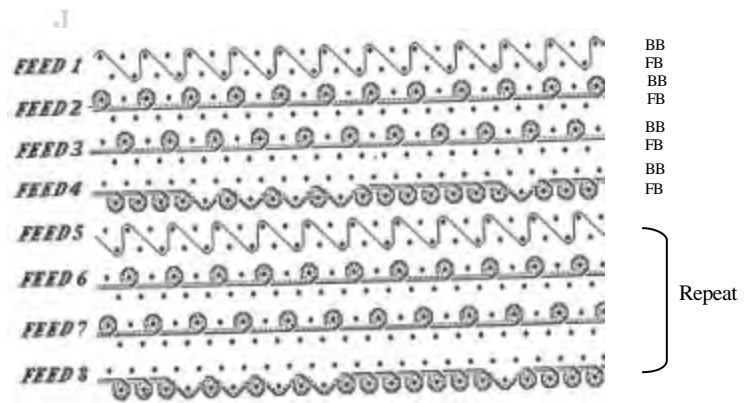
**Figure 3.1.2b: Cross-Sectional View of Jacquard Spacer Fabric**



**Figure 3.1.2c: Cross-Sectional View Of Brassier Cup**



**Figure 3.1.2d: Exemplary Weft Knit Sequence for Jacquard Spacer Fabric**



Source: USPTO (2004). Decorative Faced Multi-Layer Weft Knit Spacer Fabric, Method, and Articles Made Therefrom. US Patent Application. 0097151.

### 3.2 Spacer Fabric Production on Warp Knitting Machines

Spacer fabrics are two distinctive layers of fabric joined together by a connecting layer. Through the explanation of Tricot machines given in Section 2.4, it was established that fabrics made on traditional Tricot machines (having one set of needles) are similar to plain jersey fabrics in that they are different on the front and back. Fabrics made on Simplex machines (having two sets of needles) make fabrics similar to interlock. Neither fabrics have two distinct layers, therefore it is not possible to make a spacer fabric on a Tricot machine.

Production of spacer fabrics on a Raschel machine with two needle bars is possible and has great similarity to flat knitting in that there is a front and back bed of needles being used to create distinct layers that are connected by spacer yarns. Raschel machines produce both outer layers simultaneously on different bars using their own sets of needles. Because the layers are knit on their own needle beds it is possible for the front and back to use different yarns and have completely different structures. The two layers are connected by pile yarns which switch regularly from one needle-bar to the other in a systematic method of joining the two independent sides of the spacer structure (Phillips, et al, 1995).

Raschel spacers have the greatest production capabilities at this time due to greater range in yarn tex, higher production speeds (relative to the dial and cylinder, v-

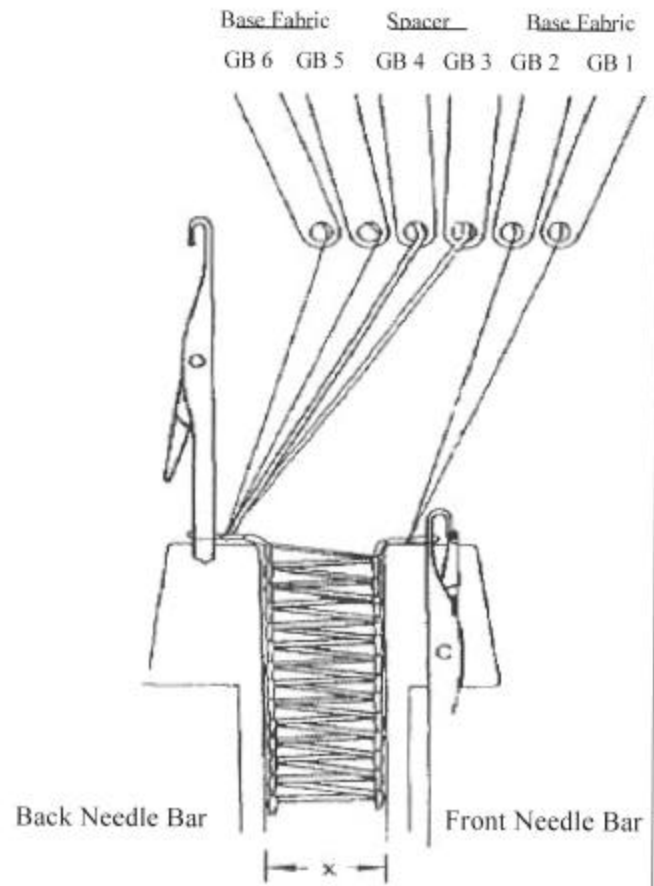
bed and purl machines), and ability to adjust the distance between the two needle bars giving greater opportunity for spacer thicknesses (Phillips, 1995; de Araujo, et al, 2001; Bohm, 2002; Onal, 2004; Unknown, 2004; Mayer, 2005; Smith, 2001).

