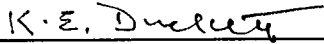


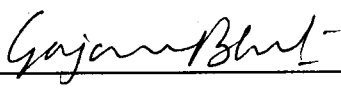
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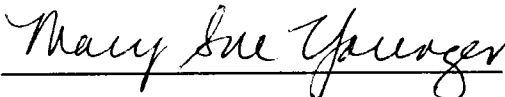
I am submitting herewith a dissertation written by Nataraj Gosavi entitled "Development of Cotton Nonwovens for Protective Applications". I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Human Ecology.


Larry C. Wadsworth, Major Professor

We have read this dissertation and
recommend its acceptance:







Accepted for the Council


Associate Vice Chancellor and
Dean of the Graduate School

DEVELOPMENT OF COTTON NONWOVENS FOR
PROTECTIVE APPLICATIONS

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Nataraj Gosavi

May 1995

DEDICATION

This dissertation is dedicated to my parents, Mr. and Mrs. G. Jagannath Bhatt whose encouragement, support, and unbelievable judgment has always been a constant and a guiding factor in my extraordinarily long student life.

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ABSTRACT

In Part A of this study, ten cotton based laminates were produced by thermally bonding cotton cores placed between melt blown webs and/or spunbond web as the outer layers. Six cotton laminates were repellent finished to further improve barrier properties. All the laminates were tested for barrier, drapability, and strength properties. Six unfinished and finished cotton laminates were tested for Kawabata Evaluation System (KES) analyses, moisture vapor transport rate (MVTR), and synthetic blood penetration test. Repellent finished laminates had better barrier properties and had higher drapability, while the unfinished laminates displayed higher strength. KES analyses showed that the laminate having 80% cotton had the best mechanical hand properties. Laminates having spunbond web had the highest MVTR among all the laminates. Repellent finishing was found to slightly decrease the MVTR of all the laminates having melt blown outer layers. The Wilcoxon Signed Rank test was used to determine if the differences in the properties of the unfinished and finished cotton laminates were statistically significant at the 0.05 level. In the comparison of cotton laminates with commercial Spunbond/Melt Blown/Spunbond (SMS) and Kappler's spunbond/ microporous/spunbond (Pro/Vent®) surgical gowns, it appeared that the SMS gown had better strength properties than the cotton laminates although the cotton laminates displayed better barrier properties. The SMS and the cotton laminates did not pass the synthetic blood test. The Pro/Vent® gown was found to be better than the cotton laminates and the SMS gown in terms of drapability, strength, and barrier properties.

Attempts were made in Part B of this research to overcome the two main deficiencies of the thermal bonded laminates (Part A) regarding the stringent

barrier requirements and higher processing speeds by thermally and adhesively bonding cotton laminates having microporous films. The thermal bonding and preliminary adhesive bonding (melt blowing a hot melt adhesive between constituent layers using a conventional melt blowing line) of cotton laminates used two commercial microporous films (such as Polytetrafluoroethylene {PTFE} Tetratex™ and the Polyethylene Exxaire®) and point calendered the laminates using rolls at ambient and slightly elevated temperatures. A few of the thermal and preliminary adhesive bonded laminates passed the synthetic blood penetration test, but did not pass the more rigorous viral penetration test.

An adhesive melt blown line was used to coat the constituent layers (including two weights of Polyethylene Exxaire® film) and the laminates were smooth and point bonded at ambient temperature. The adhesive smooth bonded laminates were most successful in resisting the rigorous blood and viral penetration, had good moisture vapor transmission rates, had much faster processing speeds, and had no restrictions on the number of layers in a laminate. The Wilcoxon Signed Rank Test was used to determine the statistically significant differences between the properties of the adhesive smooth and point bonded laminates at the 0.05 level.

Darcy's equation (for flow through porous media) and Textile Research Institute's Liquid-Air Displacement Analysis Instrumentation was used to theoretically and experimentally, respectively, determine the permeability constant of the cotton laminates. Both techniques determined that laminates having two spunbond webs were the most permeable followed by laminates having one spunbond and one melt blown layer followed by laminates having both melt blown layers.

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CHAPTER 1

INTRODUCTION

Nonwoven materials are widely used in hospitals as surgical gowns, drapes, masks, and CSR wraps to shield professionals providing healthcare, and patients receiving treatment from infection [1, 2, 3]. Besides being effective barriers, nonwoven materials are also useful in numerous applications in hospital and healthcare settings. Cotton fiber has several unique properties that are desirable in medical/surgical nonwovens such as remarkable absorbency, highly efficient wicking, excellent heat resistance, good processability, resilience, softness, and its ability to be sterilized by several techniques [3, 4]. A superior combination of comfort and aesthetics can be attained by the use of cotton based nonwovens. This, combined with the legendary feel of cotton, is a great advantage in these products. Hence the growth of cotton based nonwovens is guaranteed not only because of the few currently existing nonwoven products having cotton but also because of certain technical and aesthetic benefits provided by cotton fibers [5].

This research was conducted at the Textiles and Nonwovens Development Center (TANDEC) of The University of Tennessee, Knoxville to explore possible nonwoven medical product applications in which cotton could be utilized to take advantage of its good strength and comfort properties, as well as the fact that cotton is a renewable, biodegradable natural fiber. Preliminary research [6, 7] has been performed in developing and studying the use of laminates containing bleached, carded cotton cores with outer layers of polypropylene (PP) melt blown (MB) and/or spunbond (SB) webs serving as

binder fiber materials during the subsequent thermal point bonding step. MB and SB webs together with the cotton fibers impart both strength and barrier properties to the laminate. From earlier studies, it appeared that MB webs imparted greater barrier properties lower to the laminates than did SB webs, while SB webs imparted higher strength and air permeability.

Based on the above discoveries, The University of Tennessee Research Corporation (UTRC) filed U. S. Patent Application No. 07/842,888 on February 26, 1992 entitled "Novel Composite Web" with L. C. Wadsworth, K. E. Duckett and V. Balasubramanian being the inventors. Cotton Incorporated - the research and promotion company representing American cotton producers - has funded research and development of cotton based nonwovens at The University of Tennessee, Knoxville since July 1992. The **objective of Part A** of this study was the development of cotton based laminates for protective apparel (when repellent finished) such as surgical gowns and drapes, and for personal hygiene applications (when a heavier weight cotton core is used) such as diapers, sanitary napkins, pads, and wipes.

The cotton laminates developed in Part A of this study performed well as barriers quantified by the water resistance tests. But they were insufficient barriers to the penetration of blood.

Increased exposure to bloodborne pathogens (such as HIV and Hepatitis B) has raised the risk level of most healthcare providers. While studies have shown relatively few instances of HIV infection in the hospitals, healthcare professionals are now mandated by law [8] to wear appropriate protective apparel to protect themselves and their patients [9].

It should be borne in mind that the end users of protective apparel (such as doctors and nurses) have a notable influence on the selection of operating

room (OR) gowns and view breathability as important as barrier performance. Very few film reinforced OR gowns meet the tough dual requirements of barrier and breathability properties at a low enough cost. The reason for this difficulty prior to the development of the breathable barrier fabric containing microporous films and cotton in Part B of this study is that microporous films which have been found to be breathable are open to viral penetration. Heretofore, most of the fabrics that prevented viral penetration contained nonporous films which have no breathability but resist viral penetration.

In Part B of this research, microporous films were incorporated in cotton based laminates and the structure was bonded at ambient conditions using a hot melt adhesive. These adhesive bonded cotton laminates provide a very good balance of excellent barrier properties and good breathability properties. A patent application (Serial No. 309541) has been filed for this technology. Thus the **objectives of Part B** "to develop the combination of barrier and breathability properties in cotton based laminates to make them suitable candidates for protective apparel" appears to have been achieved in a large measure.

C H A P T E R 2

L I T E R A T U R E R E V I E W

NONWOVENS

Nonwoven materials are unconventional textile assemblies that are slowly replacing the use of traditional woven/knitted fabrics in household and industrial applications. Nonwovens are defined [10] by INDA the Association of Nonwovens Fabrics Industry as "sheet or web structures made by bonding and/or interlocking fibers, yarns, or filaments by mechanical, thermal, chemical, or solvent means". These fabrics do not require the conversion of fibers to yarns and are manufactured by processes other than spinning, weaving, or knitting, hence the name "nonwovens". Thus, the basic elements of a nonwoven structure are fibers that are either natural or synthetic. Today, various types of nonwovens are produced, aimed at meeting specific end uses. The ingenuity in fiber research is being exploited by the nonwovens industry to design functional as well as aesthetic fabrics for a wide range of products from baby diapers to aerospace applications.

Nonwoven Types

The basic nonwoven types can be classified according to the way the webs are produced, as shown in Figure 1. During the first stage, individual fibers are formed or acquired. A very weak thin web of these fibers is produced in the second stage. A coherent bonded web is produced in the final stage by

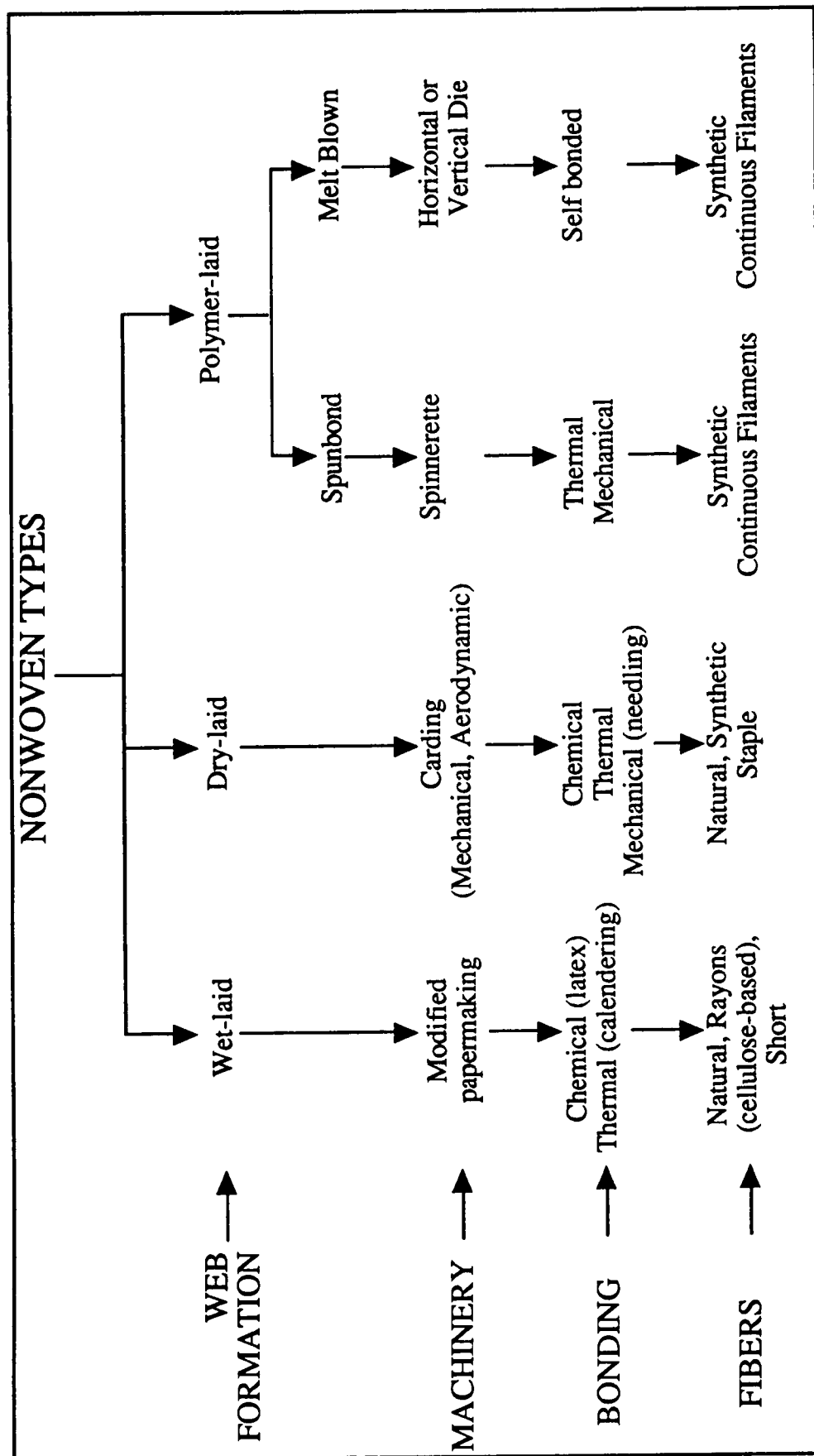


Figure 1. Classification of Nonwoven Types.

introducing fiber-to-fiber contacts with appropriate bonding. The difference in the properties between a conventional textile fabric [11] and a nonwoven web is largely dependent on the way they are engineered. The properties of a nonwoven web are dependent on:

- fiber type, diameter and fineness
- fiber strength and elongation
- fiber to fiber frictional properties
- fiber geometry and orientation
- chemical properties (functional groups of fibers)
- thermal properties (heat conductivity, melting point, glass transition etc.)
- web formation methods
- types of bonding
- number of bonds and the distance between bond areas
- number of pores, pore sizes and distribution of pores

Fibers Used in Nonwovens

All natural [12] and synthetic fibers that are commercially available can be used to produce nonwoven webs. In practice, wood pulp, which is far shorter in length than the conventional textile fibers is the only natural fiber used in large amounts because of its high water absorbency, bulk and low cost. Cotton has excellent inherent properties for nonwovens. Wool and linen are too expensive for nonwoven fabrics. Viscose rayon has been widely used in the nonwovens industry in the area of disposables and sanitary products. Rayon fibers can be easily made into nonwoven webs and readily bonded.

Among the synthetic fibers polypropylene (PP) is widely used because it is inexpensive and has very good rheological characteristics to form fine fibers. PP fibers are hydrophobic, voluminous and thermoplastic in nature. PET (polyethylene Terephthalate) is used where strength and mechanical properties are of prime importance. Nylon fibers are used for their excellent recovery

(resiliency) properties. Cellulose acetate and poly-vinyl alcohol fibers are used in nonwovens also. Bicomponent fibers with different fibers in the core and sheath are widely used in thermally bonded nonwovens.

Web Forming Methods

The basic web forming methods are shown in Figure 1. The selection of a particular method is dependent on the end use of webs, availability, and cost of fibers. The most widely used web forming methods are wet-laid, dry-laid and polymer-laid. Irrespective of the methods chosen, the webs produced should be of superior quality, clean, and without any defects such as thick and thin places. Since dry-laid and polymer-laid webs are used in this research, they are discussed below.

Dry-Laid

Dry-laid webs [13] are produced from staple fibers which range from 1.2 to 20 cm long. The fibers from the bales are thoroughly opened and cleaned by using conventional openers and beaters. The dry-laid webs can be categorized into mechanically (oriented webs) and aerodynamically (random webs) formed webs. The mechanically formed webs are usually produced by carding machines that utilize opposed moving beds of closely spaced needles to pull and tease the clumps apart. When the clumps are caught between two moving surfaces whose surface velocities are quite different from one another, the result is a disentanglement of lumps and individualization of fibers. Modern cards with sophisticated suction systems for dust extraction are currently available in the market that can be used to produce clean webs with little nep formation.

Carded webs are predominantly oriented in the machine direction and, hence, the strength of the webs is higher in the machine (5:1) than in the cross direction. To overcome this problem of unbalance in the properties, cross-laying process can be employed. In this method, an oriented web is laid down at or near alternating 45° onto another oriented web moving on a transporting belt.

The air-laying techniques are used to produce randomly oriented webs. These machines utilize a carded web or a lap. The fibers are individualized by needles and then introduced into an air stream. Total randomization would avoid any preferential orientation when the fibers are collected on the screen. The length of fibers is normally between 1.9 to 6.4 cm. Production of air-laid webs is slower and more expensive than that by carding.

Polymer-Laid

Spunbond. This falls into the category of direct conversion of polymers into nonwoven webs. A typical spun bonding process would consist of the following four steps [14]: extrusion of filaments, drawing, lay down and bonding. The first three operations are similar to the conventional melt spinning process and the bonding step results in web consolidation. The filaments formed by this method are virtually endless.

A typical spunbond line [14] consists of the following elements: an extruder, a metering pump, a die assembly, a filament spinning unit, a drawing and deposition system, a belt for collecting the filaments, a bonding zone, and a winding unit. The drawing and deposition of spun filaments in spunbonding is achieved using specially designed aerodynamic devices. The process variables [14] in the spun-laying process can be classified into operational and

material variables. The operational variables can further be classified into on-line variables (such as, polymer throughput, polymer/die temperature, quench air rate and temperature, takeup speed, bonding conditions) and off-line variables (such as spinneret hole size, spinneret-to-collector distance, etc). The material variables include polymer type, molecular weight, molecular weight distribution, etc. The following are some of the important characteristics [14] of a spunbonded web:

- a random orientation of fibers (isotropic)
- the basis weight ranges between 5 to 800 gsm
- the fiber diameter ranges between 1 to 50 μm , with the preferred range being 15 to 35 μm
- a high specific strength (strength/weight) compared to other nonwovens

Melt Blown. Microfine fibers can be produced by a Exxon patented one-step process from bulk polymers known as "Melt blowing process". The molten polymer [12] is forced through very fine holes in a special die into a high velocity air stream where the polymer is formed into very fine, although irregular filaments of indeterminate lengths. Virtually, all thermoplastic polymers can be used to produce melt blown webs. But, Polypropylene & Polyester are the most widely used fibers used in melt blowing.

Polymer throughput rate [14], air throughput rate, polymer/die temperature, air temperature, die-to-collector distance, are important operational variables. The material variables include polymer type, molecular weight, molecular weight distribution, degradation, etc. Some important [14] characteristics of melt blown webs are:

- random fiber orientation
- high cover factor
- fiber diameter of 2 to 7 μm
- basis weight of 20 to 200 gsm

- high surface area suitable for insulator and filter characteristics

Bonding Methods

The bonding of fibers gives strength to the web and influences other web properties. There are three major bonding methods that are widely employed to produce webs with sufficient integrity. They are, chemical (adhesive based), thermal (using thermoplastic fibers) and mechanical (needling to cause entanglement). Other techniques include spunlacing (using high velocity water jets), ultrasonic bonding (high frequency), stitch-bonding and powder bonding. The thermal and adhesive bonding methods were used in this research and are discussed below.

Thermal Bonding

Thermal bonding [15] of nonwovens involves the use of heat energy to activate an adhesive process for the purpose of interlocking fibers and consequently consolidating or providing dimensional stability to fiber webs. The adhesive component is subjected to heat. As the adhesive approaches its melting point, its surface softens, and area of contact with more stable fibers expand to form potential bonding sites. Upon melting, the liquefied adhesive is attached to a network fiber, and flows along the network fiber to a crossing of two or more fibers. Once the nonwoven material is cooled, the adhesive solidifies and forms a bond or thermal fusion at each fiber contact.

In thermal bonding, fiber surfaces are fused to each other by melting the fiber surfaces or by melting fusible additives in the form of a powder, granules or fibers. Calendering is a method of bonding in which the web is pulled between

heated rollers so that the web is exposed to heat and pressure necessary to bond the constituent fibers and layers together. The calender rolls [16] may be smooth or embossed, or a combination of both. Two smooth rolls lead to the bonding over the entire surface (called "area bonding") of the web making the end product stiff and less drapable. The use of one embossed roll with a raised pattern (at the top) and one smooth roll (at the bottom) leads to only a portion of the web exposed to the heat and pressure of rolls to be bonded. This is called as "point bonding". The resultant product has good drape, hand, and strength.

Polypropylene, polyester, rayon, and wood pulp are the fibers used to make webs by thermal bonding. The most commonly used fiber is polypropylene. Even though Polyester fibers are used, its high melting temperature is seen as a limiting factor [17]. The thermal bonding process has been widely accepted in the nonwovens industry because of its simplicity and its many advantages over traditional chemical bonding methods. Low raw material and energy costs, product versatility, lesser space requirements, cleanliness of the process, better product quality characteristics, and increased production rates are the features that have been the reasons for its widely gained acceptance. Since the binder powders or fibers are mixed into the web, thermal bonding processes are rapidly adaptable to the manufacturing and designing of composite structures.

Chemical Bonding

In the chemical/adhesive bonding [14] method, a film forming polymer latex is deposited in and around the fibrous structure and then cured (heated) to activate bonding. The bonding agent is usually sprayed or saturated in the web. Until recently, the most widely used bonding agents have been synthetic

latices such as polyacrylates, polyacetates, polychlorides, polyacrylonitriles, and copolymers. The advantages are the ease of handling and low cost. Latices are effective for hydrophilic fibers, but not useful for synthetic fibers like PP, PET, etc. To be a good binder [18] the polymeric material should have high strength, good adhesion to fibers, good flexibility, good elastic recovery, very good resistance to washing, dry cleaning, and aging, low weight, and color retention.

Adhesive Melt Blowing. A new method of bonding [19] called "adhesive melt blowing" uses hot air and sprays hot melt adhesive fibers on to another substrate to enable bonding of constituent layers. In conventional melt blowing, large volumes of hot, high velocity air at much higher polymer melt temperature are required to draw the viscous polymer (which are usually high molecular weight) into fine fibers.

On the other hand, in adhesive melt blowing, low volumes of air flow (1 SCFM/inch of die) and pressure (10 - 25 psi) are capable of producing relatively large hot melt filaments (30 - 125 μm) [19] which provide a very effective bond between laminate layers that does not notably restrict breathability. The adhesive melt blowing technique has been promoted as being the most effective method of substrate bonding based on: wide range of fiber size, fiber distribution, stringent edge control, excellent product aesthetics, minimal operator interface, low air consumption, and overall system maintenance [19].

Medical Nonwovens

Disposable nonwovens in the medical/healthcare area are nearly three decades old [2] and have been successful in moving from a phase of reluctance to a phase of acceptance [20]. The initial reluctance (to accept nonwovens) on the part of the medical community was mainly due to insufficient knowledge of the health and labor saving benefits, and due to a perceived poorer quality of the products.

Increasingly effective marketing strategies and distribution of technical data on the improved barrier properties, as well as improved comfort and aesthetics have helped to change this scenario. Nonwovens have been shown to be cost effective and studies at Duke University have shown that they notably reduce post operative infections [21]. The availability of nonwovens to meet specific end uses has facilitated greater convenience in storage and identification, leading to savings benefits in equipment, labor, and inventory in the healthcare establishments. Medical nonwovens are one of the more easily recognizable end use segments of the nonwovens industry [22]. Medical nonwovens have proved invaluable in varied products from surgical drapes to operating room gowns to adult incontinence products. The aforementioned wide variety of products are produced by a range of nonwoven processes.

Surgical caps, masks, and shoe covers have almost complete acceptance (90 - 100%) in the United States hospitals because they are lightweight, relatively inexpensive, and provide effective protection [2]. In the areas of surgical drapes and gowns (articles used to protect the patient and hospital personnel, respectively, from infection during a surgical procedure) the nonwovens have a 90% share of the market [23]. Only a psychological barrier

needs to be transcended for nonwovens to achieve a penetration of 75 - 80% in the entire operating room environment.

Face masks. A face mask is used to filter a wearer's breath, coughs, and sneezes to remove bacteria that could contaminate a patient. Due to this increasing concern over AIDS and hepatitis, the ability of face masks to filter out very fine particles down to 0.1 micrometer which may contain the viruses has made healthcare users even more concerned about wearing them for their own protection as well. Chemically and thermally bonded carded webs, melt blown webs, needled webs and spunbond webs are the nonwoven materials used in making surgical face masks.

Caps and shoe covers. These materials are used for the purpose of creating aseptic barriers between the patients and those serving them [24]. Spunbond, hydroentangled, and chemically bonded carded nonwovens are used in this area.

Central supply room wraps. These are used to wrap the instruments (used in surgery) before sterilization in order to keep the instruments sterile. The ability of a wrap to act as a barrier is vital in this application. The lack of sufficient barrier properties of woven reusable textiles is seen as an advantage for nonwovens to increase their market penetration in this application.

Personal hygiene products. These include diapers, sanitary napkins, adult incontinence products, and underpads. Chemical and thermal bonded, spunbond, and highloft products are used in this area. Efforts are being made to increase the share of nonwovens in wound dressings, where they provide the much needed properties like "softness, absorbency, wicking, easy don and doff, low linting and fraying, and low per-use cost" [24, 25].

Surgical drapes and gowns. The most common source of infection in the operating room environment is through microorganisms. In order to prevent infection it is vital that surgical drapes and gowns which are effective barrier for the protection of patients and hospital personnel respectively.

Concern among the healthcare professionals about infection by bloodborne pathogens has created a heightened interest in the nonwovens research area towards the development of barrier materials that provide the highest level of protection. The lack of knowledge (or lack of determination) of whether a patient is infected with (or a carrier of) bloodborne pathogens and their large numbers makes it vital for all healthcare providers to use precaution and treat every body fluid as infectious. The uncertainties stated makes it critical that all healthcare employers determine the risk of infection to their employees and equip them with the required level of protection in compliance with the Occupational Safety and Health Administration (OSHA) standard.

Traditionally, surgical gowns have been used by the healthcare providers to ensure that the patients do not contract any infection while receiving quality care in a hospital. The possibility of the healthcare provider becoming infected by Human Immunodeficiency (HIV) or Hepatitis B (HBV) viruses or any bloodborne pathogens from the patients is greater at this time than at any other time in the history of the profession of healthcare [9, 26]. In the operating room, blood frequently strikes or splashes on the surgical gown, is absorbed by the scrub suit, and has a good possibility of contaminating the doctor's skin [26]. Unfortunately, this could be a medium of spreading any bloodborne pathogens such as HIV or HBV which exist in sufficient concentrations in blood making infection possible by even a small amount of contaminated blood strikethrough [27].

According to the OSHA [8], more than 5.6 million healthcare and public safety workers are at potential risk of being exposed to these viruses. This risk has led OSHA to recognize the critical nature of bloodborne pathogens and mandate a law on personal protective equipment (PPE) with the long term goal of reducing the risk of occupational exposure to bloodborne diseases. PPE is defined by OSHA as "specialized clothing or equipment worn by an employee for protection against a hazard." Gowns, aprons, drapes, and masks are items included in this designation that utilize nonwovens in the protective apparel market. PPE is considered to be "appropriate" only if it "does not permit blood or other potentially infectious materials to pass through to or reach the employee's work clothes, street clothes, undergarments, skin, eyes, mouth, or other mucous membranes under normal conditions of use and duration of time which the protective equipment will be used" [28]. Amount of exposure, duration of usage, and conditions during usage are criteria helpful in determining the efficacy of PPE for a certain task.

Barrier protection, comfort and convenience during usage, and cost of the product are vital factors under consideration in the process of selecting any protective apparel. The Association of Operating Room Nurses (AORN) has recommended guidelines for evaluation, selection, and use of protective barrier materials [29]. AORN recommends that i) "surgical gowns and drapes should be made of materials that minimize the passage of microorganisms from nonsterile to sterile areas" and ii) "gowns and drapes should be safe and comfortable for use in the practice setting". AORN also recommends that gowns and drapes be: nonabrasive, nonglaring, maintaining integrity over its expected life, maintaining an environment appropriate to body temperature, fit well and allow freedom of movement.

In recent years, disposable nonwoven surgical gowns and drapes have been providing the highest possible barrier, comfort and convenience of use properties at a low cost. Nonwoven protective apparel over the course of the years have become irreplaceable by virtue of superior patient care, a consistently high degree of protection, comfort, and performance while providing cost savings [9].

