LIQUID TRANSPORT MECHANISMS IN COTTON-POLYPROPYLENE LAMINATED NONWOVEN FABRICS INFLUENCING PESTICIDE PENETRATION

by

Siddartha Sarin

Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Clothing and Textiles

APPROVED:

Rinn M. Cloud, Chairman
Clothing and Textiles

Marjorie J.T. Norton
Clothing and Textiles

James P. Wightman
Chemistry

Roderick W. Young
Biochemistry and Anaerobic Microbiology

May, 1994
Blacksburg, Virginia

LIQUID TRANSPORT MECHANISMS IN COTTON-POLYPRPOYLENE LAMINATED NONWOVEN FABRICS INFLUENCING PESTICIDE PENETRATION

by

Siddartha Sarin

Committee Chairperson: Rinn M. Cloud

Clothing and Textiles

(ABSTRACT)

The purpose of this research was to investigate and compare the liquid transport properties of cotton nonwoven laminates of varying cotton/polypropylene fiber content (80:20, 60:40, 40:60, by weight) with a 100% polypropylene fabric and a 100% polyethylene fabric. Capillary, pressure and impact penetration mechanisms were investigated as well as other measures of fabric wetting, wicking, and liquid retention. A water/surfactant solution of surface tension close to that of the pesticide solution was used in some tests to determine whether it could be used to simulate liquid transport characteristics of the pesticide solution. The effect of volume on capillary and pressure penetration was also evaluated.

Results indicated that the 100% polyethylene fabric offered the greatest resistance to all three penetration methods. The 80:20 cotton:polypropylene fabric, exhibited significantly greater amounts of penetration than the other fabrics in capillary penetration. There was no significant differene in the penetration values of the 100% polypropylene and the cotton laminates in the pressure penetration of the water/surfactant. There were no significant differences in the impact penetration values of the cotton laminates, but the 100% polypropylene exhibted significantly lower amounts of impact penetration than the cotton laminates. Pressure penetration was found to result in the most severe form of penetration.

A high degree of correlation was obtained between penetration by the pesticide and

penetration by the water/surfactant solution, whose surface tension was close to that of the pesticide solution. A higher retention of the pesticide resulted in lesser amounts of penetration of the pesticide solution. However, in the case of retention of water/surfactant, it was found that even though there were no significant differences in the retention values of the water/surfactant, there were significant differences in the penetration values of the water/surfactant. Surface tension of the solution was found to have an effect on the wetting and wicking responses of the fabrics, which affected the amount of capillary penetration. Increasing volume resulted in an increase in the amount of penetration that took place.

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation and gratitude to his advisor, Dr. Rinn M. Cloud, Clothing and Textiles, for her excellent guidance, invaluable assistance, and encouragement during this entire research. The author will remain grateful to her for supplying the fabrics and other important materials used in this research. Appreciation and thanks are extended to other members of the faculty research committee: Dr. Marjorie J.T. Norton, Dr. James P. Wightman, and Dr. Roderick W. Young, for their suggestions during this research.

The author would like to thank the following departments without whose help this research could never have been completed: Department of Clothing and Textiles, Department of Chemistry, Department of Biochemistry, Department of Mining, Department of Chemical Engineering, Department of Statistics, and the Department of Entomology.

The author would like to thank Cheryl Heisey for her assistance in the surface tension measurements in Dr. Wightman's Lab. The author is grateful to Jean Simmons, Joy Burroughs, and David Ruggio for their assistance in problem solving on the gas chromatograph. The author would like to thank Dr. Klaus Hinkelmann, department head, Statistics, and Michelle Marini, research associate, Statistics, for their valuable suggestions in the statistical analysis of the data.

Special acknowledgement is due to Heather Kobal, graduate student in the department of Statistics for the statistical analysis of the data, to Janet Wimmer, Lab Specialist of Clothing and Textiles, for her assistance during the experimentation, and Janet Bryant for her assistance in compiling the document.

Lastly, but not the least the author would like to thank his parents, and Dr. Ravi and Anurita Sarin, for their constant encouragement and support during the authors stay at Virginia Tech.