Figure 3.2a gives a depiction of the basic set-up of a Raschel knitting machine used to produce spacer fabrics. Guide bars 1 and 2 knit the front base fabric on the front needle bar only while guide bars 5 and 6 knit the other separate base fabric on the back needle bar only. Guide bars 3 and 4 carry the spacer yarns and knit on both needle bars in succession (Anand, 2003a). Great flexibility is associated with warp-knitted spacer fabrics because different material may theoretically be used in guide bars 1 and 2, 3 and 4, and 5 and 6 (Anand, 2003a).

Various means of forming Raschel knit spacer fabrics exist. The fabric shown in Figure 3.2b is knitted on a double needle bar machine with at least six guide bars. The front and back are composed of stretchable sets of ground and elastic yarns interknitted with one another while simultaneously knitting at least two sets of monofilament pile yarns between the ground fabrics to make a fabric used for athletic shoes and support bandages (USPTO, 1995). Guide bars one and two are feeding yarns to the front needle bar, guide bars six and seven feed yarns to the back needle bar and the pile yarns being fed on bars 3-5 alternate knitting on the front and back beds to join the two independent fabric structures.

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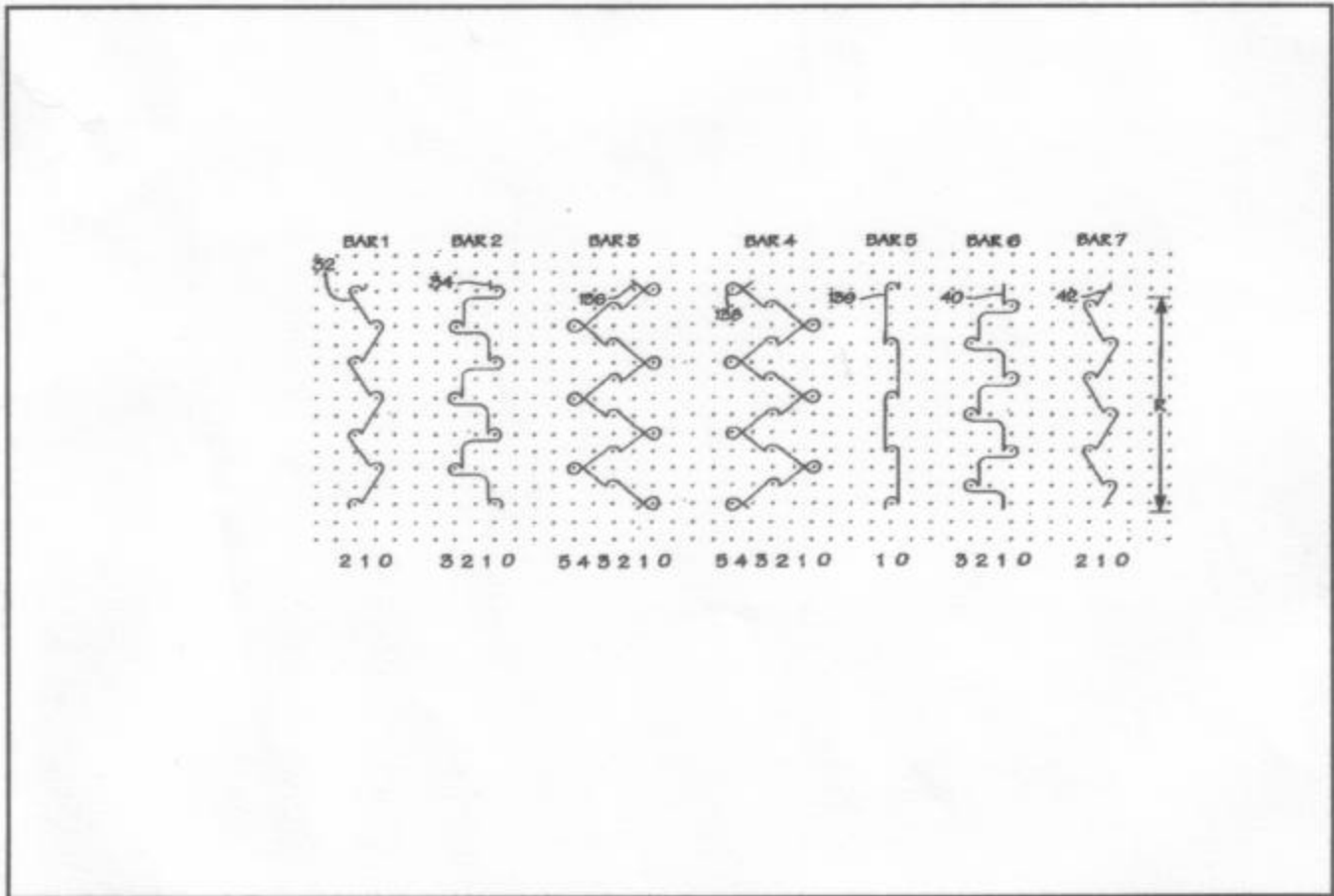
**Figure 3.2a: A Schematic Drawing of Raschel Knitting Machine Used to Produce Spacer Fabrics Having Two Pile Bars**



Source: Onal, L. (2004). Structure and applications of 3D Knitted Spacer Fabrics. *Istanbul Textile Congress*.