Different types of disposable surgical gowns have been developed by the nonwovens industry. They range from layered materials with little or no reinforcements to fully reinforced materials. The regular gowns (ex. Baxter's Optima™ 9515 spunlace gown with no reinforcement and Kimberly-Clark's Evolution Specialty 90112 zoned, fabric reinforced {PP SB Face, PP MB Microfiber core, 2 layers of PP SB back}) that have little or no reinforcing do not meet the stringent barrier test requirements regarding the blood and viral tests [30]. Gowns such as Kappler Safety Group's PRO/VENT™ (PP SB Face, microporous film core, PP SB back) having microporous film in the whole gown passes the blood penetration test whereas it does not pass the viral penetration test. It has a upright cup moisture vapor transmission rate of 1019.35 g/m².24hr. Surgical gowns such as Baxter's Optima™ Reinforced (Spunlace Face, PE Film Back) and Kimberly-Clark's Evolution Specialty 90312 zoned, (1.0 mil extrusion coated PE coating, PP SB Face, PP MB Microfiber core, PP SB back) pass both the blood and viral penetration tests. But, Baxter's Optima™ Reinforced and Kimberly-Clark's Evolution Specialty 90312 gowns are seen to have very poor breathability (0.0 g/m².hr) [31]. The most advanced group of gowns that pass the blood and viral tests and also have good moisture vapor values include Baxter's ViraBlock (Spunlace Face, Film Back) and 3M's Prevention (SB PP FACE, PP microporous membrane Back) [32]. The moisture vapor value of

Prevention is claimed to be in the 6000-10000 g/m².24hr, as measured by Kansas State University. The moisture vapor value of ViraBlock is not available from literature. It should be noted that though it is known that Baxter's ViraBlock and 3M's Prevention pass the resistance to blood and viral penetration tests, no information is available in these product brochures regarding the construction, weight, thickness, or cost of these gowns which are considered to be proprietary information. Companies thus far have not agreed to provide samples of these surgical gowns for comparative testing.

In addition to good barrier properties, surgical gowns and drapes should have properties such as high vapor transmission, good drapability, high tensile and bursting strength, and good repellency [24]. In addition to the aforementioned properties, drapes need to have good fire retardancy, low linting, and low glare [24]. Spunlace (composite of polyester fiber and wood pulp fiber) and spunbond-melt blown-spunbond (SMS) fabrics are the most used nonwoven materials in these applications.

MICROPOROUS FILMS

Microporous membranes are defined as "having a narrow pore size distribution usually in the sub-micron range, although they span the range from 1.0 to 10 microns" [33]. Historically they have been used for a wide range of functions from filtration of bacteria to being a diaper backsheet. Exxaire® microporous film is a breathable film "that is produced by stretching of a precursor film prepared from a polyolefin/filler composition" [34]. Polyolefin microporous films have been commercially available from Exxon Chemical since 1988 [35]. These films are less expensive than membranes such as

Goretex® which consists of polytetrafluoroethylene, and is mostly intended for durable or multiple use applications. Exxaire® microporous film has been promoted as having a balance of good barrier and breathable properties at relatively low cost which makes the film suitable for nonwovens. Microporous films have a better combination of barrier and breathability properties in contrast to monolithic (nonbreathable) films that have excellent barrier, but low MVTR [35]. The breathability of most of the microporous membranes depends on the pore sizes of the films. Water vapor transmission rates (WVTR) of Exxaire® microporous films used by us were in the range of 6000 to 8000 g/m²-24hr. The test procedure to determine the WVTR of these films uses a diffusion cell consisting of a dry chamber separated from a wet chamber (whose temperature and humidity is known) by a film whose WVTR is to be measured. The diffusion cell is placed in a test station where the dry chamber and the top of the film are swept with dry air. Water vapor diffusing through the film mixes with the dry air and is carried further to a pressure-modulated infrared sensor which measures the fraction of infrared energy absorbed by the water vapor and produces an electrical signal, the amplitude of which is proportional to water vapor concentration. The amplitude produced by the film being tested is compared to the amplitude of a signal produced by a calibration film of known transmission rate and the obtained information is used to calculate the WVTR through the film being tested.

CHAPTER 3

EXPERIMENTAL DESIGN and PROCEDURES

EXPERIMENTAL DESIGN

Part A: Thermal Bonded Laminates

Materials

The 1.0-meter wide polypropylene (PP) melt blown (MB) precursor webs were prepared at weights of 0.25, 0.50 and 0.75 oz/yd² (8.475, 16.95, 25.425 g/m²) at the Accurate Products Company (maximum width of MB lines at TANDEC is 0.50 meter) Hillside, New Jersey. The 0.60 oz/yd² (20.34 g/m²) PP spunbond (SB) web was produced at TANDEC using the 1.0-meter wide Reicofil spunbond line. Veratec Easy Street™ scoured and bleached cotton was used to make core webs. A Hollingsworth 40-inch (1.0-meter) card with flat tops and a Web Master Take-Off was utilized to produce a cotton core web with a weight of 1.0 oz/yd² (33.9 g/m²). Cotton webs of 1.5, 2.0 and 3.0 oz/yd² (50.85, 67.8, and 101.7 g/m²) were produced by employing a 2.50-meter Hollingsworth Master Card to feed the random carded cotton webs into a Hergeth Model 6.430 Crosslapper. These webs were lightly needled (125 punches/inch² {125 punches/6.25 x 10⁻⁴ m²} using one board) with a Dilo Model ODR needle loom using a Foster needle (15x18x3 style).

Process Description

Ten cotton-based nonwoven fabrics were produced at the John D. Hollingsworth Company in Greenville, South Carolina at a width of 40 inches (trimmed width of 36-inches {0.90 meter}) as described in Table 1. The 1.0 oz/yd² cotton web was made on-line while the heavier cotton webs (1.5, 2.0 and 3.0 oz/yd² {50.85, 67.8, and 101.7 g/m²}) were transported to the 40-inch (1.0-meter) carding and thermal bonding line and a MB/SB web was mounted at the rear of the conveyor system for the carded webs. The cotton web was unwound onto the MB/SB web traveling on the conveyor running under the card. The top MB/SB web was unwound onto the carded web and then the tri-laminate was conveyed at a 45° angle to the nip of the Kusters 2-Roll, 1.5 meter thermal calender with the top heated steel roll having a raised diamond pattern resulting in 16.6% bonded area. The bottom heated roll had a smooth steel surface.

The nomenclature adopted to identify the laminate fabrics is also explained in Table 1 in that MCM-40-2.35 represents a thermally bonded tri-laminate consisting of a PP MB web on both sides of a 100% cotton core web with the total cotton content in the laminate being 40% and a nominal weight of 2.50 oz/yd² (84.75 g/m²). Likewise, SCM-42-2.35 represents a tri-laminate fabric consisting of PP SB on the face side and PP MB on the back side with a total cotton content of 42% in the laminate and a nominal basis weight of 2.35 oz/yd² (79.665 g/m²). SCS-45-2.2 represents a tri-laminate fabric consisting of PP SB on the face and back side with a total cotton content of 42% in the laminate and a nominal basis weight of 2.2 oz/yd² (74.58 g/m²).

Table 1. Processing conditions of cotton based laminates.

Sample No.	Sample Description	Weight of Layers (oz/yd ²)	Total Weight (oz/yd ²)	Calender Speed (yd/min)	Nip Pressure (PLI)	Bonding Roll Temperature (°C)		Fabric Composition	
		Top/Middle/Bottom				Top	Bottom	% Cotton	% PP
MCM LAMINATES									
1C	MCM-40-2.5 ¹	0.75/1.0/0.75	2.5	11	200	136	131	40	60
2C	MCM-60-2.5	0.50/1.5/0.50	2.5	10	350	111	111	60	40
3C	MCM-80-2.5	0.25/2.0/0.25	2.5	10	300	110	111	80	20
4C	MCM-57-3.5	0.75/2.0/0.75	3.5	5	200	140	129	57.1	42.9
5C	MCM-67-4.5	0.75/3.0/0.75	4.5	6	330	132	130	66.7	33.3
SCM LAMINATES									
6C	SCM-42-2.35 ²	0.60/1.0/0.75	2.35	6	240	138	133	42.5	57.5
7C	SCM-53-2.85	0.60/1.5/0.75	2.85	5	600	140	130	52.6	47.4
8C	SCM-60-3.35	0.60/2.0/0.75	3.35	5	500	140	129	59.7	40.3
9C	SCM-69-4.35	0.60/3.0/0.75	4.35	4	470	140	130	69.0	31.0
SCS LAMINATE									
10C	SCS-45-2.2 ³	0.60/1.0/0.60	2.2	4	250	138	133	45.4	54.6

¹ MCM-40-2.5 represents a thermally bonded tri-laminate fabric consisting of a PP melt blown (MB) web on both sides of a 100% cotton core web with a total cotton content of 40% and a nominal weight of 2.5 oz/yd².

² SCM-42-2.35 represents a tri-laminate fabric consisting of a PP spunbond (SB) on the face side and PP MB on the back side with a total cotton content of 42% and a nominal weight of 2.35 oz/yd².

³ SCS-45-2.2 represents a tri-laminate fabric consisting of a spunbond (SB) PP on the face side and back side with a total cotton content of 45.4% and a nominal weight of 2.2 oz/yd².

Fluorochemical Finishing of Laminates

A fluorochemical finish was applied to the cotton based laminates in an attempt to improve their repellency and barrier characteristics. Dr. Ed Greenwood of the Du Pont Chemicals and Pigments Laboratory [36] recommended two different Du Pont fluorochemical (FC) and extender systems for these fabrics. The two formulations suggested were as follows:

Formulation No. 1

Zonyl 8070: 3.0%
Aerotex 96 Water Repellent: 2.0%
Remainder: Water

Formulation No. 2

Zonyl PPR: 3.5%
Aerotex 96 Water Repellent: 2.0%
Remainder: Water

The padding technique is suitable to treat these nonwovens because it has the capability of giving an uniform and deep penetration [37, 38, 39] of the finish. The padding optimization trials performed in TANDEC (using the 15-inch {0.375 m} laboratory padder) and at Cotton Incorporated's Research Facility in Raleigh, NC (using a commercial-size padder) indicated that both of the above formulations resulted in acceptable repellency properties at commercial add-on levels recommended by Du Pont. Since no notable differences could be seen between the two formulations, Formulation #1 was selected because Zonyl 8070 was more recently developed for repellent finishing polypropylene and was effective at the slightly lower add-on of 3.0%. The Aerotex 96 water repellent is a melamine resin which was added as an extender. Six cotton based (3 MCM and 3 SCM) laminates were repellent finished using Formulation No. 1 on a commercial-size Greenville Machinery Company Padder at Cotton Incorporated. The laminates were then cured off-line in a Ruckh relaxation dryer at 121°C for 2.50 minutes. The nip pressure was adjusted at 60 psi in order to get the desired wet pick up percentage (WPU%) of

100. The wet pick up percentage of the MCM and SCM laminates are given in Table 2. A suffix of "-R" was used to indicate laminates that were repellent finished.

Testing of Properties

The cotton based laminates were tested for various barrier, comfort, and strength properties. They were also tested for absorption and retention capacity, wicking capacity, vertical flammability, and 45° flammability.

All six unfinished and repellent finished laminates were sent to North Carolina State University's College of Textiles Comfort Laboratory for KES analyses and moisture vapor transport studies. The same samples were also sent to Nelson Laboratories for the Synthetic Blood Penetration Test (ASTM Designation: ES 21-92).

Part B: Cotton Laminates Incorporating Microporous Films

The thermally bonded cotton based laminates (made in Part A of this research) were sufficiently breathable and comfortable, but they failed to resist the penetration of blood as determined by ASTM ES21-92 (and hence were not subjected to the viral penetration test). The presence of a cotton core between two thermoplastic layers (such as two melt blown webs, two spunbond webs, or a combination of melt blown and spunbond webs) was like an insulator to the conduction of heat between the layers and subsequent melting necessary for thermal bonding of the cotton containing laminates. Thus the processing speed used for manufacturing the thermal bonding laminates was restricted to the

Table 2. Wet pickup % of repellent finished laminates.

Sample No.	WPU %
1C - R	111.5
2C - R	98.2
3C - R	92.4
7C - R	86.0
8C - R	91.2
9C - R	92.4

range of 4 to 11 yd/min (3.66 to 10.1 m/min). This could be a potential hindrance in the manufacturing of these laminates in an industrial environment wherein much higher processing speeds are utilized. Attempts were made in Part B of this research to overcome the two main deficiencies of the thermal bonded laminates regarding the stringent barrier requirements and higher processing speeds by:

- i) Thermally bonding cotton laminates with microporous films. Two commercially available microporous films such as the Polytetrafluoroethylene (PTFE) Tetratex™ film and the Polyethylene Exxaire® film were used.
- ii) Melt blowing a hot melt adhesive between the constituent layers (including microporous films) using a conventional vertical melt blown line. The laminates were then point bonded with the rolls at ambient and slightly elevated temperatures. Two commercially available microporous films such as the Polytetrafluoroethylene (PTFE) Tetratex™ film and the Polyethylene Exxaire® film were used.
- iii) Using an adhesive melt blown line to coat the constituent layers (including microporous films) of the laminate structure. Smooth and point bonding were used to bond the laminates at ambient temperature in an attempt to compare the effect of bonding on the properties of the laminates. Two weights of Polyethylene Exxaire® microporous film were used because Exxaire® film appeared to work well in the trial adhesive lamination and was relatively inexpensive.

Thermal Bonding of Cotton Laminates with Microporous Films

Twelve thermally bonded (without adhesives) laminates (Table 3) having melt blown and/or spunbond outer layers with cotton and microporous film core were made by feeding the constituent layers to the nip of the Kusters 2-Roll 1.0 meter wide thermal calender with the top heated steel roll having a raised diamond pattern resulting in 14.66% bonded area and the bottom heated roll having a smooth steel surface. These laminates were processed using a nip

Table 3. Processing conditions of thermally bonded laminates having microporous film.

Sample No.	Sample Description	Weight of Layers (oz/yd ²)	Calender Speed (m/min)	Nip Pressure (PLI)	Bonding Roll Temperature (°C)	
					Top	Bottom
1	MB/PTFE/C/PTFE/MB	0.5/0.5/0.75/0.5/0.5	3.6	150	121	121
2	MB/C/PTFE/MB	0.5/0.75/0.5/0.5	3.6	150	121	121
3	MB/EXXAIRE/C/MB	0.5/0.94/0.75/0.5	3.6	150	121	121
4	SB/C/PTFE/MB	0.6/0.75/0.5/0.5	3.6	150	135	135
5	MB/EXXAIRE/C/EXXAIRE/MB	0.5/0.94/0.75/0.94/0.5	3.6	150	121	121
6	SB/C/EXXAIRE/SB	0.6/0.75/0.94/0.6	3.6	150	135	135
7	SB/C/PTFE/SB	0.6/0.75/0.5/0.6	3.6	150	135	135
8	SB/C/EXXAIRE/MB	0.6/0.75/0.94/0.5	3.6	150	135	135
9	MB/EXXAIRE/MB	0.5/E0.94/0.5	3.6	150	121	121
10	SB/EXXAIRE/SB	0.6/0.94/0.6	3.6	150	135	135
11	MB/PTFE/MB	0.5/0.5/0.5	3.6	150	121	121
12	SB/PTFE/SB	0.6/0.5/0.6	3.6	150	135	135

MB = Polypropylene Melt Blown web, **PTFE** = Microporous Polytetrafluoroethylene (TEFLON) Film, Tetratex™ (0.5 oz/yd²), from Tetratex Corporation, **C** = Bleached and Carded Cotton web, **EXXAIRE** = Polyethylene Microporous Film, Exaire® (0.94 oz/yd²) from EXXON Chemical, **SB** = Polypropylene Spunbond web.

pressure of 150 pounds/linear inch (PLI), 3.6 m/min surface speed, 135°C top and bottom roll temperature for laminates having one or two SB outer layers. For laminates having both MB outer layers, processing conditions of a nip pressure of 150 pounds/linear inch (PLI), 3.6 m/min surface speed, and 121°C top and bottom roll temperature were used. Thermal bonding of the laminates with Exxair® film on one or both sides of the cotton core layer and with MB PP outer layers caused these laminates to pucker up. Apparently, the thermal bonding process also produced pin holes in that the cotton laminates containing Exxair® film failed the blood penetration test. Thermally bonded laminates with polytetrafluoroethylene (PTFE) film appeared to result in better strength and barrier properties (most samples passed the blood penetration test) than thermally bonded laminates having Exxair® film. Five of the six thermally bonded laminates that passed the resistance to synthetic blood test (ASTM ES21-92) had microporous PTFE film Tetratex™ from Tetratex Corporation. Only one of the samples that passed this test had the microporous Exxair® polyethylene film from Exxon Chemical Corporation.

Adhesive Bonding of Cotton Laminates Using Conventional Melt Blown Line to Apply a Hot Melt Adhesive

Efforts were made to minimize the detrimental effects of thermal bonding the cotton laminates containing polyolefin microporous films such as Exxair® PE film. It was decided that a PP based hot melt adhesive would be utilized that could be melt blown onto nonwoven substrates and microporous films so that bonding of the layers could be achieved with little or no applied heat in the subsequent calendering stage. The advantages to be obtained by this method included bonding at higher processing speeds and with no restrictions on the

number of layers (components) in the laminate structure since heat transfer through the component layers would not be required to achieve bonding. The hot melt adhesive was melt blown onto a 0.45 oz/yd² PP MB web, Exxair® film, and the PTFE film that were taped to a thick sheet of cardboard and passed manually below the conventional vertical melt blown die to get an add-on range of 0.088 to 0.147 oz/yd² (3 to 5 g/m²). The seven different compositions described in Table 4 were manually prepared assuring that the cotton web and the films had adhesive on either side in order to obtain adequate sticking of the cotton web and the films to the melt blown webs. The adhesive coated laminates were then fed to the nip of the Kusters 2-roll, 1.0-meter wide thermal calender with the top heated steel roll having a raised diamond pattern resulting in 14.66% bonded area and the bottom heated roll having a smooth steel surface. At room temperature ($\approx 20^{\circ}\text{C}$), a nip pressure of 200 pounds/linear inch (PLI), and two surface speeds, 5 m/min and 10 m/min, were used to make four laminates. The calender rolls were then heated to the lowest possible temperature (when the oil heating system was in operation) of 95°C for the top roll and 92.2°C for the bottom roll. Two laminates were made using 200 pounds/linear inch (PLI) nip pressure and 10 m/min processing speed. One sample having only the adhesive coated Exxair® microporous film as the core was bonded using a surface speed of 20 m/min and a nip pressure of 150 pounds/linear inch (PLI). Microporous Exxair® polyethylene film from Exxon Chemical Corporation appeared to work well with the PP based hot melt adhesive and resulted in cotton based laminates having reduced thickness and higher bursting strength. The laminates having cotton in the core along with the microporous film were softer and stronger than laminates not having cotton in the core. The laminates that had cotton and were bonded at ambient

Table 4. Processing conditions of trial adhesive bonded laminates having microporous film.

Sample No.	Sample Description	Weight of Layers* (oz/yd ²)	Calender Speed (m/min)	Nip Pressure (PLI)	Bonding Roll Temperature (°C)	
					Top	Bottom
1	MB wA/EXXAIRE wA/C/MB wA	0.45/0.94/0.75/0.45	5	200	21.7	20
2	MB wA/PTFE wA/C/MB wA	0.45/0.50/0.75/0.45	5	200	21.7	20
3	MB wA/EXXAIRE wA/C/MB wA	0.45/0.94/0.75/0.45	10	200	21.7	20
4	MB wA/PTFE wA/C/MB wA	0.45/0.50/0.75/0.45	10	200	21.7	20
5	MB wA/EXXAIRE wA/C/MB wA	0.45/0.94/0.75/0.45	10	200	95	92.2
6	MB wA/PTFE wA/C/MB wA	0.45/0.50/0.75/0.45	10	200	95	92.2
7	MB wA/EXXAIRE wA/MB wA	0.45/0.94/0.45	20	150	95	92.2
8	MB wA/C/MB wA	0.45/0.75/0.45	5	150	21.7	20

MB wA = Hot melt adhesive melt blown on Polypropylene Melt Blown web, **EXXAIRE wA**= Hot melt adhesive melt blown on Polyethylene Microporous Film, Exxaire® (0.94 oz/yd² {31.866 g/m²}) from EXXON Chemical, **C** = Bleached and Carded Cotton web, **PTFE wA** = Hot melt adhesive melt blown on Microporous Polytetrafluoroethylene (TEFLON) Film, Tetratex™ (0.50 oz/yd² {16.95 g/m²}), from Tetratex Corporation.

* The basis weights of the MB web, EXXAIRE film, and PTFE film are their actual basis and do not include the weight of the hot melt adhesive deposited onto these layers. The add on of the hot melt adhesive onto one side of the MB or microporous films in the laminates was found to be in the range of 0.088 to 0.147 oz/yd² (3 to 5 g/m²). The basis weight of the cotton web is its actual basis weight because no hot melt adhesive was melt blown onto it.

temperature appeared to work well and passed the blood barrier test in all cases. Thus it appears that even higher surface speeds at ambient temperature may be utilized. Microporous Exxair® PE film from Exxon Chemical Corporation appeared to work well with the PP based hot melt adhesive and resulted in cotton based laminates with more desirable properties than laminates having PTFE film. Furthermore, it was found that even better results were obtained when no heat was applied to the calender rolls.

Adhesive Bonding of Cotton Laminates Using Adhesive Melt Blown Line to Apply a Hot Melt Adhesive

Since the adhesive bonding trials using the conventional vertical J and M melt blown line at TANDEC resulted in laminates with desirable properties, it was decided that the 13-inch (0.325-meter) wide Adhesive Bonding Line at J and M Laboratories would be utilized for further trials. This line was specifically designed by J and M Laboratories for the melt blown application of adhesives to use greatly reduced air flow and die temperature conditions.

Materials. The 0.50 and 0.75 oz/yd² (16.95 and 25.425 g/m²) 20-inch (0.50-meter) wide PP MB precursor webs were produced at TANDEC using the J and M Laboratories vertical melt blowing line. The 0.60 oz/yd² (20.38 g/m²) PP SB web was produced at TANDEC using the one-meter wide Reicofil SB line. The 0.75 oz/yd² (25.425 g/m²) carded cotton web, 0.65 oz/yd² (22.035 g/m²) thermal bonded cotton web (60/40 Cotton:T-196 PP web made by Hercules), and the 0.60 oz/yd² (20.38 g/m²) latex bonded cotton web (made by Stearns Technical Textiles using a Rohm and Haas acrylic binder) were obtained from Cotton Incorporated. The thermal bonded and latex bonded cotton webs were used to determine if pre-bonded webs worked as well as unbonded carded cotton webs

in the laminates. The thermal bonded and latex bonded cotton webs were easier to unwind and incorporate into the laminate structures for the production of prototype fabrics for wear studies and test markets. However, in a scaled up manufacturing process, it would be more economical to use unbonded carded cotton webs. The two microporous films (0.50 oz/yd² {16.95 g/m²} with a thickness of 1.0 mil and 0.94 oz/yd² {31.866 g/m²} with a thickness of 1.5 mil) used were Exxaire®, a polyethylene film produced by Exxon Chemical Corporation. The PTFE microporous film from Tetratex Corporation was not used because Exxaire® film appeared to work well in the trial adhesive bonded laminate runs at ambient temperature and gave the necessary blood barrier performance that was being sought. In any subsequent manufacturing, it would be much more economical to use Exxaire® film because it is less expensive than the PTFE film. A lighter weight Exxaire® film was used in these trials in an attempt to determine if it could provide the necessary barrier properties while lowering the overall basis weight of the laminate. The MB webs, SB web, Exxaire® film, and the cotton webs were all slit to 13-inch (0.325 m) width in order to utilize the 13-inch (0.325 m) wide J and M melt blown adhesive lamination line at J and M Laboratories. A PP based hot melt adhesive that could be melt blown was obtained from Findley Adhesives, Wauwatosa, Wisconsin.

Process Description. The adhesive bonded laminates were prepared according to conditions given in Tables 5 and 6 as illustrated in Figures 2 to 5. The J and M melt blown adhesive line has two adhesive dies (on opposite ends of the line) from which the hot melt adhesive was melt blown onto the MB, SB, thermal bonded cotton, and/or latex bonded cotton webs. Between 0.088 to 0.147 oz/yd² (3 to 5 g/m²) of PP based hot melt adhesive was deposited on the

Table 5. Processing conditions for adhesive smooth bonded laminates produced at J and M Laboratories.

Sample No.	Sample Description	Weight of Layers* Top/Middle/Bottom (oz/yd ²)	Calender Speed (m/min)	Nip Pressure (psi)
MFCM LAMINATES				
1A	MB wA/EXXAIRE wA/C/MB wA	0.50/0.94/0.75/0.50	5	90
2A	MB wA/EXXAIRE wA/C/MB wA	0.75/0.94/0.75/0.75	5	90
3A	MB wA/EXXAIRE wA/C/MB wA	0.50/0.50/0.75/0.50	5	90
4A	MB wA/EXXAIRE wA/C/MB wA	0.75/0.50/0.75/0.75	5	90
5A	MB wA/EXXAIRE wA/TC wA/MB wA	0.50/0.94/0.65/0.50	10	90
6A	MB wA/EXXAIRE wA/LC wA/MB wA	0.50/0.94/0.60/0.50	10	90
7A	MB wA/EXXAIRE wA/TC wA/MB wA	0.75/0.94/0.65/0.75	10	90
8A	MB wA/EXXAIRE wA/LC wA/MB wA	0.75/0.94/0.60/0.75	10	90
SFCM LAMINATES				
9A	SB wA/EXXAIRE wA/C/MB wA	0.60/0.94/0.75/0.50	5	90
10A	SB wA/EXXAIRE wA/C/MB wA	0.60/0.94/0.75/0.75	5	90
SFCS LAMINATES				
11A	SB wA/EXXAIRE wA/C/SB wA	0.60/0.94/0.75/0.60	5	90
12A	SB wA/EXXAIRE wA/C/SB wA	0.60/0.50/0.75/0.60	5	90
13A	SB wA/EXXAIRE wA/TC/SB wA	0.60/0.50/0.65/0.60	10	90
14A	SB wA/EXXAIRE wA/LC/SB wA	0.60/0.50/0.60/0.60	10	90

Table 5 (contd.). Processing conditions for adhesive smooth bonded laminates produced at J and M Laboratories.

Sample No.	Sample Description	Weight of Layers* Top/Middle/Bottom (oz/yd ²)	Calender Speed (m/min)	Nip Pressure (psi)
CONTROL LAMINATES				
15A	MB wA/EXXAIRE/MB wA	0.50/0.94/0.50	10	90
16A	MB wA/EXXAIRE/MB wA	0.50/0.50/0.50	10	90
17A	MB wA/EXXAIRE/MB wA	0.75/0.94/0.75	10	90
18A	MB wA/EXXAIRE/MB wA	0.75/0.50/0.75	10	90
19A	SB wA/EXXAIRE/MB wA	0.60/0.94/0.50	10	90
20A	SB wA/EXXAIRE/SB wA	0.60/0.94/0.60	10	90
21A	MB wA/C/MB wA	0.50/0.75/0.50	5	90
22A	MB wA/C/MB wA	0.75/0.75/0.75	5	90
23A	EXXAIRE wA/TC	0.94/0.65	10	80
24A	EXXAIRE wA/LC	0.94/0.60	10	80
25A	MB wA/C/MB wA	0.75/0.75/0.50	5	90

MB wA = Hot melt adhesive melt blown on polypropylene melt blown web, SB wA = Hot melt adhesive melt blown on polypropylene spunbond web, EXXAIRE wA = Hot melt adhesive melt blown on polyethylene microporous film, Exxaire® (0.50 oz/yd² & 0.94 oz/yd²) from EXXON Chemical, TC wA = Thermal bonded cotton web (0.65 oz/yd²) with adhesive, and LC wA = Latex bonded cotton web (0.60 oz/yd²) with adhesive, C = Unbonded carded cotton web, TC = Thermal bonded cotton web (0.65 oz/yd²), and LC = Latex bonded cotton web (0.60 oz/yd²).