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**Figure 3.2b: Raschel Spacer Fabric Notation**



USPTO (1995). Warp Knitted Textile Spacer Fabric, Method of Producing Same, and Products Produced Therefrom.  
US Patent No. 5,385,036

### 3.3 Analysis of Warp and Weft Knitted Spacer Fabrics

Spacer fabrics produced on dial and cylinder, v-bed and Raschel machines have been considered thus far. Table 3.3a shows some of the common attributes that are seen as advantages of the production of spacer

fabrics over alternative fabrics. Table 3.3b indicates the advantages and disadvantages to the implementation of each type of machine.

**Table 3.3a: Common Advantages of 3-Dimensionally Knit Spacer Fabrics**

<b>Physical Properties<sup>1</sup></b>	<b>Aesthetic &amp; Comfort Properties<sup>2</sup></b>	<b>Other Properties<sup>3</sup></b>
Excellent compression elasticity <sup>7</sup>	Age resistant	Elimination of cut and sew operations
Breathability / Air permeability <sup>8</sup>	Sterilization capabilities	CAD Usage - Design flexibility - Rapid prototyping
Cushioning	Surface resistance	Yarn diversity - Increased attributes (e.g. wicking, extensibility) - Variety of end-capabilities
Insulation	Wash resistance	
Good bending performance	Temperature regulation	
Drapability <sup>9</sup>	Light weight	
Adjustable vapor transport	Diverse surface design capabilities	
Recyclable / Latex free		

Sources: 1) Onal, 2004; 2) Smith, 2001; 3) Colbert, 2003

#### **4.0 SPACER FABRIC APPLICATIONS AND END-USES**

The methods by which knit spacer fabrics are produced have been presented in the previous sections. The way that the fabrics may be used in a variety of industries and specific end-use applications are the focus of this section. Research on the market for technical textiles has found that

there will be a rising demand for knit spacer fabrics in the areas of automotive and other transportation media; medical, hygiene and healthcare; geotextiles, civil engineering, building and construction; sports and leisure; environmental protection, filtration and cleaning; and safety and protection (Elsner, 2004; Onal, 2004; Anand, 2003a, Muller, 2003, de Araujo, et al, 2002a; Mayer, 2000,).

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**Table 3.3b: Comparison of Advantages and Disadvantages of Spacer Fabrics**

<i>Spacer Fabric Type</i>	<b>Advantages</b>	<b>Disadvantages</b>
<b>Raschel</b>	No ripping or raveling Does not require bonding or lamination Pliable, flexible, retains shape  Can build in dimensional stability and/or stretch Customize thickness or volume Control permeability to air and vapor Efficient moisture transport Conformance to body parts Insulating Available in wide widths	Expensive equipment Large floor space requirements Low machine productivity  Large labor requirement per machine Limited pattern scope Spacer has a tendency to collapse and flatten
<b>Flat</b>	Fabric may be fashioned to a specific shape and size No cutting results in no waste of yarn or fabric Can accommodate almost any type of yarn  Possibility of weft insertion between fabric faces Easy jacquard patterning	Slow production speeds Small number of feeds and knitting systems Complex and expensive equipment  Not economical to make piece goods Can unravel and ladder
<b>Circular</b>	Lower yarn costs since the system can use heavier count yarns Less floor space required Low operating skill levels Can accommodate spun yarns Quick machine set-up time Extensive patterning scope Soft fabric that conforms to shape	Available in just one width Low dimensional stability Rigidity when using monofilaments Limited choice of stitch Limited variation of thickness (2-10 mm) Can unravel and ladder

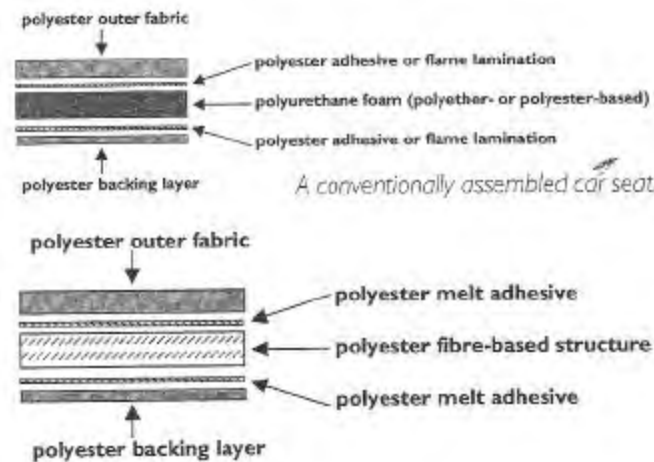
Source: Reinsfeld, A. (2002, Spring). Outer Limits. *Knit Americas*, 64-69.

**4.1 Automotive**

The current car seat offered in the global marketplace consists of three layers: the top layer which is often plush and made of polyester; the middle layer made of a polyurethane foam; and the bottom layer, a

polyamide warp knit (see Figure 3.1) (Ishtalque, et al, 2000). The demand for automotive seating fabric is met through four alternatives: wovens, nonwovens, knits and leather. A breakdown of the worldwide demand is given in Table 4.1.

**Figure 4. 1: Car Seat Construction**



Source: Gunnarsson, A. and Shishoo, R. (2002, March). Fabrics replace polyurethane foam in car seat upholstery. *Technical Textile International*, Vol. 11, No. 2, p. 29.

**Table 4.1: Relative Volume of Different Seating Fabrics**

Fabric Type	Europe	USA	Asia
Flat Woven	47%	14%	12%
Woven velour	1%	30%	24%
Tricot (incl. pile sinker)	15%	11%	44%
Double needle bar raschel	5%	23%	9%
Circular knitted	21%	1%	7%
Leather	11%	21%	4%
Total	100%*	100%*	100%*

\*Note: Figures do not include nonwovens manufactured by such companies as Toray's Alcantara™.

Source: Anand, S. (2003). Recent Advances in Knitting Technology and Knitted Structures for Technical Textiles Applications. Istek, 2003.

Alternatives to current automobile offering are presently being sought, but according to Ishtiaque, et al. (2000), must meet five requirements: 1) be luxurious in appearance through structure and color; 2) have a soft, textile feel of spun yarn; 3) be comfortable; 4) have the potential for small patterned and multi-colored designs; and 5) have a look that is similar to that of woven fabrics (Ishtiaque, et al, 2000). Because of the technology and attributes associated with the warp-knitted spacer fabric (numerous guide bars to make interesting patterns and the ability to knit a range of yarn types) it is possible to achieve all of these requirements. In addition to use in seat cushions as the prerequisites implied, spacer fabrics also offer alternatives as head liners, luggage compartment covers, seat packets and dash boards (Ishtiaque, et al, 2000). With over 20 kg of fabric used in each of the approximately 45 million cars made every year worldwide, there is a great future potential for warp-knitted spacer fabrics in automobiles (Onal, 2004).

Perhaps most importantly, knitted spacer fabrics allow for the elimination or reduction of polyurethane foam. Foams have many serious drawbacks such as flammability, lack of compression and resilience and delamination (Anand, 2003). Research on suitable alternatives have led textile manufacturers and automobile manufacturers to replacements such as

polyester fibers and nylon (Fisher, 2001). By creating car seats with this new structure, the recycling procedures are simplified at the end of the vehicle's useful life (Gunnarsson and Shishoo, 2002).

#### 4.2 Medical

The properties, such as heat and moisture regulation associated with both warp and weft-knitted spacer fabrics are ideal for use in medical textiles (Wollina, et al, 2003). The development of weft-knitted products in which loops are formed across the width of the fabric creates a functional bandage that is inelastic thereby offering high levels of compression and support (Anand, 2003a). Warp-knitted fabrics offer greater flexibility and elasticity due to the formation of loops along the length of the fabric (Anand, 2003a). According to Elsner (2004), spacer fabrics are a key new development in medical textiles as they are "composed of textile sheets interconnected by distance fibers, which may be polyamides, polyesters, viscose or even natural fibers like cotton. With these fabrics, a more even distribution of pressure becomes possible, and, depending on the selection of capillary or surface fibers, fluid transport through the fabric is enhanced" (p. 3). Bandages have been used to treat such ailments as lymphedema and were found to be as effective as traditional bandages, but more comfortable due to the microclimatic



qualities associated with spacer fabrics (Elsner, 2004).

### **4.3 Geotextiles, Civil Engineering, Building, Construction, Environmental Protection, Filtration, and Cleaning**

Geotextiles are defined by Anand (2003a) as, “permeable textile materials which are designed for use in civil engineering applications such as erosion control, soil reinforcement, separation, filtration and drainage” (pp. 3). Knitted fabrics are not commonly used in geotextiles with 70% of materials used coming from nonwovens and 25% from wovens (Anand, 2003a). An increase in the use of knitted spacer fabrics is expected as geotextiles are forecast to be the fastest growing sector within the market for technical textiles (Anand, 2003a). Knitted spacer fabrics offer an opportunity for geotextiles as their construction is exceptionally functional. As discussed with both weft and warp knit spacer fabrics, it is possible to create the two outer layers with different structures such as a grid shape or mesh which is more effective at grabbing the soil than smooth fabrics (Anand, 2003a).