All the laminates were bonded using smooth rubber coated calender rolls at ambient temperature.

- * Basis weights are for the component layers, not including the weight of the hot melt adhesive deposited onto these layers. The add on of the hot melt adhesive between the interfaces of each layer in the laminates was found to be in the range of 0.088 to 0.147 oz/yd² (3 to 5 g/m²).

Table 6. Processing conditions for adhesive point bonded laminates at TANDEC.

Sample No.	Sample Description	Weight of Layers* Top/Middle/Bottom (oz/yd ²)	Calender Speed (m/min)	Nip Pressure (psi)
MFCM LAMINATES				
1B	MB wA/EXXAIRE wA/C/MB wA	0.50/0.94/0.75/0.50	5	200
2B	MB wA/EXXAIRE wA/C/MB wA	0.75/0.94/0.75/0.75	5	200
3B	MB wA/EXXAIRE wA/C/MB wA	0.50/0.50/0.75/0.50	5	200
4B	MB wA/EXXAIRE wA/C/MB wA	0.75/0.50/0.75/0.75	5	200
5B	MB wA/EXXAIRE wA/TC wA/MB wA	0.50/0.94/0.65/0.50	10	200
6B	MB wA/EXXAIRE wA/LC wA/MB wA	0.50/0.94/0.60/0.50	10	200
7B	MB wA/EXXAIRE wA/TC wA/MB wA	0.75/0.94/0.65/0.75	10	200
8B	MB wA/EXXAIRE wA/LC wA/MB wA	0.75/0.94/0.60/0.75	10	200
SFCM LAMINATES				
9B	SB wA/EXXAIRE wA/C/MB wA	0.60/0.94/0.75/0.50	5	200
10B	SB wA/EXXAIRE wA/C/MB wA	0.60/0.94/0.75/0.75	5	200
SFCS LAMINATES				
11B	SB wA/EXXAIRE wA/C/SB wA	0.60/0.94/0.75/0.60	5	200
12B	SB wA/EXXAIRE wA/C/SB wA	0.60/0.50/0.75/0.60	5	200
13B	SB wA/EXXAIRE wA/TC/SB wA	0.60/0.50/0.65/0.60	10	200
14B	SB wA/EXXAIRE wA/LC/SB wA	0.60/0.50/0.60/0.60	10	200

Table 6 (contd.). Processing conditions for adhesive point bonded laminates at TANDEC.

Sample No.	Sample Description	Weight of Layers* Top/Middle/Bottom (oz/yd ²)	Calender Speed (m/min)	Nip Pressure (pli)
CONTROL LAMINATES				
15B	MB wA/EXXAIRE/MB wA	0.50/0.94/0.50	10	150
16B	MB wA/EXXAIRE/MB wA	0.50/0.50/0.50	10	150
17B	MB wA/EXXAIRE/MB wA	0.75/0.94/0.75	10	150
18B	MB wA/EXXAIRE/MB wA	0.75/0.50/0.75	10	150
19B	SB wA/EXXAIRE/MB wA	0.60/0.94/0.50	10	150
20B	SB wA/EXXAIRE/SB wA	0.60/0.94/0.60	10	150
21B	MB wA/C/MB wA	0.50/0.75/0.50	5	150
22B	MB wA/C/MB wA	0.75/0.75/0.75	5	150
23B	EXXAIRE wA/TC	0.94/0.65	10	150
24B	EXXAIRE wA/LC	0.94/0.60	10	150
25B	MB wA/C/MB wA	0.75/0.75/0.50	5	150

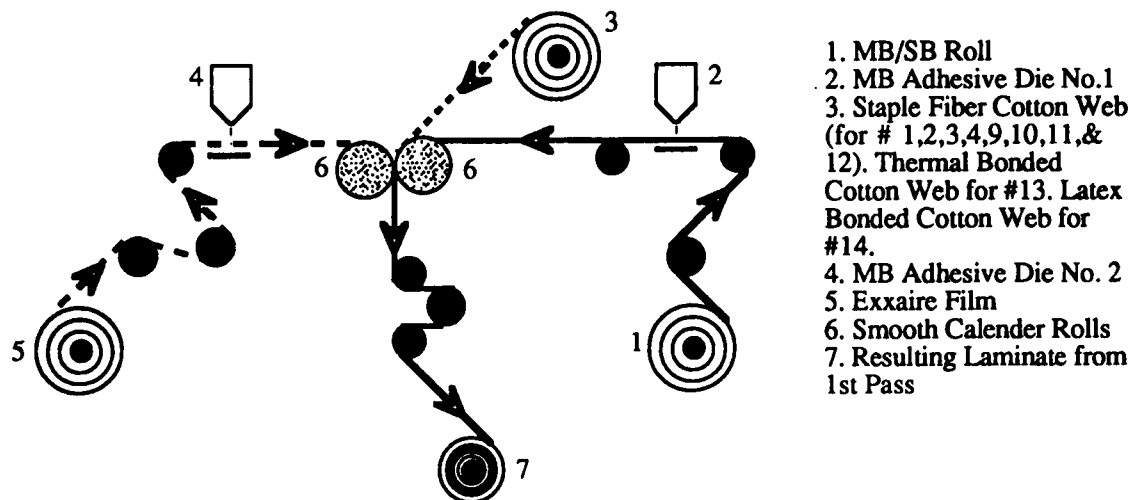
MB wA = Hot melt adhesive melt blown on polypropylene melt blown web, SB wA = Hot melt adhesive melt blown on polypropylene spunbond web, EXXAIRE wA = Hot melt adhesive melt blown on polyethylene microporous film, Exxaire® (0.50 oz/yd² & 0.94 oz/yd²) from EXXON Chemical, TC wA = Thermal bonded cotton web (0.65 oz/yd²) with adhesive, and LC wA = Latex bonded cotton web (0.60 oz/yd²) with adhesive, C = Unbonded carded cotton web, TC = Thermal bonded cotton web (0.65 oz/yd²), and LC = Latex bonded cotton web (0.60 oz/yd²).

The different substrates were laminated at J and M laboratories with an adhesive using conditions (except that there was no applied pressure for portions that were to be subsequently point bonded)

that are given in Table 5. The laminates were then calendered at TANDEC between patterned and smooth steel rolls at room temperature.

* Basis weights are for the component layers, not including the weight of the hot melt adhesive deposited onto these layers. The add on of the hot melt adhesive between the interfaces of each layer in the laminates was found to be in the range of .088 to 0.147 oz/yd² (3 to 5 g/m²).

**1st Pass for Samples No. 1,2,3,4,9,10,11,& 12 (5 m/min, No Pressure),
13,& 14 (10 m/min, No Pressure)**



**2nd Pass for Samples No. 1,2,3,4,9,10,11,& 12 (5 m/min, 90 psi Pressure),
13,& 14 (10 m/min) (90 psi Pressure)**

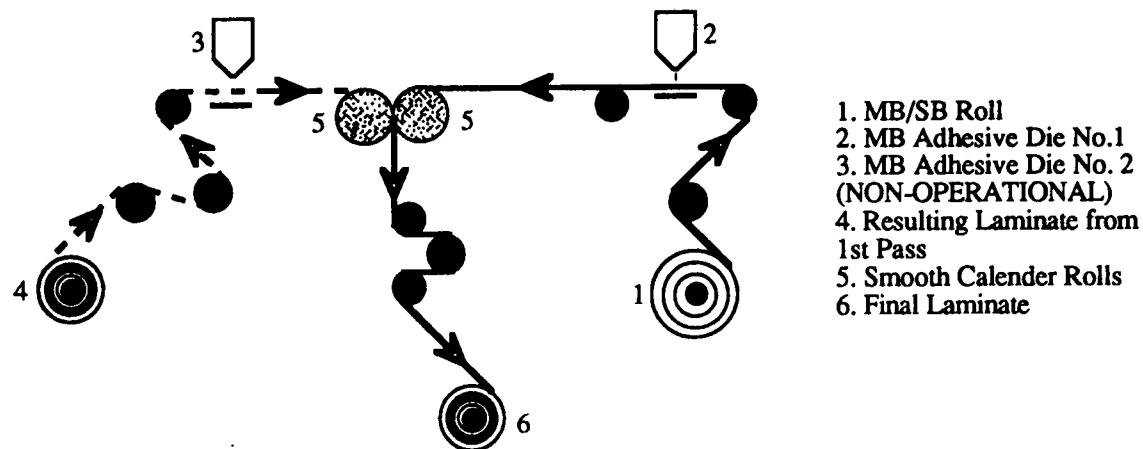
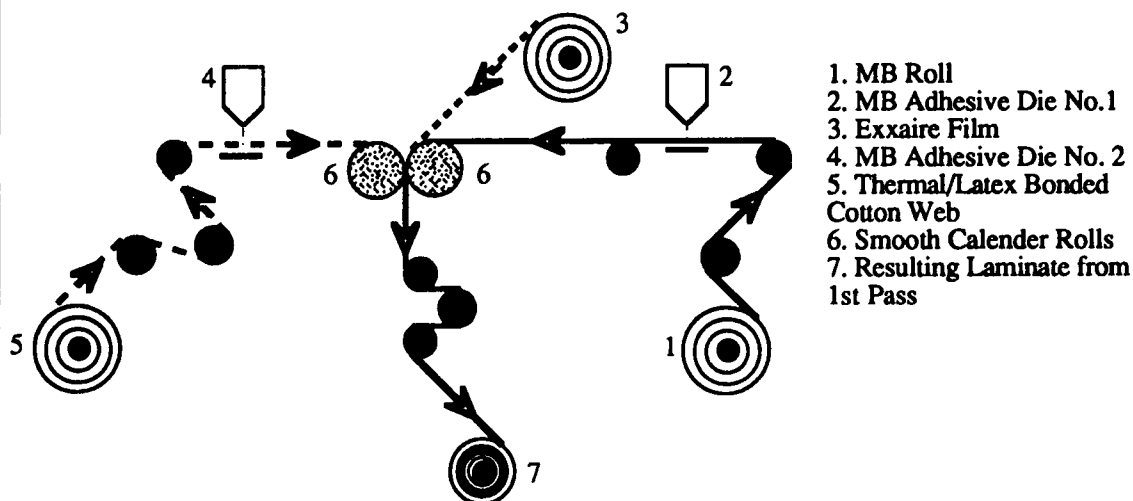


Figure 2. Schematic of process used for adhesive smooth bonding Samples No. 1,2,3,4,9,10,11,12,13, and 14.

1st Pass for Samples No. 5,6,7,& 8 (10 m/min, No Pressure)



2nd Pass for Samples No. 5,6,7,& 8 (10 m/min, 90 psi Pressure)

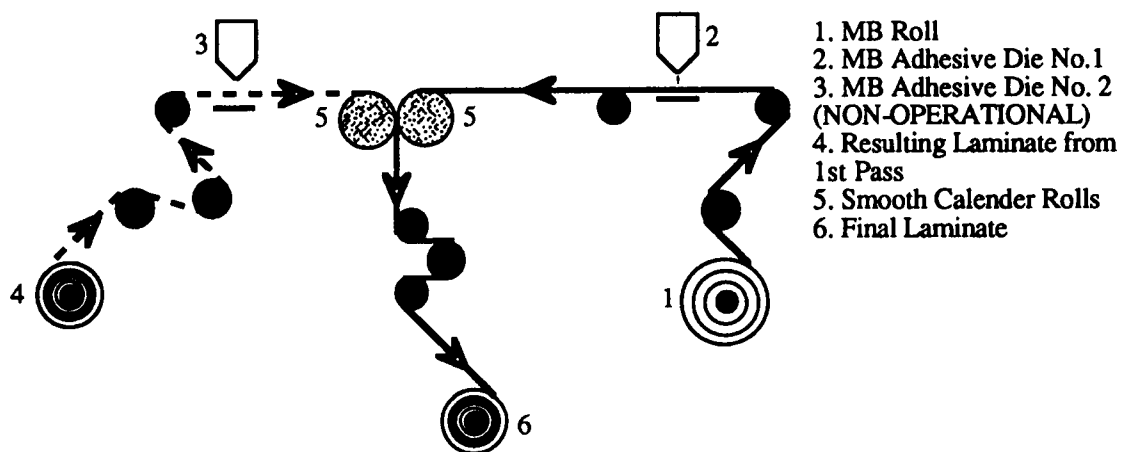
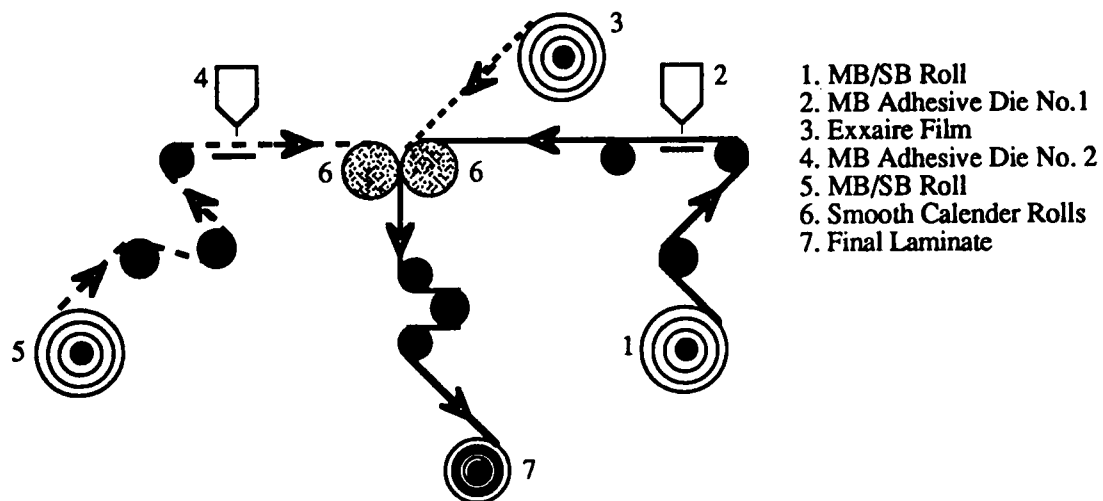


Figure 3. Schematic of process used for adhesive smooth bonding Samples No. 5, 6, 7, and 8.

**One Pass for Samples No. 15, 16, 17, 18, 19, & 20
(90 psi Pressure, 10 m/min)**



One Pass for Samples No. 21, 22, & 25 (90 psi Pressure, 5 m/min)

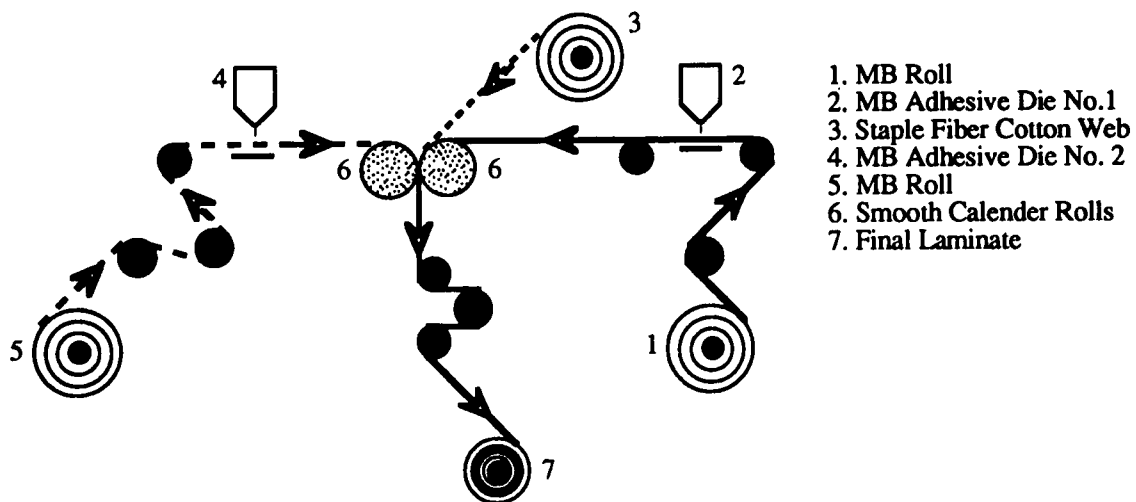


Figure 4. Schematic of processes used for adhesive smooth bonding Samples No. 15, 16, 17, 18, 19, 20, 21, 22, and 25.

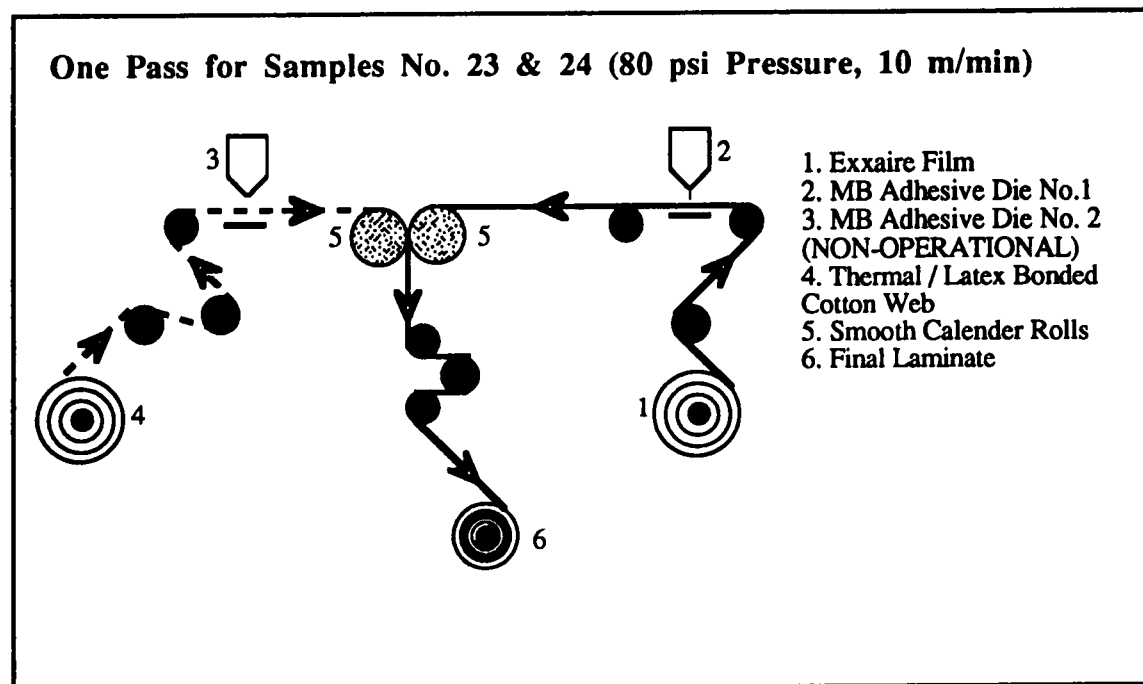


Figure 5. Schematic of process used for adhesive smooth bonding Samples No. 23 and 24.

substrates passing below each die. Eight Melt blown/Exxaire® Film/Cotton/Melt blown (MFCM) laminates, two Spunbond/Exxaire® Film/Cotton/Melt blown (SFCM) laminates, four Spunbond/Exxaire® Film/Cotton/Spunbond (SFCS) laminates, and eleven control laminates were adhesively bonded. Each of the twenty five aforementioned assemblies were adhesively smooth and point bonded in order to ascertain the effect of different bonding techniques on the final laminate properties.

Samples No. 1, 2, 3, 4, 9, 10, 11, 12, 13, and 14 required two passes as illustrated in Figure 2. In the first pass, the two substrates that had adhesive were combined with a staple fiber cotton core and passed through the smooth rubber coated roll nip at room temperature with no applied pressure on the resultant three layered laminate. The resultant laminate from the first pass was combined with the fourth layer that had adhesive on it and passed through the smooth roll nip under pressure of 90 psi. The die on the side of the laminate from the first pass was not operational. Samples No. 1, 2, 3, 4, 9, 10, 11, and 12 were run at a surface speed of 5 m/min. Samples No. 13 and 14, that had thermal bonded and latex bonded cotton webs respectively, could be unwound from the top with greater ease, were run at a surface speed of 10 m/min.

Samples No. 5, 6, 7, & 8 required two passes at a surface speed of 10 m/min as illustrated in Figure 3. In the first pass, the two substrates (MB web and thermal bonded cotton web) that had adhesive were combined with an Exxaire® film and passed through the smooth rubber coated roll nip with no applied pressure on the resultant three layered laminate. The resultant laminate from the first pass was combined with the fourth layer that had adhesive on it and passed through the smooth roll nip at room temperature with

a pressure of 90 psi. The die on the side of the laminate from the first pass was not operated in the second pass.

Samples No. 15, 16, 17, 18, 19, and 20 were three layered control laminates which contained no cotton, but incorporated an Exxaire® film, MB and/or SB webs. These laminates were made in one pass at a surface speed of 10 m/min as shown in Figure 4, without using a heated calender, but with unheated rubber coated rolls with a nip pressure of 90 psi. Samples No. 21, 22, and 25 were three layered control laminates with a cotton core, but with no Exxaire® film. These laminates were made in one pass with a nip pressure of 90 psi, under ambient conditions, and a surface speed of 5 m/min as shown in Figure 3. Samples 23 and 24 were two layered control laminates with thermal bonded and latex bonded cotton webs, respectively, with the heavier weight of Exxaire® film. These laminates were made in one pass with 80 psi nip pressure, at ambient temperature, and a surface speed of 10 m/min as shown in Figure 5. These control laminates were made to determine the individual effects of microporous film and cotton webs on the barrier properties of the laminates.

The twenty five laminates that were smooth bonded by passing them through the nip in J and M Laboratories were identified as Samples No. 1A to 25A and are described in Table 5. The other twenty five laminates were laminated (at J and M Laboratories) with no applied (minimal) nip pressure and subsequently point calendered at TANDEC using the Kusters 2-roll, 1.0 meter wide thermal calender at ambient temperature with the top steel roll having a raised diamond pattern resulting in 14.66% bonded area and the bottom roll having a smooth steel surface. Two surface speeds of 5 m/min and 10 m/min and two applied nip pressure levels of 150 and 200 pounds per linear inch (PLI)

were used to point bond the samples at TANDEC. The twenty-five laminates that were point bonded at TANDEC were identified as Samples No. 1B to 25B and are described in Table 6.

Testing of Properties. The basis weight, thickness, resistance to penetration of blood, and bursting strength of the fifty adhesively smooth and point bonded laminates were determined at TANDEC using standard test procedures. These fifty laminates were also sent to the Textile Testing Laboratory at North Carolina State University for Moisture Vapor Transmission Rate (MVTR) testing. In addition, three unbonded assemblies of Samples No. 2, 23, and 24 were sent for MVTR testing in an attempt to determine the effect of adhesive on the moisture transmission of the laminates. Both weights (0.50 and 0.94 oz/yd² {16.95 and 31.866 g/m²}) of Exxaire® microporous film were also sent to NCSU for MVTR testing. Fourteen adhesively smooth bonded laminates (1A, 2A, 3A, 5A, 6A, 7A, 8A, 9A, 10A, 11A, 13A, 15A, 16A, and 19A) and two adhesively point bonded laminates (3B and 7B) that passed the synthetic blood barrier test (ASTM ES21-92) were sent to Nelson Laboratories for the viral penetration test (ASTM ES 22-92).

EXPERIMENTAL PROCEDURES

The cotton laminates were tested using standard AATCC, ASTM, and INDA [40, 41, 42] test procedures for air permeability, bending length, breaking strength, breaking elongation, bursting strength, tear strength, hydrostatic pressure, water spray rating, water impact penetration, oil repellency rating, 45° flammability, vertical flammability, and synthetic blood barrier test. Laminates were sent to North Carolina State University for Kawabata analyses and MVTR

testing. The laminates were also sent to Nelson Laboratories for determining resistance to synthetic blood (prior to the equipment being installed in TANDEC) and resistance to bloodborne pathogens. The test standards used for testing the cotton laminates are given in Table 7 and some of the test procedures have been explained in greater detail in the following section.

Wicking Capacity Test

The readiness with which the liquid is transported within the volume (in an absorbent fabric), vertically into the fabric web and horizontally within a plane of the fabric is called the '*wicking capacity*' of the absorbent [43]. The test is an adaptation of Harnett and Mehta's [44, 45] Transverse Wicking Plate Test. The schematic representation of the test equipment is shown in Figure 6. A container holding the test liquid (in this case distilled water) is placed on a laboratory jack which rests on top of a balance. A funnel with a coarse (40-60 micron) glass frit is connected by a rubber hose to the container holding the test liquid. Circular test specimens, 100 cm² in area, are cut randomly from fabrics conditioned overnight at 20°C and 65% relative humidity.

The water container is raised to a point at which the surface of the glass frit is moist, taking care to ensure that there is no water standing upon the frit. The test specimen is placed face side down on the frit and a 100 g circular weight is placed on top of the specimen. A stop-watch is started coinciding with the weight being placed on the specimen and the reading of water being lost from the container is recorded at 10 second intervals for a period of 3 minutes. The wicking capacity results are plotted on a 'time vs. amount absorbed' curve.

Table 7. List of procedures used for testing cotton laminates.