A specific environmental application was made using Tek-Knit Industries polyethylene warp-knitted spacer fabric. The fabric offers a vertical filtration system for use in construction applications. The fabric can be placed against a building and water then can drain into a sub-grade (Cass, 2000).

### **4.4 Sports and Leisure**

Sports and athletics have been increasing worldwide, as has the demand for athletic apparel. Billion of dollars are spent each year on athletic apparel and footwear (Anand, 2003a). In order to maximize comfort and performance both moisture and temperature must be managed. To achieve the ultimate fabric three criteria are considered: 1) using the right combination of fibers; 2) using the right fabric structure; and 3) using the right chemicals or finishes on the fabric (Anand, 2003a). Spacer

fabrics are used because the various layers can offer different attributes – the layer closest to the skin can be hydrophobic, the middle can be used for diffusion, and the outer layer can be hydrophilic thereby absorbing and evaporating heat energy (Anand, 2003a).

In addition to sportswear, spacer fabrics are being used in conventional intimate apparel. Champion® is making use of the wicking capabilities offered through spacer fabrics in their Double Dry Everyday bras, as well as their the Double Dry Everyday bras with Space Aire™. The initial line offered an inner layer that wicks away moisture, while the outer layer evaporates the moisture. Recently, however, Champion® has enhanced the technology by offering the two layers that wick and evaporate with a middle layer, or spacer fabric, that features tiny knit-in air pockets giving a smooth silhouette and comfort (Champion, 2004).

### **4.5 Safety and Protection**

A variety of potentially harmful scenarios and conditions exist in the environment and knitted spacer fabrics offer a solution through their properties and construction capabilities. Weft and warp knitting machines have the ability to produce fabrics using many high performance fibers such as glass, Nomex™, Kevlar™, PEEK™, Basofil™, carbon, metals and UHMWPE (Anand, 2003a). Use of such fibers enables knitted fabrics to protect against extreme heat and fire, harmful chemicals and gases, mechanical and electrical hazards, contamination, radiation, vacuum and pressure fluctuations, extreme cold, virus and bacteria and cut and ballistic hazards (Onal, 2004; Anand, 2003a).

### **5.0 CONCLUSION: THE FUTURE OF SPACER FABRICS**

In terms of end-use products and machine progress, spacer fabrics are still seeing rapid development and improvements. Thus far, machine

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manufacturers have made basic modifications on their already existing equipment to meet the needs of those textile producers specializing in the production of three-dimensional spacer fabrics.

Special abilities and versatility offered by spacer fabrics include the ability to knit two entirely different fabrics having different properties and connect them to form a single structure. This offers end users a great deal of opportunity to modify the weight, aesthetics, properties and cost of the fabric to meet consumer demand.

It is likely that as the engineers of technical textiles, medical textiles,

automobile interiors and apparel products become more comfortable with the product, advancements will continue to be made in machine and yarn technology and the prevalence of spacer fabrics in the marketplace will increase.

As mentioned earlier, knit products are often classified in the commodity category. The use of spacer fabric technology, however, offers a niche market for machine, fiber and end-product manufacturers. By pursuing specialization in this area, manufacturers are likely to see less competition based on price compared to alternative materials such as foam and corresponding increased margins.

#### Footnotes:

<sup>1</sup> Single-sided structures are those that have different appearances on the technical face and technical rear of the fabric.

<sup>2</sup> Gauge refers to the thickness of the needles used or the number of needles per inch of fabric.

<sup>3</sup> A fabric is balanced if the structure at one part of the bed is, in relation to another part along the width, the same (Lewis & Weissman, 1986).

<sup>4</sup> A pile effect appears in the middle of an uncut fabric or on one face of a cut fabric (Smith, 2001).

<sup>5</sup> A monofilament yarn is Any single filament of a manufactured fiber usually of a denier higher than 14. Instead of a group of filaments being extruded through a spinneret to form a yarn monofilaments generally are spun individually. Monofilaments can be used for textiles such as hosiery or sewing thread or for nontextile uses such as bristles papermaker's felts fishing lines etc (<http://textile.texworld.com>).

<sup>6</sup> Yarn Tex: Methods of variously expressing the mass per unit length or the length per unit mass of a yarn (<http://textile.texworld.com>).

<sup>7</sup> Compression elasticity refers to the ability of a fabric to recover its original size and shape immediately after the removal of the force causing deformation (<http://textile.texworld.com>).

<sup>8</sup> Air permeability refers to the rate of passage of air through fabric (<http://textile.texworld.com>).

<sup>9</sup> Drapeability refers to the ability of a fabric to hang in graceful folds (<http://textile.texworld.com>).

<sup>10</sup> A synthetic linear polymer in which the linkage of the simple chemical compound or compounds used in its production takes place through the formation of amide groups, e.g., Polyamides are distinguished from one another by quoting the number of carbon atoms in the reactant molecule or molecules. For polyamide derived from an amino-acid or lactam, this is a single number. In the case of a polyamide made from a diamine and a dicarboxylic acid, the number of carbon atoms in the former is given first followed by a punctuation mark and then the number of carbon atoms in the latter (<http://textile.texworld.com>).