PROPERTY TESTED	TEST PROCEDURE USED
Weight	IST 130.0 - 70 (R82)
Thickness	IST 120.0 - 70 (R82)
Hydrostatic Pressure	AATCC Test Method 127 - 1989
Oil Repellency Rating	AATCC Test Method 118 - 1992
Water Impact Penetration	AATCC Test Method 42 - 1989
Water Spray Rating	AATCC Test Method 22 - 1989
Resistance to Synthetic Blood	ASTM ES21 - 92
Resistance to Bloodborne Pathogens	ASTM ES22 - 92
Breaking Strength	IST 110.0 - 70 (R82)
Elmendorf Tear Strength	IST 100.0 - 70 (R82)
Mullen Bursting Strength	IST 30.0 - 70 (R82)
Tensile Elongation	IST 110.0 - 70 (R82)
Frazier Air Permeability	IST 70.1 - 70 (R82)
Cantilever Bending Length	ASTM D 1388 - 64
Moisture Vapor Transmission Rate	ASTM E96 - 80
45° Flame Test	IST 50.0 - 71 (R82)
Vertical Flame Test	Federal Method 5903.1
Wicking Capacity	Harnett and Mehta
Absorption Capacity	Swedish Textile Institute (TEFO)
Retention Capacity	Swedish Textile Institute (TEFO)
Kawabata Evaluation System	Kawabata Analyses

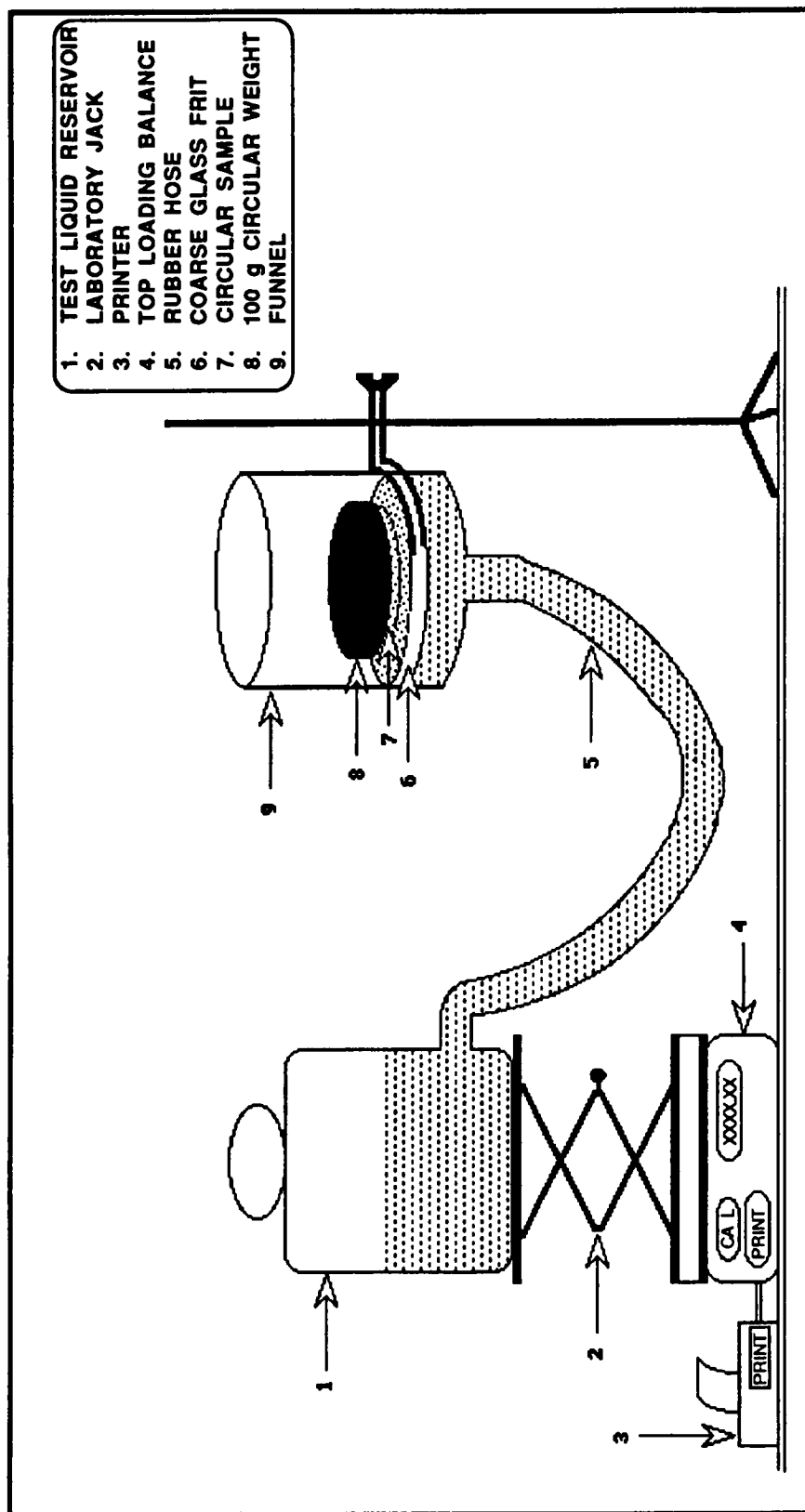


Figure 6. Schematic diagram of wicking capacity test equipment.

Absorbent Capacity Test

The volume accessible to a fluid within a surface is called the '*absorbent capacity*' of the absorbent [44]. This is an adaptation of the test procedure developed at the Swedish Institute for Textile Research (TEFO) [45, 46]. The schematic representation of the test equipment is shown in Figure 7. The test equipment consists of a funnel having a coarse (40-60 microns) glass frit. A separatory funnel is placed in such a way that it delivers 100 ml of test liquid (in this case distilled water) at a rate of 7 ml/s from a height of 2.54 cm above the top side of the test specimen placed on the glass frit as shown in (a) of Figure 7. This is done to saturate the test specimen. The test specimens (circular) must be 100 sq. cm in area and are conditioned at 20°C and 65% relative humidity overnight. A 100 sq. cm circular weight of 100 g is then placed gently on the saturated specimen as shown in (b) of Figure 7 and a stop-watch is started. In this test method [10], the weight is set in place after delivering the test liquid unlike the method of TEFO which has a weight (with a hole drilled in the center to enable a built-in tube to deliver liquid to the center of the sample) placed on the specimen through which the test liquid is delivered. The saturated specimen is then allowed to drain into a graduated collection cylinder for 10 minutes to determine the absorbent capacity (C) of the specimen in the following way:

$$C = a - b$$

Where, a = total liquid delivered (100 ml)

b = liquid unabsorbed (ml) under 100 Pa pressure

The results are reported to the nearest milliliter.

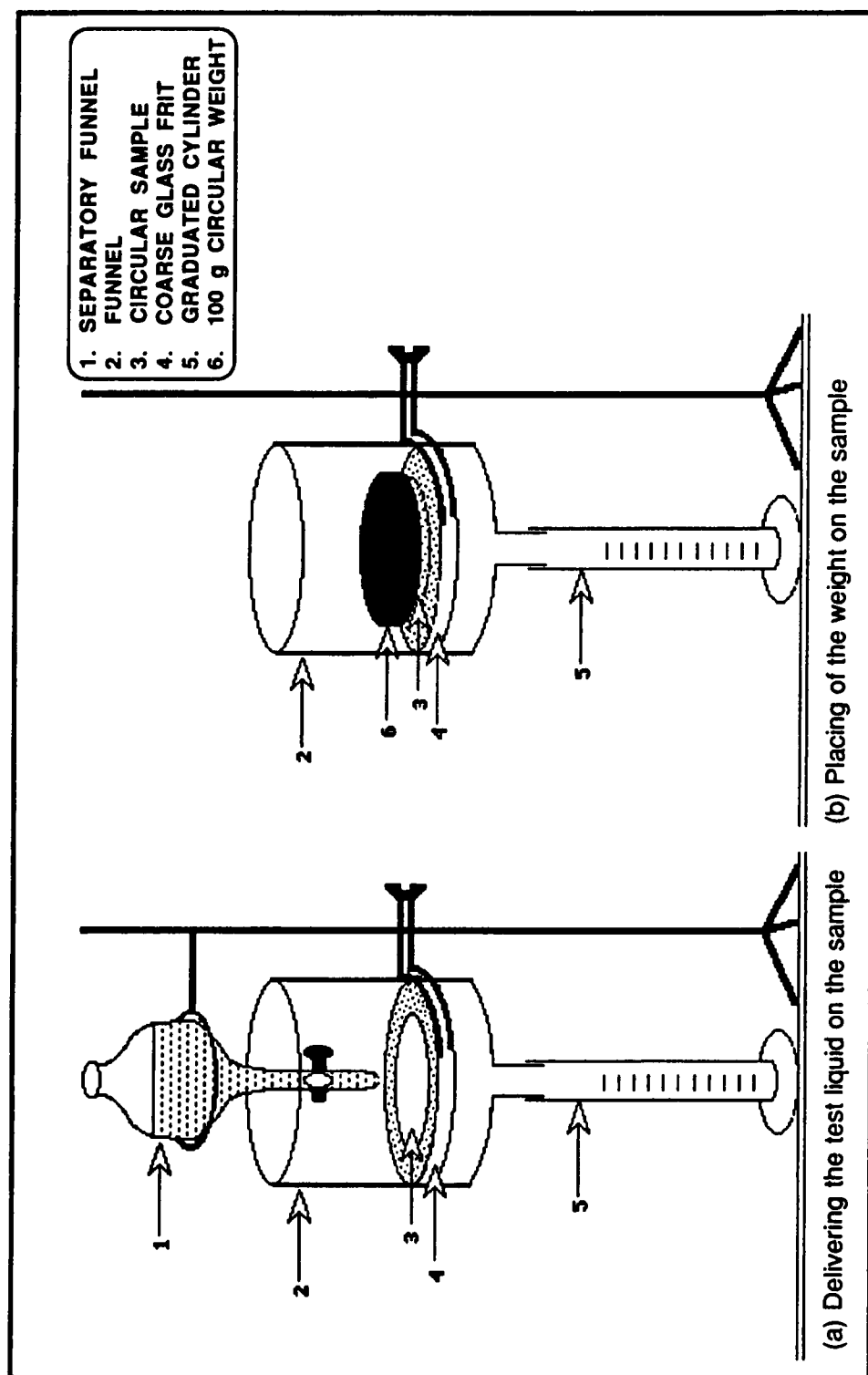


Figure 7. Schematic diagram of absorbent capacity and retention capacity test equipment.

Retention Capacity Test

The resistance offered by the surface to the removal of fluid from that volume is called its '*retention capacity*' of the absorbent. Retention is a measure of "how well voids comprising the volume resist flow outward when exposed to desorbing influences of pressure, vacuum, and adjacent absorbing structures" [43]. This test procedure is a continuation of Absorbent Capacity [45, 46] mentioned earlier and uses the same equipment shown in Figure 7.

After evaluating absorbent capacity, the pressure applied on the specimen is increased to 3 kPa by placing a weight of 2.9 kg (in addition to the 100 gm weight already there). The specimen is then allowed to drain for 5 minutes and the amount of liquid collected in a graduated collection cylinder is determined. An additional weight of 2.0 kg is added to increase the pressure applied to 5 kPa. The specimen is then allowed to drain for 5 more minutes and the amount of liquid collected in a graduated collection cylinder is determined. The retention capacity at 3.0 kPa and 5.0 kPa is determined by subtracting the test liquid unabsorbed at 3.0 kPa and 5.0 kPa respectively from the absorption capacity (C). The retention capacity values are reported to the nearest milliliter.

Kawabata Evaluation System (KES)

This system makes objective measurements of the mechanical hand properties of the test samples. The KES instruments [47, 48] measure the mechanical properties that correspond to the fundamental deformation of fabrics in hand manipulation. Five different tests (i.e. Tensile, Shear, Bending, Surface, and Compression properties) are performed using KES to obtain

eighteen different mechanical characteristics. A standard specimen size of 20 cm x 20 cm is used in triplicate. All measurements are directional, except for compression, and are made in both the machine direction (MD) and cross direction (CD) of the samples.

Upright Cup Moisture Vapor Transmission Rate (MVTR)

This test determines the values of transmission of moisture vapor through permeable and semipermeable materials. The passage of moisture vapor is an important consideration in all stages of the development, manufacturing, and marketing of medical barrier fabrics. The Simple Dish Method [47, 48] used to determine the rate of moisture vapor transport through a fabric is similar to ASTM E96-80 [49]. A sample is placed on a water dish (82 mm in diameter and 19 mm in depth) allowing a 9 mm air space between the water surface and specimen. Eight water dishes are placed on a turntable that is vibration free and rotates at 5 m/min to insure that all the dishes are exposed to the same average ambient conditions for the duration of the test. The assembled specimen dishes are allowed to stabilize for two hours before taking the first weight. They are weighed again after an interval of 24 hours. MVTR is calculated in units of $\text{g/m}^2\text{-24 hr}$.

Resistance to Synthetic Blood Penetration

This test method (ASTM Emergency Test Method ES21-92) [50, 51] has been designed to measure the effectiveness of protective clothing barrier properties using a synthetic blood mixture. This test uses the same apparatus

and specimen exposure format as ASTM F 903 [52]. Three specimens of the test material are subjected to synthetic blood at 0 psi applied pressure for 5 minutes followed by 2 psi (13.8 kPa) applied pressure for 1 minute followed by 0 psi (0 kPa) applied pressure for 54 minutes. The test is terminated if visible penetration of the synthetic blood is seen at any time during the test. The synthetic blood used in this test is "a mixture of a red dye (with surfactant) and thickening agent prepared in distilled water to have a surface tension, viscosity, and color representative of blood and other body fluids".

Resistance to Viral Penetration

This test method (ASTM Emergency Test Method ES22-92) [53, 54] has been designed to measure the effectiveness of protective clothing materials against bloodborne pathogen hazards. The test procedure has been developed by the ASTM Subcommittee F23.40 on Biological Hazards. This test uses same apparatus and specimen exposure format as the ASTM F 903 Chemical Protection Cell [52].

The øX174 bacteriophage was used at a concentration of at least 1.0×10^8 PFU/mL (plaque forming units/mL) in the challenge suspension. The øX174 bacteriophage is one of the smallest known viruses, has no envelope, has icosahedral or nearly spherical morphology (similar to all three bloodborne pathogens of concern such as hepatitis B virus, hepatitis C virus, and human immunodeficiency virus), is 25 to 27 nm in size (similar to hepatitis C pathogen which is the smallest), has excellent environmental stability, is non-infectious to humans, grows very rapidly (assay results can be observed in 4 to 8 hours), and

can be cultivated to reach very high titers similar to hepatitis B virus (the most concentrated pathogen of the ones mentioned).

Three specimens of approximately 75 mm x 75 mm were gas sterilized with Ethylene Oxide and degassed for 48 hours minimum @ $54^{\circ}\text{C} \pm 2^{\circ}\text{C}$. Before being tested, all test specimens were conditioned for a minimum of 24 hours at $21^{\circ}\text{C} \pm 5^{\circ}\text{C}$ and 30% to 80% relative humidity.

The specimens were challenged with approximately 60 ml of the øX174 bacteriophage suspension for 5 minutes at atmospheric pressure, 1 minute at 2.0 psi (13.8 kPa) pressure, and 54 minutes at atmospheric pressure. The test was terminated at any time liquid penetration was observed. At the conclusion of the one hour test duration, the observed side of the test specimen was rinsed with a sterile assay medium and then assayed for the presence of the øX174 bacteriophage. The surface tension of the challenge suspension and the assay medium was adjusted to approximately 40 - 44 dynes/cm (using surfactant-type Tween® 80 at a final concentration of approximately 0.01% by volume) in order to simulate the wetting characteristics of blood and body fluids which have a surface tension range of approximately 42 - 60 dynes/cm.

The adhesive bonded laminates that passed the blood penetration test were sent to Nelson Laboratories, Salt Lake City, Utah for the viral penetration test because of the time, expense, and high level of microbiological testing expertise needed for the same.

Statistical Procedure

Wilcoxon Signed Rank Test

The Wilcoxon Signed Rank test was used in Part A of this study to determine if the average differences in physical properties are significantly different from zero when comparing laminate fabrics before and after repellent finishing. The Wilcoxon Signed Rank test is a nonparametric analogue to the paired - difference t - test. This test assumes that each pair of observations is independent of other pairs. This test was performed using the Statistical Analysis System (SAS) software [55, 56]. Since there were paired measurements (before and after repellent finishing) for each item in the sample, these are referred to as 'paired groups'. Since no assumptions are made regarding the specific distribution of the data in these groups, the nonparametric methods of statistical analysis need to be used to analyze the data. The Wilcoxon Signed Rank test, being a nonparametric method tries to determine if a significant difference exists between the paired groups. Hence it is found to be an appropriate method for analyzing two groups of data in this study.

The Wilcoxon Signed Rank test was also used in Part B to determine if the average differences in properties are significantly different from zero when comparing adhesive laminates that were bonded using a nip of smooth rolls (smooth bonding) and a nip of pattern roll and smooth roll (point bonding). This statistical test was appropriate in determining if the treatments given these two groups are significant in terms of barrier, strength, and breathability properties since some of the differences were relatively small. It was decided that statistical analyses would not be utilized in the other parts of the study in that

only major increments in barrier and breathability properties were of interest in achieving the objectives of the study.

CHAPTER 4

RESULTS AND DISCUSSION

PART A: THERMAL BONDED LAMINATES

Ten cotton based thermally laminates described in Table 1 in Chapter 3 on "Experimental Design and Procedure" were tested for different properties in an attempt to evaluate their suitability as candidate materials for medical and personal hygiene product applications. Five of the laminates (Samples No. 1C, 2C, 3C, 4C, and 5C) had both outer MB webs and cotton cores. These five laminates are grouped as "MCM Laminates" in Table 1 in Chapter 3 on "Experimental Design and Procedure". The cotton content of the aforementioned laminates ranged from 40 to 80%. Four of the laminates (Samples No. 6C, 7C, 8C, and 9C) had a top SB web and a MB web as the bottom layer with inner cotton cores. These four laminates are grouped as "SCM Laminates" in Table 1 in Chapter 3 on "Experimental Design and Procedure". The cotton content of the aforementioned laminates ranged from 42 to 69%. Only one laminate had both outer SB webs and a cotton core. This laminate is termed as "SCM Laminate" in Table 1 in Chapter 3 on "Experimental Design and Procedure". The cotton content of the aforementioned laminate was 45%.

The physical properties of the (three) MB and (one) SB webs used to produce the laminates are given in Table 8. The 0.25 oz/yd² (8.475 g/m²) MB PP had much higher air permeability than the 0.50 and 0.75 oz/yd² (16.95 and 25.425 g/m²) MB PP webs, but had comparatively good strength properties,

Table 8. Results of melt blown and spunbond webs used to produce experimental laminates.

Sample ID	Thickness (mm)	Bending Length (cm)		Breaking Strength (mN/tex)		Elongation (%)		Bursting Strength		Air Permeability	
		MD	CD	MD	CD	MD	CD	(psi)	(kPa)	(ft ³ /min/ft ²)	(m ³ /min/m ²)
0.25 OSY MB	0.124	1.66	1.30	13.8	9.8	25.4	37.7	5.1	35.14	148.8	0.74
0.50 OSY MB	0.161	2.78	2.04	13.5	7.9	22.9	42.2	7.0	48.22	67.6	0.34
0.75 OSY MB	0.199	3.59	2.75	11.7	8.2	25.3	57.3	8.0	55.12	71.5	0.36
0.60 OSY SB	0.229	2.73	1.94	25.2	12.9	117.2	102.2	11.6	79.92	816.1	4.08

considering its very low weight. As was expected, the 0.60 oz/yd² (20.34 g/m²) SB PP had much greater strength properties and appreciably higher air permeability than did even the 0.25 oz/yd² (8.475 g/m²) MB web.

The deviation of the actual weights from the desired weights as shown in Table 9 should be even less in commercial production. In these trials, the unwind devices for the laminate layers lack the positive tension control (which could result in the drafting of the webs unevenly) that would be expected in a carding and thermal bonding line specially designed and/or retrofitted for producing these types of laminates.

Bending length "reflects the stiffness of a fabric when bent in one plane under the force of gravity" [57]. The bending lengths of the laminates (Table 10) were only different from each other within a range of 1-2 cm, but the laminates containing one or two layers of SB generally had lower bending length than laminates having both outer layers of MB. It could be possible that the smaller fiber sizes of the MB webs are better melted in the process of thermal bonding and hence are having greater stiffness (than laminates having SB webs) as is reflected by their higher bending length values.

Air Permeability is "the rate of air flow through a material under a differential pressure between the two fabric surfaces" [57]. Fabrics containing a SB layer appeared to have higher air permeability values probably because of the more open structure of SB webs. However, Sample No. 10C (SCS-45-2.2) which contains two SB outer layers had approximately ten times greater air permeability of 212.2 ft³/min/ft² (1.061 m³/min/m²) than did the MCM and SCM fabrics.

The barrier properties of the laminate fabrics are given in Table 11. Hydrostatic Pressure (AATCC Test Method 127-1989) is "the measure of the

Table 9. Weight and thickness of unfinished cotton based laminates.

Sample No.	Weight		Thickness (mm)
	(g/m ²)	(oz/yd ²)	
1C	91.25	2.69	0.6672
2C	90	2.65	0.6137
3C	82.5	2.43	0.6025
4C	97.5	2.88	0.6653
5C	141.5	4.17	0.7908
6C	79.4	2.34	0.4941
7C	92.5	2.73	0.6738
8C	138.75	4.09	0.7477
9C	116.5	3.44	0.7913
10C	68.5	2.02	0.5929

Table 10. Bending length and air permeability test results of unfinished cotton based laminates.

Sample No.	Bending Length		Air Permeability	
	(cm)		(ft ³ /min/ft ²)	(m ³ /min/m ²)
	MD	CD		
1C	7.73	5.89	15.7	0.0785
2C	6.24	4.92	18.9	0.0945
3C	6.3	4.55	18.9	0.0945
4C	8.70	6.74	16.1	0.0805
5C	8.45	6.87	11.0	0.055
6C	5.36	3.61	25.57	0.1279
7C	7.04	4.79	23.4	0.117
8C	5.57	7.79	20.7	0.1035
9C	7.19	5.15	20.6	0.103
10C	6.55	4.14	212.2	1.061

Table 11. Barrier test results of unfinished cotton based laminates.

Sample No.	Hydrostatic Pressure		Water Spray Rating (0 - 100)	Water Impact Penetration (g)	Oil Repellency Rating (0 - 8)
	(Inches)	(cm)			
1C	20.3	51.56	50	0.03	0
2C	14.2	36.07	70	0.03	0
3C	27.0	68.58	70	0.03	0
4C	12.2	30.99	80	0.1	0
5C	13.2	33.53	50	0.06	0
6C	15.58	39.57	50	0.23	0
7C	9.5	24.13	50	0.13	0
8C	10.5	26.67	80	0.5	0
9C	11.0	27.94	0	0.1	0
10C	4.3	10.92	0	22.83	0

resistance of fabrics to the penetration by water under static pressure" [40]. It is surprising that Sample No. 3C which had only 0.25 oz/yd² (8.475 g/m²) of PP MB on each side had the highest hydrostatic head of 27 inches (0.675 m). Since Samples No. 1C and 2C which have heavier melt blown webs of 0.75 and 0.50 oz/yd² (16.95 g/m²), respectively, it is assumed that the greater cotton content in Sample No. 3C also contributes to its barrier properties. Nevertheless, Sample No. 10C which had SB on both sides had the lowest hydrostatic head pressure of 4.3 inches (0.1075 m). Water impact penetration (AATCC Test Method 42-1989) is "the measure of the resistance of fabrics to the penetration of water by impact" [40]. Sample No. 10C had the highest water impact penetration of 22.8 grams. The remainder of the fabrics, all of which had at least one melt blown web, had water impact penetration values of 0.5 grams or less. Water spray rating (AATCC Test Method 22-1989) is "the measure of the resistance of fabrics to wetting by water" [40]. The samples which had water spray ratings of 0, indicating complete wetting of the surface, had a SB web on one side (Sample No. 9C) and SB webs on both sides (Sample No. 10C). It was expected that these fabrics would have no oil repellency because of the PP outer layers.

As can be seen in Table 12, the strongest fabrics in terms of bursting strength, breaking strength and tearing strength had at least one SB web. The MCM fabrics with 2.0 and 3.0 oz/yd² (67.8 and 101.7 g/m²) of cotton in the middle layer (Samples No. 3C and 5C) respectively have the greatest water absorbent capacity and retention values, as shown in Table 13. Although Sample No. 3C only has 2.0 oz/yd² (67.8 g/m²) of cotton in its core compared to 3.0 oz/yd² (101.7 g/m²) with Sample No. 4C, its greater absorption may be due

Table 12. Strength test results of unfinished cotton based laminates.

Sample No.	Bursting Strength		Breaking Strength		Elongation		Tear Strength	
	(psi)	(kPa)	(mN/tex)		(%)		(g)	
			MD	CD	MD	CD	MD	CD
1C	9.45	65.11	8.1	4.0	9.5	16.9	82	148
2C	16.5	113.69	6.3	3.6	13.4	22.0	250	264
3C	11.2	77.17	7.5	4.0	13.5	25.9	176	248
4C	14.9	102.66	3.3	2.4	9.1	18.6	212	266
5C	21.8	150.20	2.6	1.3	9.8	20.3	164	212
6C	21.5	148.14	7.8	3.6	62.2	52.1	332	368
7C	17	117.13	7.8	3.6	45.3	64.1	200	270
8C	34.4	237.02	5.4	2.3	32.0	31.2	214	244
9C	35.7	245.97	5.6	2.3	25.5	30.4	300	338
10C	32.0	220.48	9.5	4.6	51.2	76.7	440	640

Table 13. Absorbent Capacity and Retention Capacity test results of unfinished cotton based laminates.

Sample No.	Absorbent Capacity (ml) (@ 100 Pa) ¹	Retention Capacity (ml) (@ 3 kPa) ²	Retention Capacity (ml) (@ 5 kPa) ³
1C	10.0	9.0	8.5
2C	8.0	7.0	6.0
3C	14.0	12.0	11.0
4C	7.0	4.0	4.0
5C	13.0	11.0	10.0
6C	6.0	6.0	5.0
7C	10.0	9.0	9.0
8C	9.0	7.0	7.0
9C	7.0	6.5	6.0
10C	6.0	5.0	5.0

¹ Determined by subtracting the amount of liquid drained into the graduated cylinder at the end of 10 minutes from the original 100 ml dosage.

² Determined by subtracting the amount of liquid unabsorbed at 3 kPa pressure from the absorption capacity.

³ Determined by subtracting the amount of liquid unabsorbed at 5 kPa pressure from the absorption capacity.

to the much lighter melt blown web which offers less resistance to water penetration.

As shown in Table 14, all of the MCM and SCM fabrics displayed "Normal Flammability" classification in the 45° flammability test. These findings are most significant considering the fact that the samples range in cotton content from 40-80% with there being only 0.25 oz/yd² (8.475 g/m²) of PP MB web on each side of a 2.0 oz/yd² (67.8 g/m²) cotton web in the case of laminate Sample No. 3C. In the vertical flame testing shown in Table 15, all the fabrics had a char length of 12 inches (0.30 m) which was the length of the sample used in the vertical flame testing. All the samples failed the vertical flame test [58].

The effect of increasing cotton content of MCM fabrics with similar basis weights on the wicking rate is shown in Figure 8. Sample No. 1C which has the lowest cotton content and conversely the heavier MB webs on each side has the slowest wicking rate and the amount of water wicked leveled off after 150 seconds to approximately 2.7 grams. On the other hand, Sample No. 3C which had 80% cotton appeared to be decreasing only slightly in wicking rate after 180 seconds. The wicking response curves in Figure 8 for Samples No. 1C, 2C, and 3C having decreasing weights of MB webs (0.75, 0.50, and 0.25 oz/yd² respectively) and increasing weights of cotton webs (1.0, 1.5, and 2.0 oz/yd² respectively) show that the amount of water wicked increases with a decrease in the weight of the MB webs and a corresponding increase in the weight of the cotton core webs. Samples No. 4C and 5C having 0.75 oz/yd² (25.425 g/m²) MB webs on each side, but with 2.0 and 3.0 oz/yd² (67.8 and 101.7 g/m²) of cotton in the middle have much lower wicking rates compared to the lighter weight MCM fabrics.

Table 14. 45° flame test results of unfinished cotton based laminates.

Fabric Type (Plain or Raised Surface): Raised surface

Direction of Test (Length or Width): Length (MD)

Sample No.	Code ¹	Classification ²	Time (nearest 0.1 sec)
1C	TSF	Class 1, Normal Flammability	9.6
2C	TSF	Class 1, Normal Flammability	8.7
3C	TSF	Class 1, Normal Flammability	7.9
4C	TSF	Class 1, Normal Flammability	10.4
5C	TSF	Class 1, Normal Flammability	14.4
6C	TSF	Class 1, Normal Flammability	7.8
7C	TSF	Class 1, Normal Flammability	9.2
8C	TSF	Class 1, Normal Flammability	12.4
9C	TSF	Class 1, Normal Flammability	11.1
10C	TSF	Class 1, Normal Flammability	7.4

¹Code:

DNI. Specimen did not ignite.
IBE. Specimen ignited, but self-extinguished before stop-cord burned.
BB. Base burned.
SF. Surface flash (very rapid burning of the raised surface of the material and no burning of the material and no burning, charring, or fusing of the base). Stop-cord not burned.
TSF. Timed surface flash. Stop-cord burned.
SFBB. Surface flash, base burned. Includes burning, charring, or fusing of the base.

²Classification

Class 1, Normal Flammability

Fabric is considered to possess normal flammability.

- Plain surface fabric: Flame spread of at least 3.5 seconds.
- Raised surface fabric: Flame spread of at least 7.0 seconds. If a surface flash occurs where the base is not burned, charred, or fused, then the fabric is considered to be in this category.

Class 2, Intermediate Flammability

Fabric is considered to possess flammability characteristics between normal and intense burning.

- Raised surface fabric: Flame spread of 4.0 to 7.0 seconds and where the base is burned, charred, or fused.

Class 3, Rapid and Intense Flammability

Fabric is considered dangerously flammable and unsuitable for clothing.

- Plain surface fabric: Flame spread of less than 3.5 seconds.
- Raised surface fabric: Flame spread of less than 4.0 seconds and where the base is burned, charred, or fused.

Table 15. Vertical flammability test results of unfinished cotton based laminates.

Sample No.	Char Length (in)	After-flame (sec)	After-glow (sec)
1C	12	30.2	28.2
2C	12	16.8	31.0
3C	12	14.5	40.5
4C	12	29.0	33.2
5C	12	33.0	94.0
6C	12	27.8	22.8
7C	12	19.4	26.8
8C	12	30.0	56.0
9C	12	27.4	37.2
10C	12	26.2	25.6

Afterflame time is the time the specimen continues to flame after the 12 second period during which time the flame is exposed to the specimen.

Afterglow time is the time the specimen continues to glow after it has ceased to flame (as a result of the 12 second flame impingement and after flame).

The char length is the distance from the end of the specimen which was exposed to the flame to the top of the lengthwise tear made through the center of the charred area.

(In case of these samples it was the length of the entire sample because nothing was left of the sample after the afterflame and afterglow time periods)

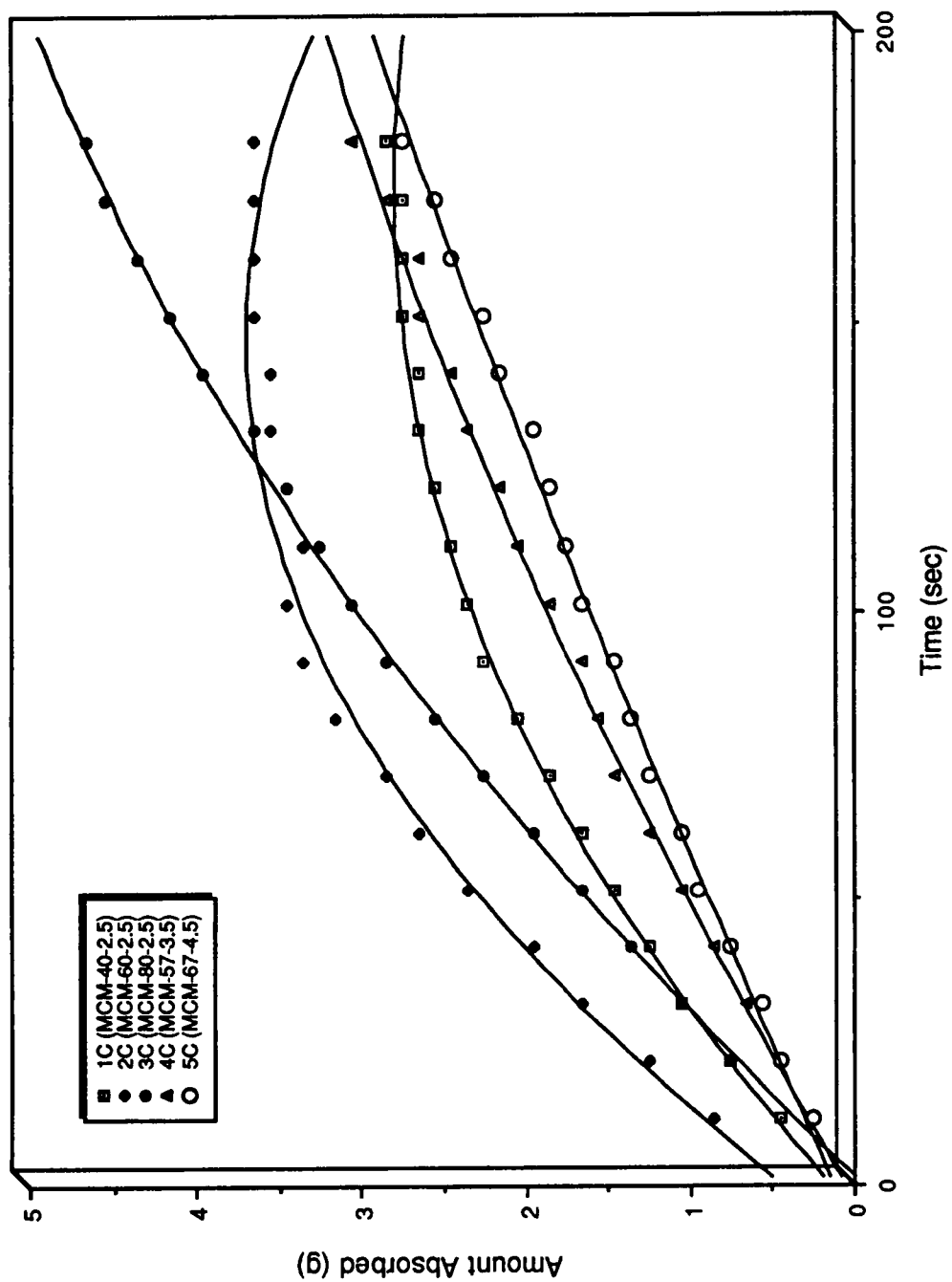


Figure 8. Wicking Response Curves for MCM Laminates With Different Cotton Contents.

The wicking rates of SCM fabrics are compared in Figure 9. Sample No. 6C, which has the least amount of cotton appears to instantaneously wick up approximately 2.2 grams of water, but wicks very little afterwards. Sample No. 8C which had 60% cotton appeared to wick the fastest and leveled off at approximately 5 grams. Sample No. 9C with 69% cotton also wicked very rapidly and showed little sign of leveling off after 180 seconds. Sample No. 10C (Figure 10) which had only 1.0 oz/yd² (33.9 g/m²) of cotton in the center (45% cotton) and SB webs on both sides wicked very rapidly, but leveled off after 150 seconds at 2.5 grams.

Comparison of Unfinished and Finished Laminates

A fluorochemical repellent finish was applied to six thermally bonded laminates (3 MCM {1C, 2C, and 3C} and 3 SCM {7C, 8C, and 9C} samples as described in Table 1 in the Chapter 3 on "Experimental Design and Procedure") using the padding technique in an attempt to improve their repellency characteristics.

The test results of the six repellent finished laminates are given in Tables 16 - 22 along with the results of their unfinished counterparts to enable easier comparison between unfinished and repellent finished laminates. Although it was expected that the weights of the laminates (Table 16) would increase after repellent finishing (and this was seen in four samples), it was surprising to see a decrease in weight of two repellent finished samples. The thickness of all samples showed an increase after repellent finishing. However, the increase in thickness of Sample No. 3C-R was accompanied by an apparent increase in bulk and softness. Unfinished and repellent finished laminates having the

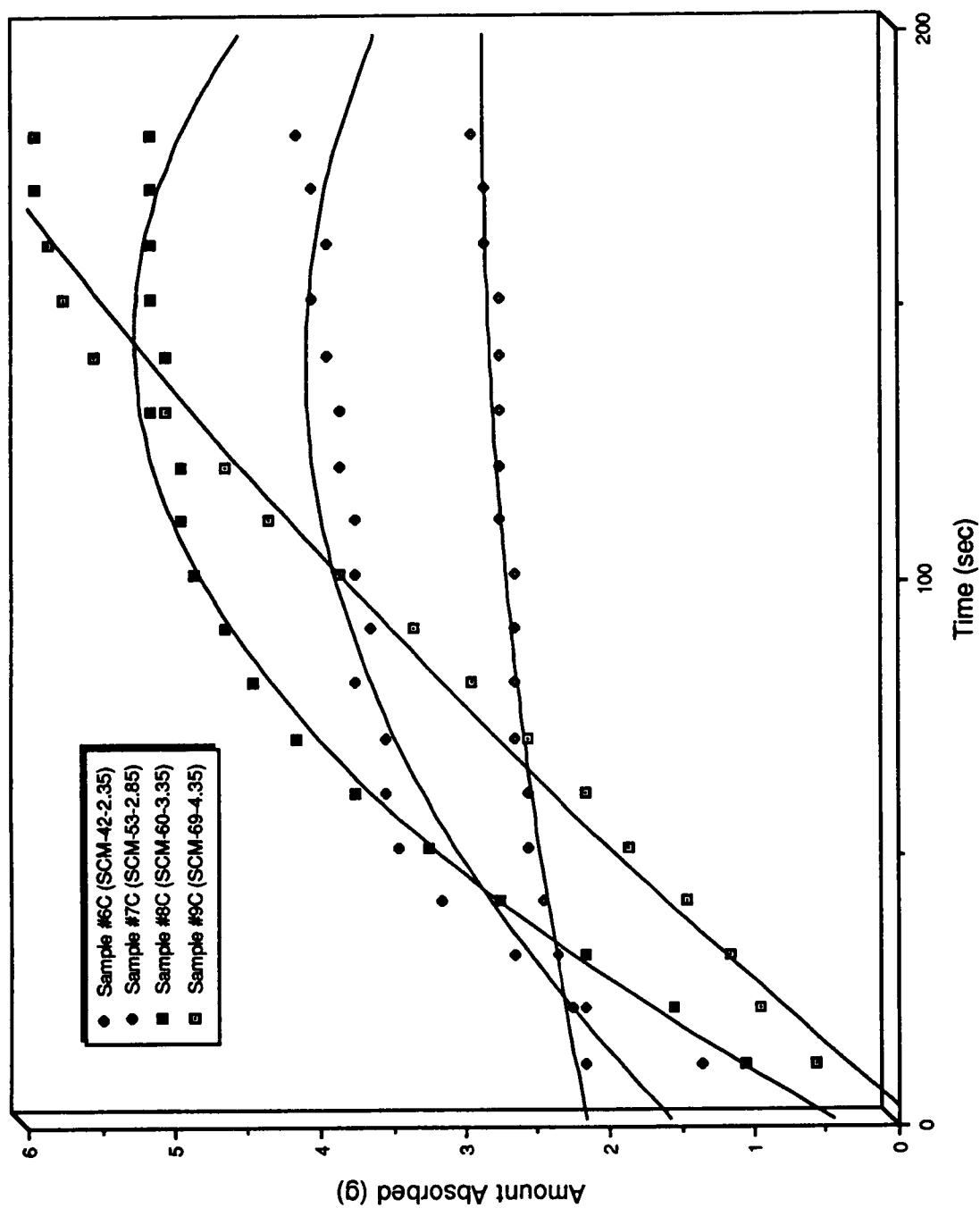


Figure 9. Wicking response curves for SCM laminate samples with different cotton contents.

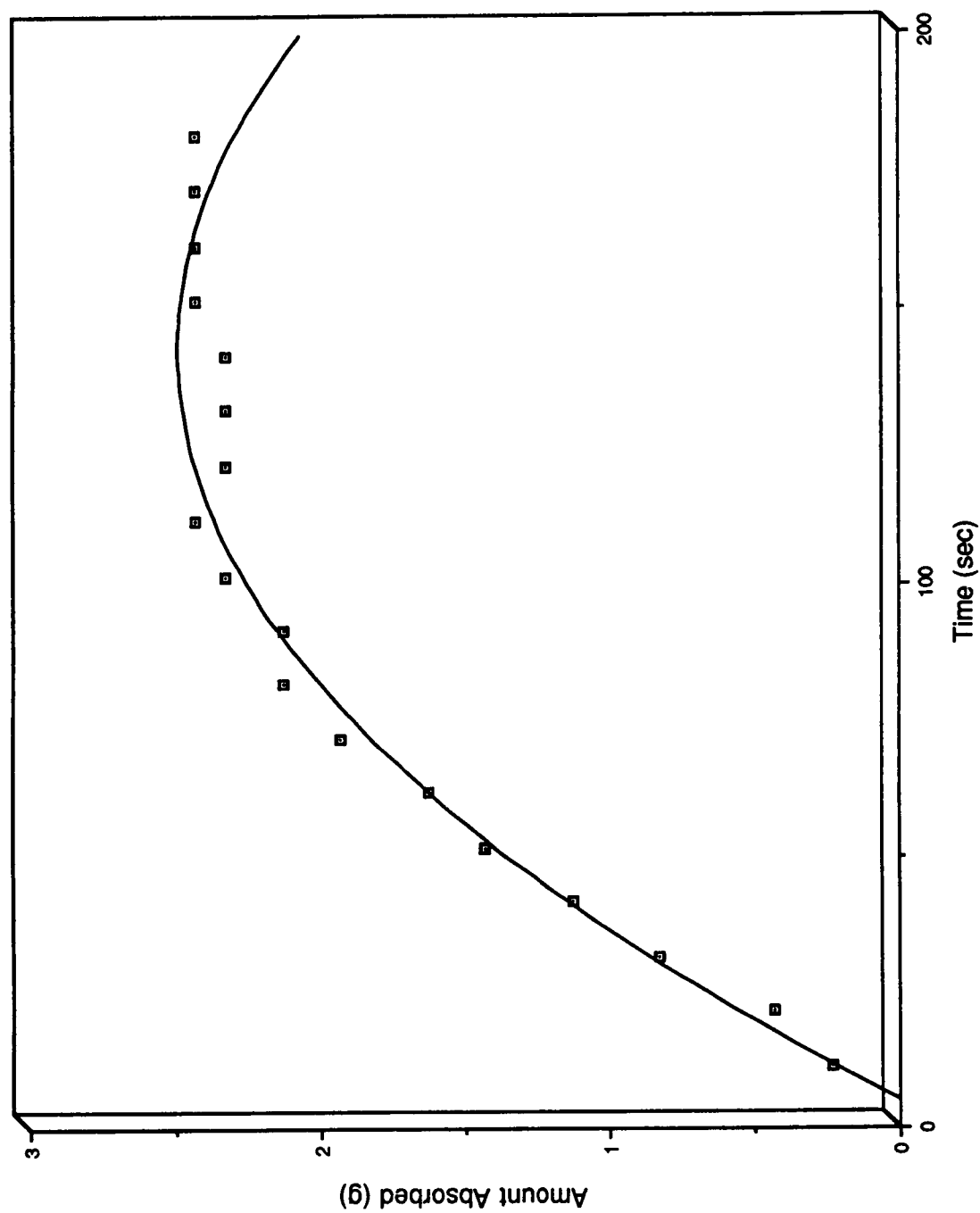


Figure 10. Wicking response curve for Sample No. 10C (SCS-45-2.2).

Table 16. Weight and thickness of cotton based laminates.

Sample No.	Weight	Thickness
	(oz/yd ²)	(mm)
UNFINISHED LAMINATES		
1C	2.69	0.6672
2C	2.65	0.6137
3C	2.43	0.6025
7C	2.73	0.6738
8C	4.09	0.7477
9C	3.44	0.7913
REPELLENT FINISHED LAMINATES		
1C - R	2.71	0.675
2C - R	2.54	0.737
3C - R	2.47	1.046
7C - R	2.86	0.800
8C - R	2.98	0.814
9C - R	3.81	1.334

Table 17. Bending length and air permeability results of cotton based laminates.

Sample No.	Bending Length		Air Permeability
	(cm)		(ft ³ /min/ft ²)
	MD	CD	
UNFINISHED LAMINATES			
1C	7.73	5.89	15.7
2C	6.24	4.92	18.9
3C	6.3	4.55	18.9
7C	7.04	4.79	23.4
8C	5.57	7.79	20.7
9C	7.19	5.15	20.6
REPELLENT FINISHED LAMINATES			
1C - R	5.49	4.49	13.90
2C - R	5.98	4.82	19.07
3C - R	5.09	4.42	54.09
7C - R	5.49	3.88	19.04
8C - R	5.13	4.68	18.75
9C - R	6.29	5.41	15.27

Table 18. Barrier results of cotton based laminates.

Sample No.	Hydrostatic Pressure (inches)	Water Spray Rating (0 - 100)	Water Impact Penetration	Oil Repellency Rating (0 - 8)
			(g)	
UNFINISHED LAMINATES				
1C	20.3	50	0.03	0
2C	14.2	70	0.03	0
3C	27.0	70	0.03	0
7C	9.5	50	0.13	0
8C	10.5	80	0.5	0
9C	11.0	0	0.1	0
REPELLENT FINISHED LAMINATES				
1C - R	24.83	80	0	6
2C - R	22.5	80	0	8
3C - R	10.5	80	0	8
7C - R	12.5	80	0	8
8C - R	12.0	90	0	8
9C - R	11.0	80	0	8

Table 19. Strength results of cotton based laminates.

Sample No.	Bursting Strength (kPa)	Breaking Strength		Elongation		Tear Strength	
		(mN/tex)		(%)		(g)	
		MD	CD	MD	CD	MD	CD
UNFINISHED LAMINATES							
1C	65.11	8.1	4.0	9.5	16.9	82	148
2C	113.69	6.3	3.6	13.4	22.0	250	264
3C	77.17	7.5	4.0	13.5	25.9	176	248
7C	117.13	7.8	3.6	45.3	64.1	200	270
8C	237.02	5.4	2.3	32.0	31.2	214	244
9C	245.97	5.6	2.3	25.5	30.4	300	338
REPELLENT FINISHED LAMINATES							
1C - R	120.92	6.0	3.6	13.7	18.5	38.8	77.8
2C - R	57.88	3.2	1.7	10.0	19.3	32	53
3C - R	43.75	1.7	0.4	6.7	16.5	29.6	77
7C - R	168.81	6.7	3.5	41.1	56.4	338	388
8C - R	169.49	4.1	3.5	33.6	33.7	200	332
9C - R	203.60	6.4	2.1	32.5	33.5	242	364

Table 20. Summary of Kawabata Evaluation System results of cotton based laminates and Kappler's PRO/VENT™ laminate.

Sample No.	Weight	Tensile			Shearing			Bending		Surface			Compression					
		EMT	LT	WT	RT	G	2HG	2HG5	B	2HB	MIU	MMD	SMD	LC	WC	RC	EMC	To
UNFINISHED LAMINATES																		
1C	2.55	2.23	0.47	0.25	64.20	6.90	15.13	16.41	0.66	0.62	0.27	0.01	3.43	0.79	0.04	57.82	15.02	0.66
2C	2.72	1.89	0.51	0.24	55.59	6.46	15.49	17.31	0.70	0.63	0.29	0.02	2.89	0.81	0.04	58.77	14.44	0.72
3C	2.52	2.54	0.47	0.29	51.82	5.51	13.39	14.79	0.46	0.46	0.29	0.02	3.71	0.85	0.04	60.19	15.35	0.69
7C	2.79	2.20	0.36	0.19	81.88	6.91	16.62	19.18	1.85	2.18	0.19	0.01	2.40	0.78	0.05	59.71	15.48	0.82
8C	3.46	1.71	0.42	0.18	72.30	7.65	22.25	24.14	3.45	4.13	0.21	0.02	2.68	0.87	0.05	60.24	11.76	0.87
9C	3.52	2.36	0.41	0.23	70.40	7.93	19.96	23.37	2.80	3.25	0.21	0.02	2.82	0.85	0.03	58.63	10.36	0.79
REPELLENT FINISHED LAMINATES																		
1C - R	2.55	2.18	0.49	0.26	77.13	6.36	10.97	12.89	0.67	0.48	0.38	0.02	3.51	0.95	0.04	55.66	11.80	0.65
2C - R	2.54	4.03	0.41	0.42	73.75	4.74	6.68	8.00	0.24	0.38	0.44	0.02	2.47	0.75	0.14	57.77	30.94	1.21
3C - R	2.74	8.18	0.36	0.74	71.12	3.63	4.76	5.59	0.20	0.28	0.38	0.02	1.97	0.72	0.40	55.21	44.04	2.50
7C - R	3.02	2.42	0.44	0.26	72.07	6.63	12.79	15.18	0.49	0.42	0.32	0.02	4.15	0.84	0.05	56.86	13.48	0.84
8C - R	3.10	2.65	0.50	0.33	68.27	6.29	11.25	13.15	0.76	0.59	0.29	0.02	5.36	0.83	0.05	58.31	13.71	0.89
9C - R	3.97	3.87	0.43	0.42	62.87	5.33	10.81	11.98	0.39	0.46	0.33	0.02	3.65	0.77	0.19	52.17	28.61	1.70
KAPPLER'S SPUNBOND/MICROPOROUS FILM LAMINATE PRO/VENT™																		
Pro/Vent™	2.35	6.75	0.26	0.44	162.6	3.87	5.95	5.78	0.06	0.05	0.24	0.02	3.83	0.82	0.14	51.53	34.11	1.01

Weight (oz/yd²)

EMT: Elongation (%), LT: Linearity, WT: Tensile Energy (gf.cm/cm²), RT: Resilience (%)

G: Shear Stiffness (gf/cm.degree), 2HG: Hysteresis at 0.5°, 2HB: Hysteresis at 5.0°
B: Bending Rigidity (gf.cm/cm²), 2HB: Hysteresis (gf.cm/cm)
MIU: Coefficient of Friction, MMD: Mean Deviation of MIU, SMD: Geometrical Roughness (micron)
LC: Linearity, WC: Compressional Energy (gf.cm/cm²), RC: Resilience (%), EMC: Thickness Compression (%), T_o: Thickness (mm)

Table 21. Moisture vapor transmission rate test results of cotton based laminates.

Sample No.	g/m ² -24 hrs
UNFINISHED LAMINATES	
1C	1324.39
2C	1330.08
3C	1356.60
7C	1121.66
8C	1112.19
9C	1108.40
REPELLENT FINISHED LAMINATES	
1C - R	1313.03
2C - R	1282.71
3C - R	1254.29
7C - R	1385.03
8C - R	1366.03
9C - R	1292.18

Table 22.Synthetic blood penetration results of cotton based laminates.

Sample No.	Time taken for blood penetration (sec)
UNFINISHED LAMINATES	
1C	Fail (1-2)
2C	Fail (1-2)
3C	Fail (1)
7C	Fail (1)
8C	Fail (1)
9C	Fail (1)
REPELLENT FINISHED LAMINATES	
1C - R	Fail (3-4)
2C - R	Fail (3-4)
3C - R	Fail (2)
7C - R	Fail (1-2)
8C - R	Fail (2)
9C - R	Fail (1-2)

lightest cotton core of 1.0 oz/yd² (33.9 g/m²) did not show a large difference in thickness, while laminates (Samples No. 3C-R and 9C-R) having a cotton core of 2.0 oz/yd² and 3.0 oz/yd² (67.8 and 101.8 g/m²) respectively showed a notable increase in thickness after finishing.

Bending length and air permeability values have been given in Table 17. The bending length of the finished laminates appeared to be lower than that of the unfinished laminates. This is an indication of decreased stiffness and thereby better drapability. The decreased bending length values and accompanying improved softness of the finished laminates may have been due to the mechanical forces experienced in the pad application of the finish and the heat received during drying/curing. The majority of the repellent finished laminates displayed lower air permeability values. However, the air permeability of Sample No. 3C-R increased almost three-fold from 18.9 ft³/min/ft² to 54.09 ft³/min/ft² (0.0945 to 0.27045 m³/min/m²). This increase may be because Sample No. 3C-R had a much greater increase in apparent bulk after finishing. Sample No. 3C-R showed signs of delamination after repellent finishing and may be a reason for displaying increased air permeability after the process of repellent finishing.

The barrier test results are given in Table 18. The hydrostatic head values of most of the repellent finished samples were generally higher than the unfinished laminate samples. However, the hydrostatic pressure of MCM Sample No. 3C-R, which only had 0.25 oz/yd² (8.475 g/m²) of melt blown PP web on each side with 2.0 oz/yd² (67.8 g/m²) of cotton in the center, decreased from 27.0 inches (0.675 m) to 10.5 inches (0.2625 m) after repellent finishing. Although this sample displayed increased porosity and became much softer, it did not delaminate upon finishing.

The repellent finished samples showed a marked improvement in water spray rating (Table 18) with an excellent range of 80 to 90 (0 denoting complete wetting and 100 denoting complete lack of wetting). Sample No. 9C had a very poor water spray rating of 0, but upon repellent finishing Sample No. 9C-R displayed a good water spray rating of 80. Also, the water impact penetration values (Table 18) which were already negligibly low in the unfinished samples, resulted in no detectable penetration in the finished samples.

The greatest advantage of repellent finishing was a significant increase in the oil repellency rating (Table 18) from a very poor 0 in the unfinished laminates to an excellent rating of 6 to 8 in finished laminates, with 8 being the maximum oil repellency rating.

The strength test results of unfinished and repellent finished laminates are given in Table 19. The bursting strength, breaking strength, and tearing strength of the laminates notably decreased after finishing. Sample No. 3C-R having 80% cotton content displayed the greatest loss in strength when compared to its unfinished counterpart (Sample No. 3C). This loss in strength in Sample No. 3C-R may be because the sample delaminated after going through the process of finishing. The elongation-at-break values were only slightly affected by the finishing process.

The KES measurements [47, 48] of the mechanical hand properties of the unfinished cotton laminates, finished cotton laminate, and Kappler's PRO/VENT™ are given in Table 20. Among the unfinished cotton laminates, Sample No. 3C (that had 80% cotton) was lightest in weight, most extensible (highest EMT), most shearable (lowest G), displayed least resistance to bending (lowest B), roughest (highest SMD), and had the second highest resilience (RC value next to Sample No. 9C). Sample No. 3C also had a high coefficient of

friction (highest MIU value) which is typically obtained for softer materials. Sample No. 9C is the least extensible (lowest EMT), least bendable (highest B), least shearable next to Sample No. 9C (second highest G), smooth (second lowest SMD after Sample No. 7C), has a high coefficient of friction, and had highest compressional resilience (highest RC). Sample No. 9C is the least shearable (highest G), least bendable after Sample No. 8C (second highest B), had second highest EMT value and ranks next to Sample No. 3C as the most extensible, and was least compressible (lowest EMC). Sample No. 7C was most compressible (highest EMC), lowest coefficient of friction (lowest MIU), and smoothest (lowest SMD).

Repellent finished laminates with the softest hand (Samples No. 3C-R and 2C-R) were found to be most extensible, offered the least resistance to shearing (lowest G) compared to samples having a stiffer hand, displayed lowest bending rigidity (B) and lowest energy loss in bending, high Coefficients of friction (MIU) values, and appeared to absorb more energy in compression. Repellent finishing made Samples No. 3C-R and 2C-R more extensible, more shearable, more bendable, more smooth, and more compressible. Sample No. 3C-R also was the thickest (highest T_0), had a high coefficient of friction, and absorbed most compression energy (WC). This could be the reason for Sample No. 3C-R to be more 'springy' and most soft. Sample No. 2C-R was the lightest and had the highest coefficient of friction. Sample No. 8C-R had the roughest surface and Sample No. 7C-R also had a rougher surface than other samples.

The results of MVTR testing [47, 48] are given in Table 21. Among the unfinished cotton laminates, Sample No. 3C which had the best mechanical hand properties also had the highest moisture vapor diffusion of 1356.60 g/m² during a period of 24 hours. Sample No. 2C and Sample No. 1C had 1330.08

g/m²-24hr and 1324.39 g/m²-24hr respectively. Among the repellent finished cotton laminates, Sample No. 7C-R and 8C-R had the highest levels of moisture vapor transport of 1385.03 g/m²-24hr and 1366.08 g/m²-24hr respectively. Samples No. 3C-R and 2C-R, which had good mechanical hand properties, had the lowest levels of moisture vapor transport.