<sup>11</sup> Lymphoedema is the swelling of the subcutaneous tissues caused by obstruction of the lymphatic drainage. It results from fluid accumulation and may arise from surgery, radiation or the presence of a tumor in the area of the lymph nodes (<http://cancerweb.ncl.ac.uk>).

<sup>12</sup> Microclimatic refers to a small climate of a specific place within an area as contrasted with the climate of the entire area.

<sup>13</sup> The state or quality of being penetrable by fluids or gases (<http://textile.texworld.com>).

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<sup>14</sup> Tek-Knit Industries is based in Montreal, Quebec, Canada and manufactures spacer fabrics on a Raschel-knit machine.

<sup>15</sup> Lacking affinity for or the ability to absorb water

<sup>16</sup> Diffusion is the movement of substance owing to the existence of a concentration gradient.

<sup>17</sup> Having strong affinity for or the ability to absorb water

## References

Anand, S. (2003, July 2003). Spacers – At the Technical Frontier. *Knitting International*, 110(1305), 38-41.

Anand, S. (2003). Recent Advances in Knitting Technology and Knitted Structures for Technical Textiles Applications. *Istek*, 2003.

Bohm, C. (2002, February 2002). Rib Raschel For Spacer Fabrics. *Knitting International*, 109(1289), 38-39.

Bohm, C. (2002, August, 2002). Spacer Fabric Focus. *Knitting International*, 109(1295), 22-25.

Bremner, N. (2004, June 2004). Spacers About to Take-Off? *Knitting International*, 111(1315), 40-41.

Brown, P. (1973). *Knitting Principles*, 2nd edition. North Carolina: Textiles Extension and Continuing Education School of Textiles.

Cass, J. (2000, July 2000). Spacer Consideration. *Industrial Fabric Product Review*, 77(3), 20-24.

Champion. Champion Double Dry Everyday Bras. Champion. Available: [http://www.championcatalog.com/html/Dou-bleDryEveryDay\\_Bra.html](http://www.championcatalog.com/html/Dou-bleDryEveryDay_Bra.html) [2004, November 19].

Colbert, T. (2003). Three Dimensional Knitting - Advantages. *Teknit*. Available: <http://www.teknit.com/Pages/3d.htm>. [2004, September 9].

De Araujo, M., Fangueiro, R., Cataring, A. and Hong, H. (2001). Recent Developments in Weft-Knitting Science and Technology: The Way Ahead in the New Millennium. *Textile Institute*.

De Araujo, M. Hong, H., Fangueiro, R., and Ciobanu, O. (2002, March 2002). Weft-knitting fabric design for technical applications. *Textile Asia*, 23-27.

De Araujo, M., Hong, H., Fangueiro, R., and Ciobanu, O. (2002). Designing Shaped 3D Textile Performs Using Weft-Knitting and Braiding Technologies. *Textile Institute*.

Elsner, P. (2004). Textiles and the Skin. *Karger Gazette*, 67. Available: [http://www.karger.com/gazette/67/Elsner/art\\_1.htm](http://www.karger.com/gazette/67/Elsner/art_1.htm). [2004, November 19].

Fisher, G. (2001, June). Automotive Potential for 3D Spacer Fabrics. *Knitting International*, 21-25.

Gunnarsson, A. and Shishoo, R. (2002, March). Fabrics replace polyurethane foam in car seat upholstery. *Technical Textile International*, Vol. 11, No. 2, p. 29-33.

Ishtalque, S., Yadav, P, and Sharma, N. (2000, March, 2000). A New Approach to Improve the Performance of Spacer Fabrics for Automobiles. *Man-Made Textiles in India*, 67-74.

Iyer, C., Mammel, B., & Schach, W. (1992). *Circular Knitting*, 2nd edition. Germany: Meisenbach.

Knitting International. (2002, February 2002). Breathing Room. *Knit Americas*. <http://www.inteletex.com/FeatureDetail.asp?PubID=27&NewsId=191>. [2005, January 17].

Karl Mayer (retrieved February 2, 2005). Source: <http://cgi.karlmayer.de/english/Products/nav/index.html>.

Lewis, S. & Weissman, J. (1986). *A Machine Knitter's Guide*. Asheville, Lark Books.

Mayer, K. (2000). *The Karl Mayer Guide to Technical Textiles*. Karl Mayer. Available:

<http://www.karlmayer.de/pdf/technicaltextiles.pdf>. [2004, December 9].

Mayer & Cie. (retrieved February 2, 2005). [http://www.mayercie.de/en/produkte/43\\_547.htm](http://www.mayercie.de/en/produkte/43_547.htm)

Muller Ag, J. (2003). *Intelligent Products in the Technical Textile Sector*. Pakistan Textile Journal. Available: <http://www.ptj.com.pk/Web%202003/3-2003/mueller.htm>. [2004, November 19].