The test results of the blood barrier test according to ASTM Standard ES21-92 are reported in Table 22. All the laminates displayed penetration of synthetic blood in the pressurization step and did not pass this test. The test procedure suggests that the results be recorded as either "Pass" or "Fail" to indicate its performance as a protective material. Since none of the cotton based laminates passed this test, the time taken for the penetration of blood was recorded. This was done in an attempt to determine if there were differences between individual samples. The time taken for penetration to occur for different laminate was in the range of 1-2 sec in the case of unfinished laminates and 1-4 sec in the case of repellent finished laminates.

Statistical Analysis of data

A fluorochemical treatment was given to the laminates in order to improve repellency characteristics - to water, oil, blood, alcohol, and other aqueous liquids - and barrier properties of the laminates. These properties are necessary for hospital operating room drape and gown fabric materials. From the results obtained it is seen that repellency characteristics and barrier properties of the fluorochemically finished laminates definitely improved over the unfinished cotton laminates. In order to see if the difference in properties were statistically significant for unfinished and finished laminates the Wilcoxon Signed Rank test was used. The Wilcoxon Signed Rank test was performed

using the SAS software. The results obtained from the Wilcoxon Signed Rank test are given in Table 23.

While comparing paired groups (as is being done here) by using the Wilcoxon Signed Rank test, the null hypothesis (H_0) is that the mean difference between the groups is zero, and the alternative hypothesis (H_a) is that the mean difference between the groups is different from zero. In the Wilcoxon Signed Rank test, the hypotheses are tested by calculating a test statistic from the data and comparing its value to that expected if the null hypothesis were to be true. For the Wilcoxon Signed Rank test, the two possible outcomes are: i) the probability (p) value is lower than the reference probability (0.05 in this study), or ii) the probability (p) value is higher than the reference probability. If the former outcome is obtained, the result is statistically significant, the null hypothesis is rejected, and it is concluded that the mean difference between the paired groups is significantly different from zero. If the latter outcome is obtained, the null hypothesis is not rejected, and it is concluded that there is not sufficient evidence to say that the mean difference between the paired groups is significantly different from zero.

For Part A of the study, the hypotheses are:

H_0 : The mean difference in the properties of the unfinished and finished laminates is not significantly different from zero.

H_a : The mean difference in the properties of the unfinished and finished laminates is significantly different from zero.

In the Wilcoxon Signed Rank test results (Table 23), one needs to look at the *signed rank statistic* and also its *associated probability*. In the case of "Thickness", the signed rank statistic is -10.5 and its associated probability (p-value) is 0.0313. Since the p-value is less than 0.05 (associated with a reference 5% significance level), the result is statistically significant, the null

Table 23. Wilcoxon Signed Rank Test Results of unfinished and finished laminates.

Comparison of	No. of Samples (N)	Signed Rank Statistic (S)	Probability of Signed Rank Statistic (Prob > S)
Weight	6	-1.5	0.8438
Thickness	6	-10.5	0.0313
Hydrostatic Pressure	6	-2.5	0.6250
Water Spray Rating	6	-10.5	0.0313
Water Impact Penetration	6	10.5	0.0313
Oil Repellency Rating	6	-10.5	0.0313
Bursting Strength	6	3.0	0.6250
MD Tear Strength	6	6.5	0.2188
CD Tear Strength	6	-3.5	0.5625
MD Breaking Strength	6	9.5	0.0625
CD Breaking Strength	6	6.5	0.2188
MD Breaking Elongation	6	-0.5	1.0000
CD Breaking Elongation	6	3.5	0.5625
MD Bending Length	6	10.5	0.0313
CD Bending Length	6	7.5	0.1563
Air Permeability	6	3.5	0.5625
Moisture Vapor Rate	6	-4.5	0.4375

Table 23 (contd.). Wilcoxon Signed Rank Test Results of unfinished and finished laminates.

Comparison of	No. of Samples (N)	Signed Rank Statistic (S)	Probability of Signed Rank Statistic (Prob > S)
Weight	6	-2.5	0.6250
Elongation, EMT	6	-9.5	0.0625
Linearity, LT	6	0.5	1.000
Tensile Energy, WT	6	-10.5	0.0313
Resilience, RT	6	-4.5	0.4375
Shear Stiffness, G	6	10.5	0.0313
Hysteresis at 0.5°, 2HG	6	10.5	0.0313
Hysteresis at 5.0°, 2HG5	6	10.5	0.0313
Bending Rigidity, B	6	9.5	0.0625
Hysteresis, 2HB	6	10.5	0.0313
Coefficient of Friction, MIU	6	-10.5	0.0313
Mean Deviation of MIU, MMD	6	-1.5	0.50
Geometrical Roughness, SMD	6	-4.5	0.4375
Linearity, LC	6	2	0.75
Compressional Energy, WC	6	-3	0.25
Resilience, RC	6	10.5	0.0313
Thickness Compression, EMC	6	-5.5	0.3125
Thickness, T _o	6	-9.5	0.0625

hypothesis can be rejected, and it can be concluded that there is a significant difference between the thickness of unfinished and finished laminates. The unfinished fabrics are seen to have lower thickness which agrees with the fact that they appear to be less bulky than finished fabrics.

Based on the Wilcoxon Signed Rank test results, the unfinished and finished laminates were different in thickness, water spray rating, water impact penetration, oil repellency rating, and MD bending length. In the KES analyses, tensile energy, shear stiffness, hysteresis at 0.5°, hysteresis at 5.0°, hysteresis, coefficient of friction, and resilience properties were different in the unfinished and finished laminates.

Since Wilcoxon Signed Rank test compared the laminates before and after finishing, the "+" or "-" of the Signed Rank Statistic is an indication whether the value was higher "before finishing" or "after finishing". A "+" Signed Rank Statistic is an indication that the value was higher "before finishing" and a "-" Signed Rank Statistic is an indication that the value was higher "after finishing". The value of the Signed Rank Statistic showed properties which were better before finishing and those which were better after finishing. However, it should be noted that a "+" Signed Rank Statistic for the MD Bending Length is an indication that the value was higher "before finishing", meaning higher stiffness and lower drapability, and was lower "after finishing" indicating higher drapability. Also, a "+" Signed Rank Statistic for the Water Impact Penetration was an indication that the value was higher "before finishing", meaning greater penetration of water, and was lower "after finishing" indicating greater resistance to penetration.

The Signed Rank Statistic being negative indicated that the finished laminates had higher thickness values, higher water spray ratings (indicating

higher repellency), and higher oil repellency ratings. The finished laminates had lower water impact penetration values (indicating better resistance to water penetration) and lower MD bending length values (indicating greater softness and better drapability). The complete printouts got by the Univariate Procedure are in the Appendix.

The Wilcoxon Signed Rank test showed that the repellency and barrier properties of cotton laminates underwent a significant improvement with the application of a repellent fluorochemical finish.

Comparison of Cotton Laminates with Commercially Available Gowns

Gowns made of Spunbond/Melt Blown/Spunbond (SMS) laminate obtained from a commercial vendor and Kappler Safety Group's Spunbond/Microporous film laminate (PRO/VENT™) provided by Kappler Safety Group, Guntersville, Alabama were tested for different properties in an attempt to compare the cotton based laminates of this study to commercially available operating room apparel gowns. The results of the various tests for these commercially available gowns are summarized in Table 24.

The SMS and spunbond (presumably polyethylene Tyvek®) fabrics have the largest share (36% of 1.3+ billion square yards) of the overall US medical nonwoven market [59]. SMS offers the best balance of barrier, strength and breathability properties compared to other nonwoven materials and is used predominantly for surgical gowns and sterilization wraps. Hence it was chosen as a candidate to be compared against the developmental cotton based laminates of this study.

Table 24. Comparison of test results of commercially available operating room gowns.

Property	Unit/ Rating	MD/CD	SMS Gown	Kappler's Pro/Vent™
Weight	oz/yd ²		1.5	2.2
Thickness	mm		0.308	0.738
Air Permeability	ft ³ /min/ft ²		42	-
Bending Length	cm	MD	2.73	2.6
		CD	2.38	3.14
Breaking Strength	mN/tex	MD	5.1	15.1
		CD	2.6	12.9
Elongation - at - break	%	MD	38.6	86.3
		CD	47.7	105.5
Bursting Strength	kPa		167.43	255.96
Tear Strength	g	MD	432	1124
		CD	716	1660
Hydrostatic Pressure	inches		15.5	49+
Water Spray Rating	0-100		70	90
Water Impact Penetration	g		0	0
Oil Repellency Rating	0-8		8	0
Resistance to Synthetic Blood Penetration	Pass/Fail		Fail	Pass
Moisture Vapor Transmission Rate	g/m ² -24hr		-	1019.35

- Not tested

Presently, impervious films are used as reinforcements in certain portions (such as the chest area and sleeves) of the surgical gowns to meet the barrier requirements with particular reference to the penetration of blood and bloodborne pathogens. The PRO/VENT™ gown from Kappler has outer layers of spunbond webs and a inner overall microporous film core to pass the ASTM ES21-92, resistance to synthetic blood. Hence it was selected as a candidate in the comparative study.

The SMS gown did not have an impervious film in its construction. The spunbond (SB) outer layers contribute to the high bursting, breaking and tearing strength of the SMS gown fabric and the MB inner layer, in conjunction, to the repellent finish applied to the laminate are responsible for the good barrier properties. On the hand, the repellent finished cotton laminates which contained no SB layer (MCM laminates) or only contained one SB layer (SCM laminates) had comparable barrier properties, but, lower strength properties. The higher air permeability and lower bending length of the SMS gown may be explained by the lower weight of the SMS gown fabric in addition to having SB webs on both sides which are of course much more permeable than MB webs containing superfine fibers. The comparison between the barrier properties shows that the cotton laminates displayed higher hydrostatic pressure (in case of MCM laminates) and higher water spray rating (indicating higher resistance to wetting by water) compared to the SMS gown fabric. SMS gown and the cotton laminates displayed similar water impact penetration (which is an indication of slightly lower resistance to the penetration of water) and oil repellency (resistance to wetting by a series of liquid hydrocarbons of different surface tension) rating. Neither the cotton laminates nor the commercially obtained SMS gown fabric passed the Synthetic Blood Penetration test ASTM

Standard ES21-92. In terms of other barrier and repellency performance tests, the cotton laminates had acceptable properties which were in the same range as the commercially available SMS fabrics.

Kappler Safety Group's Spunbond/Microporous film laminate PRO/VENT™ gown was developed by Kappler to meet the new standards of apparel used in operating room environments, and is being promoted by Kappler as providing a superior balance between barrier and comfort properties. This gown was found to be better than the cotton laminates and the SMS gown in terms of drapability, strength, and barrier properties. However, its oil repellency rating of 0 was similar to that of the unfinished cotton laminates. The PRO/VENT™ gown "passed" the ASTM ES21-92 while the cotton laminates and the SMS gown "failed" to pass the ASTM ES21-92 and allowed penetration as soon as pressure was applied. It should be pointed out that many suppliers of breathable barrier fabrics are now laminating impervious films to areas of gowns where penetration by body fluids is more likely. The PRO/VENT™ gown showed a MVTR of 1019.35 g/m²-24hr which is lower than the MVTR values obtained for the cotton based laminates.

Kappler's PRO/VENT™ gown was sent for KES measurements (Table 20) to North Carolina State University [48]. The SMS gown was not sent for KES analyses because of insufficient quantity of sample. Compared to the cotton based laminates, Kappler's gown laminate PRO/VENT™ was found to be the lightest in weight, most extensible (highest EMT), most shearable (lowest G), displayed least resistance to bending (lowest B), and roughest (highest SMD). All these values were found to be better than Sample No. 3C (the unfinished cotton laminate). However, upon repellent finishing, Sample No. 3C-R was found to be more extensible (higher value of elongation), more shearable

(lower value of shear stiffness) than PRO/VENT™. Samples No. 3C and 2C had higher coefficient of friction (highest MIU value) than Kappler's laminate indicating higher softness. Most of the unfinished cotton based laminates had lower thickness (T_o) values than Kappler's laminate.

PART B: COTTON LAMINATES INCORPORATING MICROPOROUS FILMS

Thermally Bonding Cotton Laminates Combined With Microporous Films Without Adhesives

Thermally bonding cotton based laminates with microporous films without using adhesives was the first technique used towards overcoming the lower processing speeds and the lack of stringent blood barrier properties of the thermally bonded cotton based laminates of Part A of this study. Twelve laminates having MB and/or SB outer layers with cotton and microporous film (polytetrafluoroethylene Tetratex™ and PE Exxaire®) inner layers were thermally point bonded with the conditions given in Table 3 of Chapter 3 on "Experimental Design and Procedure".

The results of the thermally bonded cotton based laminates containing microporous films are given in Table 25. The laminates having PTFE microporous film had lower basis weight and lower thickness values than laminates having Exxaire® film. The thickness of Sample No. 3 is higher than the remaining laminates because of the shrinkage of Exxaire® film in the laminate that resulted in the cotton side (bottom side) of the laminate puckering

Table 25. Results of thermally bonded laminates having microporous film.

Sample No.	Weight		Thickness	Air Permeability	Bursting Strength	Resistance to Blood
	(g/m ²)	(oz/yd ²)	(mm)	(ft ³ /min/ft ²)	(psi)	Pass/Fail
1	102	3.01	0.6807	-	34.7	Pass
2	83	2.45	0.6181	-	14.6	Pass
3	102	3.01	1.3469	-	15.3	Fail
4	92	2.71	0.7887	-	17.4	Fail
5	140	4.13	0.8860	-	22.9	Fail
6	99	2.92	0.7257	168.75	26.6	Fail
7	97	2.86	0.8729	265.68	38.0	Pass
8	98	2.89	0.7563	8.18	17.6	Fail
9	79	2.33	0.7083	-	14.0	Pass
10	78	2.30	0.5313	148.36	21.2	Fail
11	55	1.62	0.4482	-	15.7	Pass
12	61	1.80	0.4510	-	29.2	Pass

- Could not be determined on Frazier Air Permeability Tester.

up. There was no puckering when SB outer layers were used. This puckering of laminates containing Exxaire® film could possibly be avoided by the use of lower temperature during bonding. The laminates having cotton in the core appeared to have a better hand than laminates not having cotton in the core.

The air permeability of only four of the twelve laminates made could be determined on the Frazier Air Permeability Tester because the others had lower air permeability values than could be determined using this instrument. Samples No. 6, 7, and 10 that displayed much higher air permeability had SB webs as both the outer layers of the laminates. Sample No. 6 which had SB outer layers and a core of cotton and Exxaire® film displayed a much higher air permeability of $168.75 \text{ ft}^3/\text{min}/\text{ft}^2$ ($0.84375 \text{ m}^3/\text{min}/\text{m}^2$) than Sample No. 8 which had a cotton and Exxaire® film in the core between SB and MB outer layers with an air permeability of $8.18 \text{ ft}^3/\text{min}/\text{ft}^2$ ($0.0409 \text{ m}^3/\text{min}/\text{m}^2$). Sample No. 6 which had a core of cotton and Exxaire® film displayed higher air permeability of $168.75 \text{ ft}^3/\text{min}/\text{ft}^2$ than Sample No. 10 which had a core of Exxaire® film with no cotton which had an air permeability of $148.36 \text{ ft}^3/\text{min}/\text{ft}^2$ ($0.7418 \text{ m}^3/\text{min}/\text{m}^2$). Sample No. 7 which had SB outer layers and a core of cotton and PTFE film displayed a much higher air permeability of $265.68 \text{ ft}^3/\text{min}/\text{ft}^2$ ($1.3284 \text{ m}^3/\text{min}/\text{m}^2$) than Sample No. 6 which had SB outer layers and a core of cotton and Exxaire® film which had an air permeability of $168.75 \text{ ft}^3/\text{min}/\text{ft}^2$ ($0.84375 \text{ m}^3/\text{min}/\text{m}^2$).

The bursting strength of the laminates was generally found to be higher when PTFE film was used compared to the laminates having Exxaire® film. This was seen by comparing Samples No. 1 and No. 5 which contain PTFE film and Exxaire® had bursting strength values of 34.7 psi (239.083 kPa) and 22.9 psi (157.781) respectively. The bursting strength values of 38.0 psi (261.82 kPa)

and 26.6 psi (183.274 kPa) were obtained in Sample No. 7 (PTFE) and Sample No. 6 (Exxaire®) respectively. The laminates having SB webs as the outer layers appeared to have higher bursting strength than laminates using MB webs as the outer layers. This was indicated from comparing Sample No. 7 (SB outer layers) and Sample No. 2 (MB outer layers) which had bursting strength values of 38.0 psi (261.82 kPa) and 14.6 psi (100.594 kPa), respectively. Also, Sample No. 6 (SB outer layers) and Sample No. 4 (SB at the top and MB at the bottom) had bursting strength values of 26.6 psi (183.274 kPa) and 17.4 psi (119.886 kPa) respectively. The presence of cotton in the core of the laminates generally appeared to result in higher bursting strength values than laminates that had only microporous film in the core. The bursting strength values of laminates having two layers of microporous films (Samples No. 1 and 5) was found to be higher than laminates having one layer of microporous film (Samples No. 2 and 3).

The twelve thermally bonded laminates were subjected to ASTM Emergency Test Method ES 21-92 to determine the resistance to penetration by synthetic blood. Six of the twelve laminates passed this test. Five of the samples that passed this test had microporous PTFE film Tetratex™ from Tetratex Corporation. One had the microporous Exxaire® polyethylene film from Exxon Chemical Corporation. Samples No. 11 and 12 had only PTFE film in the core and passed this test. Samples No. 2 and 7 that were similar to Samples No. 11 and 12, respectively, but had cotton along with PTFE in the core also passed this test. Sample No. 1 that had two layers of PTFE in the core along with cotton passed this test, whereas, Sample No. 5 that had two layers of Exxaire® film in the core failed this test. But two layers of PTFE film may not be necessary to pass the blood barrier test because Sample No. 2 that had only

one layer of the microporous PTFE film also passed this test. It was surprising that Sample No. 9 that had only a microporous Exxaire® film in the core (with MB outer layers) passed this test whereas Samples No. 3 and 5 (which had one and two layers of Exxaire® in the core respectively along with cotton) failed this test. It is believed that during the thermal bonding process the Exxaire® film melted and flowed around the cotton fibers and possibly creating pin holes. Thus it would appear that the use of adhesives would allow bonding to occur at ambient or slightly elevated temperature and that better adhesion could be obtained without forming pin holes.

Adhesive Bonding of Cotton Laminates Using Conventional Melt Blown Line to Apply a Hot Melt Adhesive

Melt blowing a hot melt adhesive between constituent layers of cotton laminates using a conventional vertical J and M Laboratories MB line was the second technique used towards overcoming the lower processing speeds and the lack of stringent blood barrier properties of the thermally bonded cotton based laminates of Part A of this study. This technique was used to minimize the detrimental effects of thermal bonding (without adhesives) the cotton laminates containing microporous films such as PE Exxaire® film. Seven laminates having both MB outer layers with cotton and microporous film (polytetrafluoroethylene Tetratex™ and PE Exxaire®) inner layers were point bonded using unheated or slightly heated calender rolls as described in Table 4 of Chapter 3 on "Experimental Design and Procedure".

The results of the trial adhesive bonded cotton based laminates incorporated with microporous film are given in Table 26. The laminates having

Table 26. Results of trial adhesive bonded laminates having microporous film.

Sample No.	Weight		Thickness (mm)	Bursting Strength (psi)	Resistance to Blood
	(g/m ²)	(oz/yd ²)			
1	92	2.71	0.7685	16.0	Pass
2	86	2.54	0.7820	11.0	Pass
3	88	2.60	0.6794	16.33	Pass
4	77	2.27	0.6973	12.0	Pass
5	94	2.77	0.8350	13.33	Fail
6	72	2.12	0.7971	9.66	Fail
7	71	2.09	0.6672	14.0	Fail
8	56	1.65	0.7856	9.0	Fail

Exxaire® microporous film had higher basis weight than the laminates having PTFE microporous film because the Exxaire® microporous film was nearly twice as heavy as the PTFE microporous film. Generally, laminates having Exxaire® film displayed lower thickness values than the laminates having PTFE film. This may be because the hot melt adhesive did not adhere to the PTFE film and formed a separate layer. The hot melt adhesive having a PP base appeared to adhere well to the polyethylene Exxaire® film which would account for laminates having lower thickness values in most cases. The PTFE film in the core also did not bond well to the other layers such as cotton and melt blown webs (Samples No. 1, 2, 4, and 7).

Unlike the thermally bonded laminates without adhesives, the bursting strength values of these laminates were generally found to be higher when Exxaire® film was used compared to the laminates having PTFE film. This can be seen by comparing Sample No. 1 (Exxaire®) and Sample No. 2 (PTFE) which had bursting strength values of 16.0 psi (110.24 kPa) and 11.0 psi (75.79 kPa), respectively, as well as, Sample No. 3 (Exxaire®) and Sample No. 4 (PTFE) which had bursting strength values of 16.33 psi (112.514 kPa) and 12.33 psi (84.954 kPa) respectively. This can also be shown by comparing Sample No. 5 (Exxaire®) and Sample No. 6 (PTFE) which had bursting strength values of 13.33 psi (91.844 kPa) and 9.66 psi (66.558 kPa) respectively. The lack of adherence of different constituent layers in laminates having PTFE may also be a reason for its lower bursting strength values.

The seven laminates were subjected to ASTM Emergency Test Method ES 21-92 to determine the resistance to penetration by synthetic blood. Four of the seven laminates passed this test. Two of the samples that passed this test had microporous PTFE film Tetratex™ from Tetratex Corporation and two had

the microporous Exxair® polyethylene film from Exxon Chemical Corporation. All the samples that passed this test had cotton along with the microporous film in the core and had been laminated at ambient temperature with two different surface speeds of 5 m/min and 10 m/min. The three laminates that failed this test were laminated at the lowest possible calender roll temperature, at 92.2 to 95°C when the oil heating system was in operation. The fact that better results were obtained by bonding the laminates with melt blown adhesive at ambient rather than at even slightly elevated temperature was encouraging in that the bonding speed would not be limited by the time required for heat transfer through the fabric in the production process.

Adhesive Bonding of Cotton Laminates Using Adhesive Melt Blown Line to Apply a Hot Melt Adhesive

Melt blowing a hot melt adhesive between constituent layers of cotton laminates using a J and M Laboratories adhesive MB line was the third technique used towards overcoming the lower processing speeds and the lack of stringent blood barrier properties of the thermally bonded cotton based laminates of Part A of this study. This technique was used to minimize the detrimental effects of thermal bonding (without adhesives) the cotton laminates containing microporous films such as PE Exxair® film. Twenty-five laminates having MB and/or SB outer layers with cotton (unbonded carded, thermal bonded, and latex bonded webs) and microporous film (PE Exxair®) inner layers were smooth and point bonded using unheated calender rolls as described in Table 5 of Chapter 3 on "Experimental Design and Procedure".

The results of the adhesive smooth bonded and point bonded laminates are given in Tables 27 and 28, respectively. It was important to determine at this stage of the work whether smooth versus point bonding gave better strength, breathability, and barrier properties. Thus the Wilcoxon Signed Rank Test was used to statistically determine any significant differences in (weight, thickness, bursting strength, and moisture vapor transmission rate) properties between the laminates that were smooth and point bonded. The results of the Wilcoxon Signed Rank Test analysis is given in Table 29.

The basis weight of the adhesive smooth bonded laminates was found to be lower than the point bonded laminates. The majority of the smooth bonded laminates had higher thickness values than the point bonded laminates. This can be accounted for by the fact that the point bonded laminates had an additional step through the calender nip, which also greatly compressed the laminates at the points corresponding to the raised diamond pattern against the smooth steel roll.

The bursting strength values of the adhesive smooth bonded laminates were greater than those of the adhesive point bonded laminates. The reason for smooth laminates having higher bursting strength values may be because there is higher percentage of bonding (100%) in smooth bonding compared to only 14.66% bonding in the point bonding process. The bursting strength values of (smooth and point bonded) laminates having thermal bonded and latex bonded cotton webs in the core appeared to be only slightly greater than laminates having staple fiber carded cotton webs. This can be seen by comparing Samples No. 7A (thermal bonded cotton web) and 8A (latex bonded cotton web) which had bursting strength values of 28.75 and 26.5 psi (198.088 and 182.585 kPa), respectively, with Sample No. 2A (carded cotton web) which

Table 27. Results of adhesive smooth bonded laminates.

Sample	Weight		Thickness	Bursting Strength	M V T R	Resistance to Blood	Resistance to Virus
	(g/m ²)	(oz/yd ²)	(mm)	(psi)	(g/m ² - 24hr)	(Pass/Fail)	(Pass/Fail)
MFCM LAMINATES							
1A	99.0	2.92	0.6156	17.25	615.78	Pass	Pass
2A	120.0	3.54	0.8089	23.0	659.36	Pass	Pass
3A	94.0	2.77	0.6325	18.25	718.09	Pass	Fail
4A	115.0	3.39	0.7463	21.5	716.20	Pass	-
5A	98.0	2.89	0.5283	18.5	689.67	Pass	Pass
6A	103.0	3.04	0.4836	18.5	680.20	Pass	Fail
7A	114.0	3.36	0.6776	28.75	678.30	Pass	Pass
8A	118.0	3.48	0.6352	26.5	587.36	Pass	Pass
SFCM LAMINATES							
9A	116.0	3.42	0.6947	27.0	602.51	Pass	Pass
10A	117.0	3.45	0.8084	28.0	591.15	Pass	Pass
SFCS LAMINATES							
11A	113.0	3.33	0.6546	31.5	611.99	Pass	Fail
12A	106.0	3.13	0.7985	32.5	735.14	Pass	-
13A	110.0	3.24	0.6329	33.0	674.51	Pass	Fail
14A	107.0	3.16	0.5734	36.0	632.83	Fail	-

- = Not Tested

Table 27 (contd.). Results of adhesive smooth bonded laminates.

Sample No.	Weight		Thickness	Bursting Strength	M V T R	Resistance to Blood	Resistance to Virus
	(g/m ²)	(oz/yd ²)	(mm)	(psi)	(g/m ² - 24hr)	(Pass/Fail)	(Pass/Fail)
CONTROL LAMINATES							
15A	73.0	2.15	0.3693	17.5	568.41	Pass	Pass
16A	72.0	2.12	0.3479	13.75	659.36	Pass	Fail
17A	92.0	2.71	0.6050	15.0	562.73	Pass	-
18A	90.0	2.65	0.5121	15.5	621.46	Pass	-
19A	80.0	2.36	0.4540	22.5	500.20	Pass	Fail
20A	84.0	2.48	0.5034	28.0	515.36	Pass	-
21A	63.0	1.86	0.5203	12.5	727.56	Fail	-
22A	81.0	2.39	0.6919	14.0	778.72	Fail	-
23A	53.0	1.56	0.2270	10.5	638.51	Pass	-
24A	57.0	1.68	0.2230	10.5	634.72	Fail	-
25A	72.0	2.12	0.6292	11.75	765.46	Fail	-

- = Not Tested

Table 28. Results of adhesive point bonded laminates.

Sample No.	Weight		Thickness	Bursting Strength	M V T R	Resistance to Blood	Resistance to Virus
	(g/m ²)	(oz/yd ²)	(mm)	(psi)	(g/m ² - 24hr)	(Pass/Fail)	(Pass/Fail)
MFCM LAMINATES							
1B	99.0	2.92	0.6430	16.0	589.25	Fail	-
2B	122.0	3.60	0.7264	19.5	632.83	Pass	-
3B	100.0	2.95	0.5888	16.0	725.67	Pass	Fail
4B	127.0	3.75	0.7034	18.5	699.14	Pass	-
5B	100.0	2.95	0.5056	19.0	610.09	Fail	-
6B	102.0	3.01	0.5287	19.0	623.36	Fail	-
7B	119.0	3.51	0.6884	23.5	634.73	Pass	Fail
8B	117.0	3.45	0.6504	24.5	562.73	Fail	-
SFCM LAMINATES							
9B	112.0	3.30	0.6334	23.5	583.57	Fail	-
10B	122.0	3.60	0.7398	21.5	577.88	Pass	-
SFCS LAMINATES							
11B	112.0	3.30	0.8783	25.75	619.57	Fail	-
12B	111.0	3.27	0.7920	29.5	693.46	Fail	-
13B	118.0	3.48	0.5909	30.0	649.88	Fail	-
14B	107.0	3.16	0.5504	33.5	613.88	Fail	-

- = Not Tested

Table 28 (contd.). Results of adhesive point bonded laminates.

Sample No.	Weight		Thickness	Bursting Strength	M V T R	Resistance to Blood	Resistance to Virus
	(g/m ²)	(oz/yd ²)	(mm)	(psi)	(g/m ² - 24hr)	(Pass/Fail)	(Pass/Fail)
CONTROL LAMINATES							
15B	75.0	2.21	0.4530	13.0	539.99	Pass	-
16B	78.0	2.30	0.4637	11.5	543.78	Pass	-
17B	93.0	2.74	0.5349	14.5	534.31	Pass	-
18B	88.0	2.60	0.4815	13.25	589.25	Pass	-
19B	72.0	2.12	0.3669	22.0	589.25	Fail	-
20B	83.0	2.45	0.5460	26.0	492.62	Fail	-
21B	67.0	1.98	0.6379	10.75	723.78	Fail	-
22B	81.0	2.39	0.6744	11.5	773.04	Fail	-
23B	57.0	1.68	0.2464	10.25	615.78	Fail	-
24B	55.0	1.62	0.2151	5.0	608.20	Fail	-
25B	69.0	2.04	0.6569	9.75	780.62	Fail	-

- = Not Tested

Table 29. Wilcoxon Signed Rank Test results of adhesive smooth bonded and adhesive point bonded laminates.

Comparison of	No. of Samples (N)	Signed Rank Statistic (S)	Probability of Signed Rank Statistic (Prob > S)
Weight	25	-55.5	0.0696
Thickness	25	8.5	0.8244
Bursting Strength	25	155.5	0.0001
Upright Cup MVTR	25	125.5	0.0002

had a bursting strength value of 23.0 psi (158.47 kPa). The same trend was observed in the case of the adhesive point bonded laminates. As expected, laminates having one or two outer SB layers generally displayed higher bursting strength values.

The MVTR values of the adhesive smooth bonded laminates were generally found to be higher than adhesive point bonded laminates. The MVTR of the point bonded laminates decreases probably because of the additional bonding that occurs at about 14.66% of the fabric. Laminates having the lower weight of the Exxaire® film (0.50 oz/yd² {8.475 g/m²}) had higher MVTR values than the laminates having heavier weight (0.94 oz/yd² {31.866 g/m²}) of the film. This can be seen by comparing samples (3A vs. 1A, 4A vs. 2A, 12A vs. 11A, 16A vs. 15A, 18A vs. 17A). The adhesive point bonded laminates displayed a similar trend. Thus it appears that the MVTR value of the microporous film is dictating the MVTR value obtained by the cotton based laminates.

Three unbonded assemblies of Samples No. 2, 23, and 24 (identified as Samples No. 2C, 23C, and 24C) were sent for MVTR testing in an attempt to determine the effect of adhesive on the moisture transmission rate of these laminates. These values are given in Table 30. These unbonded assemblies displayed comparable MVTR values with the adhesive smooth bonded and point bonded laminates. The microporous films were also tested for their moisture vapor transmission rates and it showed that the lighter (0.50 oz/yd² {16.95 g/m²}) Exxaire® film displayed a value of 725.67 g/m² for 24hr and the heavier (0.94 oz/yd² {31.866 g/m²}) Exxaire® film gave a value of 621.46 g/m² for 24hr. Table 28 also lists the bursting strength values of the unbonded laminates, microporous films, cotton core webs, and melt blown webs. The unbonded assemblies displayed slightly higher bursting strength values than

Table 30. Results of unbonded laminates, microporous films, cotton core webs, and MB webs.

Sample No. / Sample Identification	Bursting Strength	M V T R
	(psi)	(g/m ² - 24hr)
2C	18.0	642.30
23C	16.0	661.25
24C	11.0	621.46
0.50 oz/yd ² Film	8.5	725.67
0.75 oz/yd ² Film	9.5	621.46
Thermal Bonded Cotton	3.5	-
Latex Bonded Cotton	6.0	-
0.50 oz/yd ² PP MB	5.75	-
0.75oz/yd ² PP MB	6.5	-

• = Not Tested

the adhesive bonded laminates, with the exception of Sample No. 2C that displayed lower strength. This could be possibly because of the ability of the layers to dissipate some of the bursting force by slipping more freely past each other.

The adhesive bonded laminates were subjected to ASTM Test Method ES21-92 to determine the resistance to penetration by synthetic blood. Twenty adhesive smooth bonded laminates and nine point bonded laminates successfully resisted the penetration of blood. In the case of adhesive smooth bonded laminates, 13 out of 14 four-layered laminates passed, 6 out of 9 three-layered control laminates passed, 1 out of 2 two-layered laminates passed the ASTM ES21-92. The only four-layered laminate that did not pass this test was Sample No. 14A, which had both SB outer layers, and a core consisting of a combination of a 0.50 oz/yd² (16.95 g/m²) Exxaire® film and a 0.60 oz/yd² (20.34 g/m²) latex bonded cotton web. The three-layered laminates that failed this test did not have a microporous film in the core and were not expected to pass this test because of a lack of sufficient barrier. The two-layered laminate that did not pass this test was Sample No. 24A, which was a combination of a 0.94 oz/yd² (31.866 g/m²) Exxaire® film and a 0.60 oz/yd² (20.34 g/m²) latex bonded cotton web. Only one (two-layered) laminate having a 0.94 oz/yd² (31.866 g/m²) Exxaire® film and only one (four-layered) laminate having a 0.50 oz/yd² (16.95 g/m²) Exxaire® film failed the blood penetration test. This is evidence of the effectiveness of the microporous films in combination with the smooth bonding using melt blown adhesives at ambient temperature in resisting the penetration of blood.

Nine adhesive point bonded laminates successfully resisted the penetration of blood. Ten laminates having the heavier weight microporous film

and three laminates having lower weight film failed this test. It is believed that the patterned top roll could have created pin holes in the laminates that may be the reason for a majority of these fabrics failing the ASTM ES21-92. However, it is possible that lower nip pressures could be used in point bonding to decrease pin holes, if a patterned texture is desired.

Sixteen of the twenty-nine laminates that passed the ASTM ES21-92 were sent to Nelson Laboratories for the much more stringent viral penetration test, ASTM ES22-92. Fourteen adhesively smooth bonded laminates (Samples No. 1A, 2A, 3A, 5A, 6A, 7A, 8A, 9A, 10A, 11A, 13A, 15A, 16A, and 19A) and two adhesively point bonded laminates (Samples No. 3B and 7B) were tested for viral penetration. Eight laminates passed the viral penetration test. All the laminates that passed this test were adhesive smooth bonded and had the heavier weight 0.94 oz/yd² (31.866 g/m²) Exxaire® microporous film. Five of them were four-layered MFCM laminates (Samples No. 1A, 2A, 5A, 7A, and 8A), two were four-layered SFCM laminates (Samples No. 9A and 10A), and one of them was a three-layered control laminate consisting of two MB outer layers and a core having 0.94 oz/yd² (31.866 g/m²) Exxaire® film (Sample No. 15A). Seven out of the eight laminates that passed the viral penetration test had cotton web in the core. Among the ones that passed, four of them (Samples No. 1A, 2A, 9A, and 10A) had an unbonded carded cotton web in the core, two of them (Samples No. 5A and 7A) had a thermal bonded cotton web in the core, and one (Sample No. 8A) had a latex bonded cotton web. It could be possible that the cotton layer was in some way contributing to the resistance of viral penetration. It has been theorized that cotton or other hydrophilic materials may absorb water, thereby increasing the viscosity of the synthetic blood containing the virus and make it more difficult to penetrate.

The laminate structures that were most successful in resisting the rigorous blood and viral penetration and also had good moisture vapor transmission rates generally had four layers with at least one melt blown web (0.50 or 0.75 oz/yd²) with the other outside web being a melt blown or a spunbond web (0.60 oz/yd²), microporous Exxaire® film (0.94 oz/yd²), and an inside layer of an unbonded or pre-bonded cotton web (0.75 oz/yd²).

Statistical Analysis of Smooth Bonded and Point Bonded Laminates' Data

The Wilcoxon Signed Rank Test was used to determine if the differences in properties of the adhesive smooth bonded and adhesive point bonded laminates were statistically significant. The null hypothesis and alternative hypothesis for Part B of this study are:

H₀ : The mean difference in the properties of the adhesive smooth bonded and adhesive point bonded laminates is not significantly different from zero.

H_a : The mean difference in the properties of the adhesive smooth bonded and adhesive point bonded laminates is significantly different from zero.

The Wilcoxon Signed Rank Test results are given in Table 29. As mentioned earlier, *signed rank statistic* and its *associated probability* are of importance. The bursting strength and upright cup moisture vapor transmission rate (MVTR) are seen to be statistically significant with probability values being 0.0001 and 0.0002 respectively. Positive signed rank statistic values of 155.5 and 125.5 for bursting strength and MVTR indicates that the adhesive smooth bonded cotton laminates had higher bursting strength and MVTR values than the adhesive point bonded cotton laminates. Though it was concluded that the basis weight

of the adhesive smooth bonded cotton laminates were lower than the adhesive point bonded cotton laminates, this does not seem to be true at a p-value of 0.05. But the signed rank statistic for the basis weight was -55.5 indicating that the adhesive smooth bonded cotton laminates did have lower weight values. The complete printouts got by the Univariate Procedure are in Part B of the Appendix.

Summary. The fact that the adhesive smooth bonded laminates developed in this study passed the viral penetration test in combination with good moisture vapor rates is considered to be a notable achievement because there are no widely accepted commercially available disposable fabrics that possess this unique combination of barrier and breathability properties which also appear to be economical to produce. These experimental fabrics now meet the OSHA guidelines for protection of healthcare givers against bloodborne pathogens in the workplace [8]. These adhesive bonded cotton laminates also meet the AORN requirements for OR gowns regarding "minimal passage of microorganisms from nonsterile to sterile areas" [29]. Examples of commercial disposable nonwoven OR gowns that meet these requirements include "Prevention Surgical Gown" from 3M Healthcare Surgical Division (St. Paul, Minnesota) and "Virablock" from Baxter Healthcare Corporation (Mc Gaw Park, Illinois).

The adhesive bonded laminates developed in this study appear to be unique and meet the immediate requirements of the medical/surgical drapes and gowns. Hence a US Patent has been applied for this technology titled "Microporous Film/Nonwoven Composites" via Serial No. 309541 with Larry C. Wadsworth, Nataraj Gosavi, and Ahamad Yacub A. Khan being the inventors.

The success of the adhesive bonding trials using the 13-inch (0.325 m) adhesive lamination line at J and M Laboratories, Dawsonville, Georgia and the unique combination of properties of these laminates prompted us to use the 2.50-meter wide adhesive lamination line at Poly-Bond Inc., Waynesboro, Virginia to make 1.0-meter wide laminates. The trials at Poly-Bond Inc. indicated the feasibility of producing these laminates on a commercial scale so that they could be produced at industrial processing speeds (≈ 50 m/min) and be easily fabricated into OR gowns to take advantage of their barrier and comfort properties.

ANALYSIS FOR PREDICTING BARRIER PERFORMANCE OF LAMINATES

In an earlier study done at The University of Tennessee, Knoxville [60] a theoretical framework was developed using the Darcy's equation for flow through porous substrates to understand and predict the barrier behavior of fabrics.

Darcy's Law is an empirical relationship which describes the fluid flow through a porous media (such as a bed of sand or rock or sand) in terms of the driving force and the permeability of the medium. In beds of sand or rock the porous media are often modeled as an ideal bed of spheres or cylinders of constant radius. Nonwoven fiber webs or mats are regarded as porous media of cylinders.

Darcy's equation for flow of liquids through nonwoven porous media is given by:

$$\frac{\Delta P}{L_o} = \frac{\eta V_o}{K_2} \dots\dots\dots (1)$$

where, ΔP is the net pressure difference that causes the flow
 L_o is the length of the capillary pore
 V_o is the superficial velocity (i.e. the total volumetric flow rate per unit cross-sectional area of flow)
 η is the viscosity of the fluid
 K_2 is the permeability constant

Equation (1) can further be written as:

$$V_o = \frac{K_2}{\eta} \cdot \frac{\Delta P}{L_o} \dots\dots\dots (2)$$

Equation (2) can also be given as:

$$M = V_o \rho_L A = \frac{K_2}{\eta} \cdot \frac{\Delta P}{L_o} \cdot \rho_L \cdot A \dots\dots\dots (3)$$

where, M is the mass in grams per second of water penetrating through the fabric
 ρ_L is the density of the liquid
 A is the surface area of the porous fabric

The pressure difference is given by:

$$\Delta P = \rho_L \cdot g \cdot (h - h_o) \dots\dots\dots (4)$$

where, g is the acceleration due to gravity
 h is the height of fall of liquid
 h_o is the critical height at which penetration is zero

Combining equations 3 and 4, the following expression is obtained:

$$M = K_2 \left(\frac{\rho_L A}{\eta L_o} \right) (\rho_L \cdot g \cdot [h - h_o]) \dots\dots\dots (5)$$

Equation (6) can also be given as:

$$K_2 = \left(\frac{M}{\rho_L \cdot g \cdot [h - h_o]} \right) \cdot \left(\frac{\eta L_o}{\rho_L \cdot A} \right) \dots\dots\dots (6)$$

In Equation (6), the factors on the right hand side are either known or can be experimentally determined to calculate the permeability constant (K_2) of a given finished or unfinished fabric. The value of "h" and critical height " h_o " depends on the repellency and resistance offered by the treated fabric and can be determined experimentally using the water impact penetration test. The amount of water that penetrates the fabric (M) can also be obtained by performing the water impact penetration test.

This theoretical framework shows that the amount of water penetrating through the fabric is explained by the permeability constant K_2 for different fabrics. It was also observed by the above mentioned framework that the amount of penetration of water is dependent on the height from which water impacts the surface of the fabric. This is given by the quantity $\rho_L \cdot g \cdot (h - h_o)$. The better the barrier properties of the fabric, the greater the energy (ΔP) needed for the penetration of the fabric.

Table 31 shows the permeability constants (K_2) calculated for cotton laminate Samples No. 1C (thermally bonded sample having both melt blown outer layers, MCM-40-2.5, described in Table 1), 2A (adhesive smooth bonded laminate, MFCM, described in Table 5), 2B (adhesive point bonded laminate, MFCM, described in Table 6), 8C (thermally bonded sample having one melt blown and one spunbond outer layers, SCM-60-3.35, described in Table 1), and 10C (thermally bonded sample having both spunbond outer layers, SCS-45-2.2, described in Table 1) using Equation (7). The different factors from the equation are given at the bottom of the table. It is seen that the permeability constant (K_2 calculated using the equation) of the cotton laminates tends to

Table 31. Theoretical permeability constants for different cotton laminates.

Sample No.	Mass of Water Penetrated (M) g/s	Length of Capillary Pore (L_o) cm	Permeability Constant (K_2) $\text{cm}^2 (\times 10^{-5})$
1C	0.03	0.0667	0.288
2A	0.0	0.08089	-
2B	0.0	0.07264	-
8C	0.05	0.07477	0.5382
10C	22.83	0.05929	1.9488

- = Could not be determined.

ρ of water = 1 g/cm^3

$g = 981 \text{ cm/sec}^2$

A (Surface area of laminate) = 309.9 m^2

η of water (@ 20°C) = 1 cp

h (Height of fall of liquid) = 61.0 cm

h_o (Critical Height at which penetration is zero) = 38.1 cm

increase with an increase in the amount of water penetrating the fabric. The various cotton laminates had theoretical permeability constants (K_2) ranging from 0.288×10^{-5} to 1.9488×10^{-5} cm². Three factors (M , h , h_0) were equal to zero for adhesively smooth bonded Sample No. 2A and adhesively point bonded Sample No. 2B because they had a microporous film in their structures and therefore showed no penetration (0 grams) whatsoever in the water impact penetration test. Hence the permeability constants were not calculated for Samples No. 2A and 2B.

The trends obtained by the theoretical prediction of permeability constants were: Sample No. 10C (SCS-45-2.2) was the most permeable followed by Sample No. 8C (SCM-60-3.35) followed by Sample No. 1C (MCM-40-2.5). This confirms that spunbond outer layers contributed to greater permeability (and lower repellency) as is seen by Sample No. 10C having two outer spunbond layers having the highest permeability, followed by Sample No. 8C having one spunbond outer layer, and followed by Sample No. 1C that had both melt blown outer layers and no outer spunbond layers.

MEASUREMENT OF PERMEABILITY CONSTANT 'K' USING TRI'S AUTOMATED LIQUID-AIR DISPLACEMENT ANALYSIS INSTRUMENTATION

Permeability Constant 'K' in equation (6) can also be determined using Textile Research Institute's (TRI) automated Liquid-Air Displacement Analysis Instrumentation. Five samples from Part A and Part B of this study (Thermal bonded laminates No. 1C, 8C, and 10C, adhesive smooth bonded laminate 2A,

and adhesive point bonded laminate 2B) were sent to TRI, Princeton to determine the Permeability Constant using their Liquid-Air Displacement Analysis apparatus. The experimental procedure and theory [61] used for this analysis by TRI is given in the following section.

Experimental Procedure and Theory. A sketch of the automated Liquid-Air Displacement Analysis Instrumentation is given in Figure 11. The cell consisting of a fabric holder and transparent cylindrical tube is suspended in a liquid contained in a cylindrical reservoir on the platform of a top loading balance. The fabric is sealed between a pair of rubber gaskets. A differential pressure transducer is mounted in the top of the cylindrical tube. The tube is coupled with a vacuum manifold providing evacuation to a large reservoir and a vent valve.

The cell is suspended in the liquid with the vent valve open and the liquid is allowed to rise in the cell until the point at which the liquid level is the same on the inside and outside of the cell. At this point, the vent is closed and the valve between the vacuum reservoir and cell is opened, causing the liquid to rise in the tube of the cell.

The permeability constant K , in Darcy's, per unit length, 1 in cm, is given by

$$\frac{K}{l} = \frac{\mu Q}{98.1 A_s \Delta P^*}$$

where μ = viscosity in cp

Q = volumetric flow rate in cm^3/s

A_s = cross sectional area of the specimen opening in cm^2

ΔP^* = driving pressure across the specimen, in cm H_2O

The driving pressure is

$$\Delta P^* = \Delta P - h$$

where, ΔP = the difference between atmospheric pressure and that in the tube as measured by the transducer, in cm H_2O

h = the height of the liquid, in cm

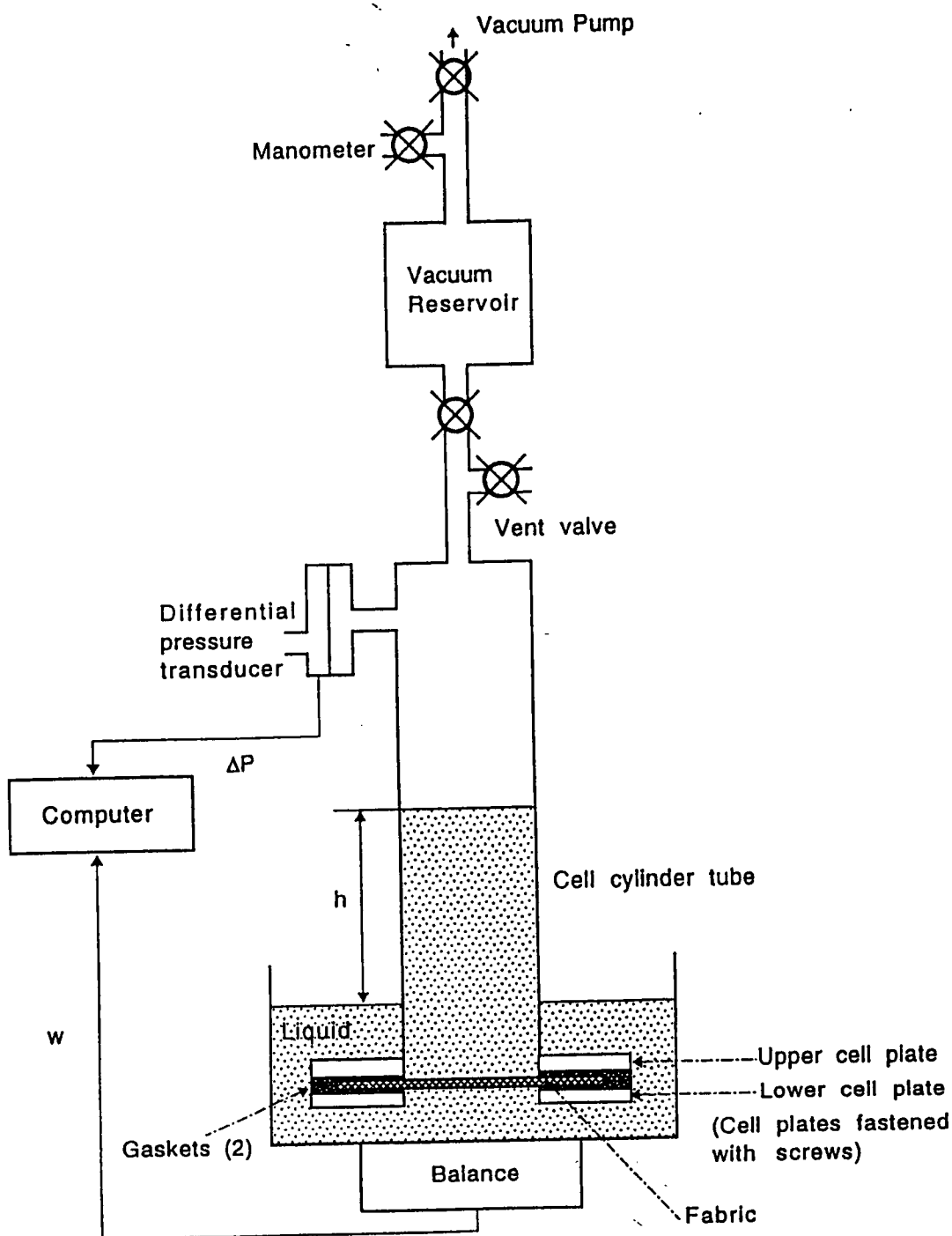


Figure 11. Schematic of the automated Liquid-Air Displacement Analysis Instrumentation used by Textile Research Institute.

The values of h and Q are determined from the balance reading w corrected for buoyancy, using the following equations:

$$h = -\frac{A - \alpha + a}{\rho a A} \cdot (w - w_0)$$

$$Q = -\frac{A - \alpha}{\rho A} \cdot \frac{dw}{dt}$$

Where, A = cross sectional area of the liquid reservoir in cm^2

α = cross sectional area of the cell tube exterior in cm^2

a = cross sectional area of the cell tube interior in cm^2

ρ = density of the liquid in g/cm^3

w = balance reading in g

w_0 = balance reading at the start of the measurement in g

t = time in s.

Specimen thickness was not measured and used in TRI's experimental procedure because of the irregular surfaces of the laminates.

Initial measurements were made using water, but since the samples were very hydrophobic, it was not possible to draw water through the fabric (in order to create the same level inside and outside the cell) without the cell being evacuated. This approach was found to be unsatisfactory because those pore sizes that became active channels were dependent on the ΔP imposed across the fabric. Thus, only some of the pores would allow liquid to flow through them resulting in very poor reproducibility.

A solution of 0.1% Triton X-100 was used to reduce the surface tension of water and flow spontaneously through the samples (except No. 2A and 2B). Other attempts to further reduce the surface tension of water in order that it flow through Samples No. 2A (smooth bonded MB wA/Exxaire wA/C/MB wA) and 2B (point bonded MB wA/Exxaire wA/C/MB wA) were also unsuccessful.

Balance and transducer readings were made at 1 second intervals as the liquid rose. Values of dw/dt were evaluated from average values just before

and just after each pressure reading. The density and viscosity of the liquid were 1 g/cm^3 and 1 cp , respectively.

The experimental measurement of K using TRI's Liquid-Air Displacement Instrumentation determined that the permeabilities of Samples No. 1C (K value of $0.9 \times 10^{-3} \text{ cm}^2$) and 8C (K value of $1.0 \times 10^{-3} \text{ cm}^2$) were nearly the same. Their trends were also the same in that permeability decreased as the face velocity (or ΔP^*) decreased as the measurement progressed. This may be because the pores may have been enlarged by the rapid flow at the start of the measurement and then closed as the flow rate decreased. Sample No. 10C was found to be the most permeable (K value of $7.0 \times 10^{-3} \text{ cm}^2$) among all the samples tested. Samples No. 2A and 2B could not be tested because there was no flow through these materials. It has been concluded that the permeabilities of Samples No. 2A and 2B were infinitesimal compared to the other samples. The reason for Samples No. 2A and 2B being the least permeable may be because of the presence of microporous films.

The trends obtained by the experimental values of permeability constants: Sample No. 10C was the most permeable followed by Sample No. 8C followed by Sample No. 1C and Samples No. 2A and 2B.

Comparison of Theoretical and Experimental Permeability Constant 'K'

The trends obtained by the theoretical prediction and experimental determination of permeability constants were similar in that: Sample No. 10C (thermally bonded sample having both spunbond outer layers, SCS-45-2.2, described in Table 1 in the Experimental Design Chapter) was the most

permeable followed by Sample No. 8C (thermally bonded sample having one melt blown and one spunbond outer layers, SCM-60-3.35, described in Table 1) followed by Sample No. 1C thermally bonded sample having both melt blown outer layers, MCM-40-2.50, described in Table 1). This confirms that spunbond outer layers resulted in greater permeability (and lower repellency) as was shown by Sample No. 10C (two outer spunbond layers) having the highest permeability, followed by Sample No. 8C (one spunbond outer layer), and followed by Sample No. 1C (both melt blown outer layers).

The difference in the permeability constant values determined theoretically and experimentally is probably due to the different sample sizes (309.9 cm^2 in the theoretical consideration as opposed to 3.879 cm^2 used in the TRI technique) and the length of flow through the samples (a range of 0.5929 to 0.8089 cm in the theoretical consideration compared to 1 cm in the TRI technique).

It was not possible to theoretically determine the value of permeability constant using the equation (6) because three values (M , h , h_0) were equal to zero for adhesively smooth bonded Sample No. 2A and adhesively point bonded Sample No. 2B by virtue of having a microporous film in their structures. These adhesively bonded samples passed the penetration of blood test and hence exhibited very good barrier properties and extremely low permeability.

CHAPTER 5

SUMMARY AND CONCLUSIONS

This research was conducted to explore possible nonwoven medical product applications for both absorbent and personal hygiene products and as breathable medical protective apparel with the necessary barrier properties. Cotton was utilized to take advantage of its good strength and comfort properties, as well as the fact that it is a renewable, biodegradable natural fiber.