Onal, L. (2004). *Structure and applications of 3D Knitted Spacer Fabrics*. Istanbul Textile Congress.

Paling, D. (1965). *Warp Knitting Technology*. London: Columbine.

Philips, D. (1999). *Characterisation and Development of 3D Knitted Composites*. Composite Materials Groups. Available: [www.mtm.kuleuven.ac.be/Research/C2/poly/phd\\_dp.html](http://www.mtm.kuleuven.ac.be/Research/C2/poly/phd_dp.html) [2004, September 9].

Raz, S. (1993). *Flat Knitting Technology*. Westhausen: C.F. Rees GmbH, Druck.

Raz, S. (1987). *Warp Knitting Production*. Heidelberg: Heidelberger Verlagsanstalt und Druckerei GmbH.

Reisfeld, A., Rotenstein, C., Paling, D. & Lancashire, J (1953). *Fundamentals of Raschel Knitting*. New York: National Knitted Outerwear Association.

Reisfeld, A. (1966). *Warp Knit Engineering*. New York: National Knitted Outerwear Association.

Reinsfeld, A. (2002, Spring). *Outer Limits*. Knit Americas, 64-69.

Shinn, W. (1957). *Principles of Knitting, Volume One*, 3rd edition. Charlotte, Clark Publishing Company.

Smith, G. (1984). *Knits. Industrial Fabric Products Review / Buyers Guide*, Vol. 60, No. 10A, pg. 42-44.

Smith, G. (2001, March 1). *Warp Knitting Fundamentals Short Course*. North Carolina State University.

Smith, G. (2004). *Circular Knitting Fundamentals Short Course*. North Carolina State University.

Spencer, David J. (1983). *Knitting Technology*. New York: Pergamon Press.

Spencer, D. (2001). *Knitting Technology*, 3rd edition. Cambridge: Woodhead Publishing Limited.

Terrot. (retrieved February 2, 2005). <http://www.terrot.de/aktuelles/en/berichte/04-05.asp>.

Textile World. <http://Textile.texworld.com>

Thomas, D. (1976). *Introduction to Warp Knitting*. England: Merrow.

Unknown. (2004, September 2004). *Ultra-thick Fabric Finishing*. Available: <http://www.inteletex.com/FeatureDetail.asp?PubId=4&NewsId=3250>. [2004, November 19].

USPTO (1986). *Padded Knit Fabric, Particularly For Lingerie, And Methods of Its Manufacture*. US Patent No. 4,601,940

USPTO (1995). *Warp Knitted Textile Spacer Fabric, Method of Producing Same, and Products Produced Therefrom*. US Patent No. 5,385,036

USPTO (2000). *Blunt Trauma Reduction Fabric for Body Armor*. US Patent No. 6,103,641

USPTO (2000). *Three-Dimensional High-Low Bulk Spacer Fabric*. US Patent No. 6,156,406.

J  
T  
A  
T  
M

USPTO (2004). Decorative Faced Multi-Layer Weft Knit Spacer Fabric, Method, and Articles Made Therefrom. US Patent Application. 0097151

USPTO (2004). Knitted Stretch Spacer Material and Method of Making. US Patent No. 6,755,052.