PART A: THERMAL BONDED LAMINATES

- It appeared that MB webs imparted greater barrier properties to the cotton based laminates than did SB webs, but the SB webs imparted greater strength than did MB webs. In applications requiring faster wicking rates such as towels and personal hygiene products, it appeared that the use of SB web on at least one side of the web was more suitable. Hence, laminates with a SB on one side and a MB web on the other side were produced to take advantage of the attributes of both SB and MB webs.
- The repellent finished cotton based laminates containing at least one MB outer web appeared to provide excellent barrier properties in regards to water and oil repellency tests. Also, even the unfinished laminates containing at least one outer MB web had excellent resistance to water impact penetration due to the high cover factor of the hydrophobic MB ultrafine fibers. However, the cotton based laminates did not resist the penetration of synthetic blood in the ASTM ES21-92 blood barrier test.

- In the comparison of cotton laminates with commercially available Spunbond/Meltblown/Spunbond (SMS) and Kappler's PRO/VENT™ gowns, it was found that the cotton based laminates of this study had better comfort properties than the other gowns. The cotton laminates had better barrier properties than the SMS fabric. Neither of them resisted penetration of blood in the ASTM ES21-92 test. The Kappler fabric passed the ASTM ES 21-92 blood barrier test, and had better drapability, strength, and barrier properties than the cotton based laminates and the SMS gown. The SMS gown appeared to have higher strength than cotton based laminates.
- The comparative study with commercially available OR gowns indicated that further work should be done towards enhancing the barrier properties of the cotton based laminates.

PART B: COTTON LAMINATES INCORPORATING MICROPOROUS FILMS

- Thermal bonding of cotton based laminates incorporating polyethylene Exxaire® microporous films (to meet the stringent barrier test requirements) caused the laminates to pucker up. It was theorized that thermal bonding also caused pin holes in the Exxaire® film as is evidenced by the fact that the majority of these laminates failed the synthetic blood penetration test (ASTM ES21-92). Thermally bonded laminates with polytetrafluoroethylene (PTFE) film Tetratex™ resulted in laminates with better strength properties and resistance to the synthetic blood penetration test .
- The laminates that were point bonded at room temperature appeared to possess better barrier properties than laminates bonded with slightly heated

rolls. The preparation of adhesive bonded cotton based laminates (including microporous film) by melt blowing PP based hot melt adhesive on the substrates to form an adhesive MB fiber layer between each layer resulted in better barrier properties than the thermally bonded laminates. Furthermore, the laminates containing the microporous PE film did not pucker in that heat was not required for bonding.

It was further determined that all of these laminates containing a microporous PE film, a cotton web, and at least one MB outer web passed the synthetic blood penetration test when bonded between smooth rolls, but failed the test when point bonding was used, even without heat.

- Since microporous Exxaire® PE film appeared to work well with the hot melt adhesive using smooth roll calendering of the cotton based laminates, any subsequent manufacturing process should use microporous PE film because it should be much less expensive than PTFE film.
- In the case of the synthetic blood penetration test, ASTM ES21-92, both the 0.50 oz/yd² and 0.94 oz/yd² Exxaire® microporous films provided the necessary barrier performance when combined with the nonwoven and cotton core webs in the adhesive bonded cotton laminates.
- In the case of adhesively smooth bonded laminates, the heavier weight microporous film when combined with the nonwoven and cotton core webs in the adhesive smooth bonded cotton laminates was more effective in meeting the viral penetration test (ASTM ES22-92) standards.
- Adhesive bonded laminates having cotton in the core appeared to be softer than those laminates that did not have cotton in the core. The smooth roll adhesively bonded laminates containing unbonded carded cotton cores demonstrated excellent barrier and breathability properties and appeared to

have the softest hand of the smooth calendered laminates. However, the thermal bonded and the latex bonded cotton webs had more integrity by virtue of a thermal and a latex binder respectively, were more easily handled during lamination, and were found to be equally effective in meeting the barrier and breathability requirements for operating room (OR) fabrics. Nevertheless, carded or airlaid cotton webs could be readily deposited in line in a fabric production plant designed for this innovative new technology.

- The laminate structures that were most successful in meeting the rigorous blood and barrier test requirements and also having good moisture vapor transmission rates generally had four layers with one melt blown web (0.50 and 0.75 oz/yd²) or a spunbond web (0.60 oz/yd²), microporous Exxaire® film (0.94 oz/yd²), unbonded or pre-bonded cotton web (0.75 oz/yd²), and a melt blown web.
- These smooth roll adhesively bonded cotton based laminates with microporous films meet the OSHA and AORN specified requirements for OR fabrics by providing a means of keeping the potentially infectious microorganisms out while being breathable (as determined by the moisture vapor transmission rate) and convenient to use as single-use products.

ANALYSIS FOR PREDICTING BARRIER PERFORMANCE

- Darcy's equation for flow through porous media was applied to the cotton laminates to theoretically determine their permeability. The Liquid-Air Displacement Analysis Instrumentation of Textile Research Institute was also used to experimentally determine the permeability constant of the cotton laminates. Both these techniques determined that laminates having two

spunbond webs were the most permeable followed by laminates having one spunbond and one melt blown layer followed by laminates having both melt blown layers. The permeability constant could not be theoretically determined for laminates having a microporous film in their construction indicating very low permeability (and therefore very high barrier) properties. TRI's technique also concluded that laminates having a microporous film had infinitesimal permeability values in comparison to other laminates tested.

RECOMMENDATIONS FOR FUTURE WORK

- Determine if other hydrophilic fiber webs used as the inner layers of adhesive smooth bonded laminates will help contribute towards resistance to synthetic blood and viral penetration.
- Determine if 100% unbonded PP web and thermally bonded PP webs results in laminates that pass the synthetic blood barrier and viral penetration tests.
- Additional prototype adhesive smooth bonded fabrics may be prepared at a width of 1.0-meter to enable the fabrication of surgical gowns and conduct wear tests.
- Continued attention should be paid towards reducing the weight of the precursor components and also decreasing the number of layers constituting the adhesive bonded laminates. Reduced weight and decreased number of components would translate into a much less expensive laminate structure while also making it more functional in the process of commercializing these adhesive smooth bonded laminates.

- Adhesive bond two adjacent layers of light weight microporous PE film with either MB or SB webs in an attempt to determine if they provide the necessary resistance to blood and viral penetration tests. It is expected that putting two microporous films together may compensate for imperfections in either of the films.
- Commercially available laminate surgical gowns that demonstrate excellent barrier (resistance to blood and viral penetration) and breathability (high moisture vapor transmission rate values) should be procured and should be compared in a wear study with the adhesive smooth bonded cotton based laminates.
- Textile Research Institute's Liquid-Air Displacement Analysis apparatus may still be useful in studying the flow through behavior of liquids in the adhesive bonded laminates by testing laminates that otherwise pass the blood and viral penetration test, except the microporous film could be removed entirely for the TRI test, or much lighter weight films may be used.

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APPENDIX

PART A

Wilcoxon Signed Rank Test Results.

Comparison of Weight

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	0.11	Sum	0.66
Std Dev	0.515248	Variance	0.26548
Skewness	1.90809	Kurtosis	4.249993
USS	1.4	CSS	1.3274
CV	468.4068	Std Mean	0.210349
T:Mean=0	0.522941	Prob > T	0.6234
Num ^ = 0	6	Num > 0	2
M (Sign)	-1	Prob > M	0.6875
Sgn Rank	-1.5	Prob > S	0.8438

Comparison of Thickness

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-0.2183	Sum	-1.3098
Std Dev	0.219487	Variance	0.048174
Skewness	-0.88186	Kurtosis	-1.33441
USS	0.526801	CSS	0.240872
CV	-100.544	Std Mean	0.089605
T:Mean=0	-2.43625	Prob > T	0.0589
Num ^ = 0	6	Num > 0	0
M (Sign)	-3	Prob > M	0.0313
Sgn Rank	-10.5	Prob > S	0.0313

Wilcoxon Signed Rank Test Results.

Comparison of MD Bending Length

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	1.1	Sum	6.6
Std Dev	0.734221	Variance	0.53908
Skewness	0.519803	Kurtosis	-0.42244
USS	9.94554	CSS	2.6954
CV	66.74733	Std Mean	0.299744
T:Mean=0	3.669794	Prob > T	0.0144
Num ^ = 0	6	Num > 0	6
M (Sign)	3	Prob > M	0.0313
Sgn Rank	10.5	Prob > S 	0.0313

Comparison of CD Bending Length

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	0.898333	Sum	5.39
Std Dev	1.241989	Variance	1.542537
Skewness	1.319752	Kurtosis	1.559188
USS	12.5547	CSS	7.712683
CV	138.2548	Std Mean	0.50704
T:Mean=0	1.771721	Prob > T	0.1366
Num ^ = 0	6	Num > 0	5
M (Sign)	2	Prob > M	0.2188
Sgn Rank	7.5	Prob > S 	0.1563

Wilcoxon Signed Rank Test Results.

Comparison of Air Permeability

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-3.65333	Sum	-21.92
Std Dev	15.57398	Variance	242.549
Skewness	-2.36233	Kurtosis	5.670173
USS	1292.826	CSS	1212.745
CV	-426.295	Std Mean	6.358052
T:Mean=0	-0.5746	Prob > T	0.5904
Num ^ = 0	6	Num > 0	4
M (Sign)	1	Prob > M	0.6875
Sgn Rank	3.5	Prob > S 	0.5625

Comparison of Bursting Strength

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	15.27333	Sum	91.64
Std Dev	54.72312	Variance	2994.62
Skewness	-0.77643	Kurtosis	-1.84514
USS	16372.75	CSS	14973.1
CV	358.2919	Std Mean	22.34062
T:Mean=0	0.683658	Prob > T	0.5246
Num ^ = 0	6	Num > 0	4
M (Sign)	1	Prob > M	0.6875
Sgn Rank	3	Prob > S 	0.6250

Wilcoxon Signed Rank Test Results.

Comparison of MD Tear Strength

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	56.93333	Sum	341.6
Std Dev	121.6378	Variance	14795.75
Skewness	-0.43247	Kurtosis	0.734953
USS	93427.2	CSS	73978.77
CV	213.6495	Std Mean	49.65842
T:Mean=0	1.146499	Prob > T	0.3035
Num ^ = 0	6	Num > 0	5
M (Sign)	2	Prob > M	0.2188
Sgn Rank	6.5	Prob > S 	0.2188

Comparison of CD Tear Strength

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-43.4667	Sum	-260.8
Std Dev	153.673	Variance	23615.39
Skewness	-0.06522	Kurtosis	-0.03568
USS	129413	CSS	118076.9
CV	-353.542	Std Mean	62.73673
T:Mean=0	-0.69284	Prob > T	0.5193
Num ^ = 0	6	Num > 0	2
M (Sign)	-1	Prob > M	0.6875
Sgn Rank	-3.5	Prob > S 	0.5625

Wilcoxon Signed Rank Test Results.
Comparison of MD Breaking Strength
Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	2.105	Sum	12.63
Std Dev	2.224444	Variance	4.94815
Skewness	0.691774	Kurtosis	1.184583
USS	51.3269	CSS	24.74075
CV	105.6743	Std Mean	0.908125
T:Mean=0	2.317962	Prob > T	0.0682
Num ^ = 0	6	Num > 0	5
M (Sign)	2	Prob > M	0.2188
Sgn Rank	9.5	Prob > S 	0.0625

Comparison of CD Breaking Strength
Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	0.833333	Sum	5
Std Dev	1.676504	Variance	2.810667
Skewness	0.843857	Kurtosis	0.614036
USS	18.22	CSS	14.05333
CV	201.1805	Std Mean	0.68443
T:Mean=0	1.217558	Prob > T	0.2777
Num ^ = 0	6	Num > 0	5
M (Sign)	2	Prob > M	0.2188
Sgn Rank	6.5	Prob > S 	0.2188

Wilcoxon Signed Rank Test Results.

Comparison of MD Elongation

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	0.266667	Sum	1.6
Std Dev	5.370537	Variance	28.84267
Skewness	-0.2108	Kurtosis	-1.74303
USS	144.64	CSS	144.2133
CV	2013.951	Std Mean	2.192513
T:Mean=0	0.121626	Prob > T	0.9079
Num ^ = 0	6	Num > 0	3
M (Sign)	0	Prob > M	1.0000
Sgn Rank	-0.5	Prob > S 	1.000

Comparison of CD Elongation

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	2.1	Sum	12.6
Std Dev	5.420332	Variance	29.38
Skewness	0.520414	Kurtosis	-2.04139
USS	173.36	CSS	146.9
CV	258.1111	Std Mean	2.212841
T:Mean=0	0.949006	Prob > T	0.3862
Num ^ = 0	6	Num > 0	3
M (Sign)	0	Prob > M	1.000
Sgn Rank	3.5	Prob > S 	0.5625

Wilcoxon Signed Rank Test Results.

Comparison of Hydrostatic Pressure

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-0.13833	Sum	-0.83
Std Dev	8.634768	Variance	74.55922
Skewness	1.841435	Kurtosis	4.014621
USS	372.9109	CSS	372.7961
CV	-6242	Std Mean	3.525129
T:Mean=0	-0.03924	Prob > T	0.9702
Num ^ = 0	5	Num > 0	1
M (Sign)	-1.5	Prob > M	0.3750
Sgn Rank	-2.5	Prob > S	0.6250

Comparison of Water Spray Rating

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-28.3333	Sum	-170
Std Dev	27.1416	Variance	736.6667
Skewness	-1.79218	Kurtosis	3.378923
USS	8500	CSS	3683.333
CV	-957939	Std Mean	11.08051
T:Mean=0	-2.55704	Prob > T	0.0508
Num ^ = 0	6	Num > 0	0
M (Sign)	-3	Prob > M	0.0313
Sgn Rank	-10.5	Prob > S	0.0313

Wilcoxon Signed Rank Test Results.

Comparison of Water Impact Penetration

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	0.136667	Sum	0.82
Std Dev	0.183048	Variance	0.03507
Skewness	2.165553	Kurtosis	4.858942
USS	0.2796	CSS	0.167533
CV	133.9378	Std Mean	0.074729
T:Mean=0	1.828827	Prob > T	0.1270
Num ^ = 0	6	Num > 0	6
M (Sign)	3	Prob > M	0.0313
Sgn Rank	10.5	Prob > S 	0.0313

Comparison of Water Oil Repellency Rating

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-7.66667	Sum	-46
Std Dev	0.816497	Variance	0.666667
Skewness	2.44949	Kurtosis	6
USS	356	CSS	3.333333
CV	-10.65	Std Mean	0.333333
T:Mean=0	-23	Prob > T	0.0001
Num ^ = 0	6	Num > 0	0
M (Sign)	-3	Prob > M	0.0313
Sgn Rank	-10.5	Prob > S 	0.0313

Wilcoxon Signed Rank Test Results.

Comparison of Upright Moisture Vapor Transmission Rate

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-89.9917	Sum	-539.95
Std Dev	162.3717	Variance	26364.58
Skewness	0.021634	Kurtosis	-2.69432
USS	180413.9	CSS	131822.9
CV	-180.43	Std Mean	66.28798
T:Mean=0	-1.35759	Prob > T	0.2327
Num ^ = 0	6	Num > 0	3
M (Sign)	0	Prob > M	1.0000
Sgn Rank	-4.5	Prob > S	0.4375

Wilcoxon Signed Rank Test Results.
Comparison of Weight in KES Analyses
Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-0.06	Sum	-0.36
Std Dev	0.29806	Variance	0.08884
Skewness	0.224323	Kurtosis	-1.01077
USS	0.4658	CSS	0.4442
CV	-496.767	Std Mean	0.121683
T:Mean=0	-0.49309	Prob > T	0.6428
Num ^ = 0	5	Num > 0	2
M (Sign)	-0.5	Prob > M	1.0000
Sgn Rank	-2.5	Prob > S 	0.6250

Comparison of Elongation (EMT) in KES Analyses
Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-1.77167	Sum	-10.63
Std Dev	2.045731	Variance	4.185017
Skewness	-1.71661	Kurtosis	3.281634
USS	39.7579	CSS	20.92508
CV	-115.469	Std Mean	0.835166
T:Mean=0	-2.12133	Prob > T	0.0874
Num ^ = 0	6	Num > 0	1
M (Sign)	-2	Prob > M	0.2188
Sgn Rank	-9.5	Prob > S 	0.0625

Wilcoxon Signed Rank Test Results.

Comparison of Linearity (LT) in KES Analyses

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	0.001667	Sum	0.01
Std Dev	0.084479	Variance	0.007137
Skewness	0.553605	Kurtosis	-1.84321
USS	0.0357	CSS	0.035683
CV	5068.728	Std Mean	0.034488
T:Mean=0	0.048326	Prob > T	0.9633
Num ^ = 0	6	Num > 0	2
M (Sign)	-1	Prob > M	0.6875
Sgn Rank	0.5	Prob > S 	1.0000

Comparison of Tensile Energy (WT) in KES Analyses

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-0.175	Sum	-1.05
Std Dev	0.151493	Variance	0.02295
Skewness	-1.30596	Kurtosis	2.498076
USS	0.2985	CSS	0.11475
CV	-86.5672	Std Mean	0.061847
T:Mean=0	-2.82958	Prob > T	0.0367
Num ^ = 0	6	Num > 0	0
M (Sign)	-3	Prob > M	0.0313
Sgn Rank	-10.5	Prob > S 	0.0313

Wilcoxon Signed Rank Test Results.

Comparison of Resilience (RT) in KES Analyses

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-4.83667	Sum	-29.02
Std Dev	13.40357	Variance	179.6557
Skewness	-0.02371	Kurtosis	-2.88511
USS	1038.638	CSS	898.2783
CV	-277.124	Std Mean	5.471984
T:Mean=0	-0.8839	Prob > T	0.4172
Num ^ = 0	6	Num > 0	3
M (Sign)	0	Prob > M	1.0000
Sgn Rank	-4.5	Prob > S 	0.4375

Comparison of Shear Stiffness (G) in KES Analyses

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	1.396667	Sum	8.38
Std Dev	0.86814	Variance	0.753667
Skewness	-0.06053	Kurtosis	-1.00544
USS	15.4724	CSS	3.768333
CV	62.15798	Std Mean	0.354417
T:Mean=0	3.940749	Prob > T	0.0110
Num ^ = 0	6	Num > 0	6
M (Sign)	3	Prob > M	0.0313
Sgn Rank	10.5	Prob > S 	0.0313

Wilcoxon Signed Rank Test Results.

Comparison of Hysteresis at 0.5° (2HG) in KES Analyses

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	7.596667	Sum	45.58
Std Dev	2.91664	Variance	8.506787
Skewness	-0.58005	Kurtosis	-1.5675
USS	388.79	CSS	42.53393
CV	38.39368	Std Mean	1.190713
T:Mean=0	6.37993	Prob > T	0.0014
Num ^ = 0	6	Num > 0	6
M (Sign)	3	Prob > M	0.0313
Sgn Rank	10.5	Prob > S 	0.0313

Comparison of Hysteresis at 5° (2HG5) in KES Analyses

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	8.068333	Sum	48.41
Std Dev	3.453424	Variance	11.92614
Skewness	-0.70274	Kurtosis	-1.81802
USS	450.2187	CSS	59.63068
CV	42.8022	Std Mean	1.409854
T:Mean=0	5.722813	Prob > T	0.0023
Num ^ = 0	6	Num > 0	6
M (Sign)	3	Prob > M	0.0313
Sgn Rank	10.5	Prob > S 	0.0313

Wilcoxon Signed Rank Test Results.

Comparison of Bending Rigidity (B) in KES Analyses

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	1.195	Sum	7.17
Std Dev	1.149343	Variance	1.32099
Skewness	0.429827	Kurtosis	-2.10226
USS	15.1731	CSS	6.60495
CV	96.17935	Std Mean	0.469217
T:Mean=0	2.546794	Prob > T	0.0515
Num ^ = 0	6	Num > 0	5
M (Sign)	2	Prob > M	0.2188
Sgn Rank	9.5	Prob > S	0.0625

Comparison of Resilience (RT) in KES Analyses

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-4.83667	Sum	-29.02
Std Dev	13.40357	Variance	179.6557
Skewness	-0.02371	Kurtosis	-2.88511
USS	1038.638	CSS	898.2783
CV	-277.124	Std Mean	5.471984
T:Mean=0	-0.8839	Prob > T	0.4172
Num ^ = 0	6	Num > 0	3
M (Sign)	0	Prob > M	1.0000
Sgn Rank	-4.5	Prob > S	0.4375

Wilcoxon Signed Rank Test Results

Comparison of Coefficient of Friction (MIU) in KES Analyses

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-0.11333	Sum	-0.68
Std Dev	0.02582	Variance	0.000667
Skewness	-0.07746	Kurtosis	0.867
USS	0.0804	CSS	0.00333
CV	-22.7823	Std Mean	0.010541
T:Mean=0	-10.7517	Prob > T	0.0001
Num ^ = 0	6	Num > 0	0
M (Sign)	-3	Prob > M	0.0313
Sgn Rank	-10.5	Prob > S 	0.0313

Comparison of Mean Deviation of MIU (MMD) in KES Analyses

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-0.00333	Sum	-0.02
Std Dev	0.005164	Variance	0.000027
Skewness	-0.96825	Kurtosis	-1.875
USS	0.0002	CSS	0.000133
CV	-154.919	Std Mean	0.002108
T:Mean=0	-1.58114	Prob > T	0.1747
Num ^ = 0	2	Num > 0	0
M (Sign)	-1	Prob > M	0.5000
Sgn Rank	-1.5	Prob > S 	0.5000

Wilcoxon Signed Rank Test Results

Comparison of Geometrical Roughness (SMD) in KES Analyses

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-0.53	Sum	-3.18
Std Dev	1.578531	Variance	2.49176
Skewness	0.065926	Kurtosis	-0.50029
USS	14.1442	CSS	12.4588
CV	-297.836	Std Mean	0.644433
T:Mean=0	-0.82243	Prob > T	0.4483
Num ^ = 0	6	Num > 0	2
M (Sign)	-1	Prob > M	0.6875
Sgn Rank	-4.5	Prob > S	0.4375

Comparison of Linearity (LC) in KES Analyses

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	0.015	Sum	0.09
Std Dev	0.10616	Variance	0.01127
Skewness	0.97265	Kurtosis	0.180383
USS	0.0577	CSS	0.05635
CV	707.735	Std Mean	0.4334
T:Mean=0	0.346103	Prob > T	0.7434
Num ^ = 0	6	Num > 0	4
M (Sign)	1	Prob > M	0.6875
Sgn Rank	2	Prob > S	0.7500

Wilcoxon Signed Rank Test Results
Comparison of Compressional Energy (WC) in KES Analyses
Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-0.10333	Sum	-0.62
Std Dev	0.14222	Variance	0.020227
Skewness	-1.43714	Kurtosis	1.778408
USS	0.1652	CSS	0.101133
CV	-137.633	Std Mean	0.058061
T:Mean=0	-1.77973	Prob > T	0.1352
Num ^ = 0	3	Num > 0	0
M (Sign)	-1.5	Prob > M	0.2500
Sgn Rank	-3	Prob > S 	0.2500

Comparison of Resilience (RC) in KES Analyses
Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	3.23	Sum	19.38
Std Dev	2.071116	Variance	4.28952
Skewness	0.827023	Kurtosis	-0.65221
USS	84.045	CSS	21.4476
CV	64.12123	Std Mean	0.845529
T:Mean=0	3.820092	Prob > T	0.0124
Num ^ = 0	6	Num > 0	6
M (Sign)	3	Prob > M	0.0313
Sgn Rank	10.5	Prob > S 	0.0313

Wilcoxon Signed Rank Test Results

Comparison of Thickness Compression (EMC) in KES Analyses

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-10.0283	Sum	-60.17
Std Dev	12.98611	Variance	168.6389
Skewness	-0.3744	Kurtosis	-1.73075
USS	1446.599	CSS	843.1947
CV	-129.494	Std Mean	5.301555
T:Mean=0	-1.89158	Prob > T	0.1171
Num ^ = 0	6	Num > 0	2
M (Sign)	-1	Prob > M	0.6875
Sgn Rank	-5.5	Prob > S	0.3125

Comparison of Thickness (T_o) in KES Analyses

Univariate Procedure

Variable = DIFF

Moments

N	6	Sum Wgts	6
Mean	-0.54	Sum	-3.24
Std Dev	0.7205	Variance	0.51912
Skewness	-1.3245	Kurtosis	1.1736
USS	4.3452	CSS	2.5956
CV	-133.426	Std Mean	0.294143
T:Mean=0	-1.83584	Prob > T	0.1258
Num ^ = 0	6	Num > 0	1
M (Sign)	-2	Prob > M	0.2188
Sgn Rank	-9.5	Prob > S	0.0625

Part B

Wilcoxon Signed Rank Test Results.

Comparison of Weight

Univariate Procedure

Variable = DIFF

Moments

N	25	Sum Wgts	25
Mean	-0.0472	Sum	-1.18
Std Dev	0.127394	Variance	0.016229
Skewness	-0.25133	Kurtosis	0.680984
USS	0.4452	CSS	0.389504
CV	-269.903	Std Mean	0.025479
T:Mean=0	-1.85251	Prob > T	0.0763
Num ^ = 0	22	Num > 0	9
M (Sign)	-2	Prob > M	0.5235
Sgn Rank	-55.5	Prob > S	0.0696

Comparison of Thickness

Univariate Procedure

Variable = DIFF

Moments

N	25	Sum Wgts	25
Mean	-0.0049	Sum	-0.1226
Std Dev	0.072299	Variance	0.005227
Skewness	-1.30855	Kurtosis	2.220346
USS	0.126054	CSS	0.125452
CV	-1474.29	Std Mean	0.01446
T:Mean=0	-0.33915	Prob > T	0.7374
Num ^ = 0	25	Num > 0	14
M (Sign)	1.5	Prob > M	0.6900
Sgn Rank	8.5	Prob > S	0.8244

Wilcoxon Signed Rank Test Results.

Comparison of Bursting Strength

Univariate Procedure

Variable = DIFF

Moments

N	25	Sum Wgts	25
Mean	2.58	Sum	64.5
Std Dev	1.869046	Variance	3.493333
Skewness	0.361934	Kurtosis	-0.22807
USS	250.25	CSS	83.84
CV	72.44365	Std Mean	0.373809
T:Mean=0	6.901916	Prob > T	0.0001
Num ^ = 0	25	Num > 0	23
M (Sign)	10.5	Prob > M	0.0001
Sgn Rank	155.5	Prob > S 	0.0001

Comparison of Upright MVTR

Univariate Procedure

Variable = DIFF

Moments

N	25	Sum Wgts	25
Mean	22.4116	Sum	560.29
Std Dev	35.69941	Variance	1274.448
Skewness	-0.44722	Kurtosis	4.690059
USS	43143.75	CSS	30586.75
CV	159.2899	Std Mean	7.139882
T:Mean=0	3.138931	Prob > T	0.0045
Num ^ = 0	25	Num > 0	21
M (Sign)	8.5	Prob > M	0.0009
Sgn Rank	125.5	Prob > S 	0.0002

V I T A

Nataraj Gosavi hails from the south Indian state of Karnataka. He received his Bachelor of Technology (B. Tech) Degree in Textile Technology in December 1988 from the University of Mysore. His final year project was the "Computerization of Yarn Realization" in a spinning mill. He obtained the first rank in the University of Mysore in the final year of his engineering degree. He came to the USA in December 1989 and worked on his MS degree at the University of Tennessee, Knoxville. The topic of his thesis was "Thermally Bonded Laminates of Novel Binder Fiber Materials With Natural Fibers" and he graduated with a Master's degree in May 1992. He continued with his graduate work to obtain a PhD. He has been working since June 1992 on a Cotton Incorporated sponsored project on the development of cotton nonwovens for protective apparel. During his stay at the University of Tennessee, he has received several awards, served on different organizations, presented his research findings at major nonwoven conferences, and has also published in the field of nonwovens.