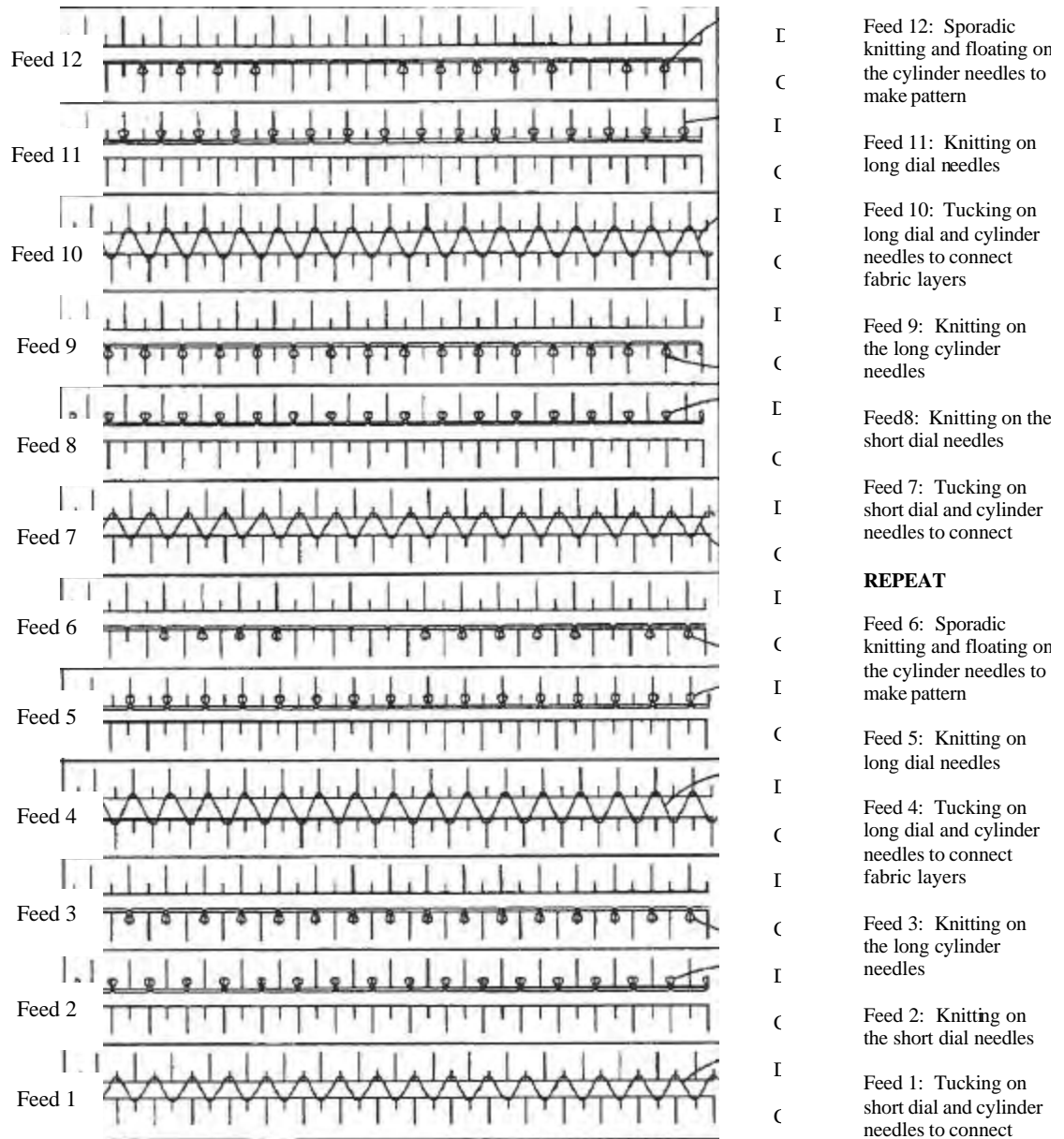
USPTO (2004). Weft Knitted Spacer Fabrics. US Patent No. 6,779,369.

Wheatley, B. (1972). Knitting of Outerwear Fabrics on Tricot and Raschel Machines – Part 9. Knitting Times, November 13, 1972, 78-84.

Wollina, U., Heide, M., Mueller-Litz, W., Obenauf, D., & Ash, J. (2003). Functional Textiles in Prevention of Chronic Wounds, Wound Healing and Tissue Engineering. Textiles and the Skin, 31, 82-97.

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## Appendix 1: Knitting Structure Diagram for Flat Pattern Jacquard Spacer Fabric



*Managing Editor's note:*

Correspondence received regarding this article (February 2006; Professor Subhash Anand, the University of Bolton), indicated that the article had errors, both technical and content. Technical errors, especially in the figures and tables, were due in part to the Journal's electronic format; these errors have been corrected in this current article presentation.

This article was included in the Scholarly section of the Journal; the article reflects a *review of the literature*, rather than new research in the area of knitting and spacer fabrics. An extensive review of the literature is required for NC State College of Textiles' doctoral students (TTM Ph.D. program). This article represents a textile technology review (limited length approximately 30 pages), with citations noted throughout the article. When errors occur in the literature, the graduate student's direction was to report the literature, not test or correct inaccuracies. This would suggest that some areas are in need of knitting research by experts in this area.

The first author, Bruer, is a doctoral student in our program and this paper was written to satisfy the textile technology component of the TTM program, under the direction of two faculty members (Professors Powell and Smith). Ms. Bruer's doctoral dissertation research focuses on the textile technology management issue of branding.

We appreciate Professor Anand's correspondence and JTATM welcomes correspondence, including *Letters to the Editor*.

*Co-authors notes:*

In response to Dr. Subhash Anand's letter of concern about the inaccuracies in the article "Three-Dimensional Knit Spacer Fabrics: A Review of Production Techniques and Applications" by Bruer, Powell and Smith (JTATM, Vol. 4, Iss. 4, Summer 2005), the authors have reviewed the publication.

The scholarly section of this online journal includes articles which reflect existing knowledge rather than new discoveries. This was a graduate student paper with the intent of focusing on the existing literature rather than exploring/pursuing new research.

We acknowledge there were technical and formatting errors in the initial published paper. The major errors and selected minor errors were changed. In particular, Dr. Anand's figure from the Istek Proceedings was incorrectly reproduced and the original article figure has been substituted.

Our apologies are extended to the cited experts and to the readers of the journal. We also thank you for calling this to our attention.