Table of Contents

List of Tables

Table

Page

List of Figures

Figure Page

CHAPTER I

INTRODUCTION

The use of pesticides in the United States has grown ten-fold in the past three decades and continues to grow (Easter and Nigg, 1992). Pesticides protect crops from insects, weeds, disease and hunger but also are hazardous to humans.

The routes of pesticide exposure of humans are inhalation, ingestion, and skin absorption (dermal exposure) (Wolfe, Durham and Armstrong, 1976). Skin is the most important portal of entry for pesticides (Maibach, Fieldman, Milby, and Serat, 1971). Since dermal absorption is the main route of pesticide entry, a barrier is essential between the pesticide and the worker (Easter and Nigg, 1992). The use of protective clothing, as a barrier, can be the single most important factor in minimizing pesticide exposure of agricultural workers who handle pesticides in mixing, application or clean up situations (Leonas and DeJonge, 1986).

Laughlin (1986) identified three major classifications of protective apparel worn by agricultural workers using pesticides: (1) conventional work clothing of cotton, cotton/polyester blends, 100% polyester or polyester with limited amounts of rayon, nylon, or acrylic; (2) clothing for full body encapsulation made of vinyl, neoprene and rubber; and (3) disposable protective apparel made from spunbonded or melt-blown nonwovens. Staiff, Davis, and Stevens (1981) found that, while clothing made from vinyl or rubber-coated fabrics afforded good protection against pesticide penetration, it was perceived as being extremely uncomfortable due to poor moisture vapor transmission through the fabrics. Easter and Nigg (1992) reviewed the work done on fabrics that have been tested against pesticide penetration, and concluded that 100% spunbonded polyethylene nonwoven fabrics offered significantly better protection than conventional work clothing. However, 100% spunbonded polyethylene fabrics are also perceived as being uncomfortable.

Recent work at the Textile and Nonwoven Development Center at the University of Tennessee, Knoxville, has led to the development of experimental trilaminate nonwoven fabrics composed of a cotton core, sandwiched between layers of melt blown polypropylene. These fabrics may have the potential for protective clothing uses as well as for other products. Agricultural experiment station workers participating in Regional Research Project S-250 are investigating the various aspects of the performance characteristics of these fabrics. Liquid penetration characteristics of the fabrics are critical to the fabric's potential use in protective clothing for agricultural workers.

The purpose of this research was to investigate penetration of liquid-pesticide and distilled water containing an anionic surfactant (water/surfactant) through the trilaminate cotton/polypropylene nonwoven fabrics. The effect of varying cotton content (80%, 60%, 40%) on the liquid transport properties of the experimental fabrics was evaluated. Properties of the cotton nonwoven laminates were compared to a 100% spunbonded polyethylene (Tyvek®) and a 100% melt-blown polypropylene fabric.

CHAPTER II

LITERATURE REVIEW

This chapter reviews theories and empirical research related to liquid transport in fabrics, with emphasis on mechanisms influencing the penetration of liquids through fabrics. The review of literature specifically examines studies that have evaluated various fabrics for pesticide penetration. Literature dealing with the manufacture of nonwoven fabrics is reviewed in order to understand the structure of the fabrics under study.

Liquid Transport Mechanisms

The barrier effectiveness of a fabric refers to the fabric's ability to prevent or inhibit the movement of a chemical through a fabric (Schowpe, 1983). Two concepts have been defined to describe this movement: permeation and penetration. These terms have been defined by the ASTM Subcommittee F23.30 on Chemical Resistance, a subcommittee of ASTM Committee F-23 on Protective Clothing. Permeation is the process by which a chemical moves through a protective clothing material on a molecular level. Permeation involves: (1) sorption of molecules of the chemical into the contacted surface of a material; (2) diffusion of the sorbed molecules in the material; and (3) desorption of the molecules from the opposite surface of the material. Penetration is the flow of a chemical through closures, porous materials, seams, and pinholes or other imperfections in a protective clothing material on a nonmolecular level (ASTM, 1992). Ehntholt, Bodek, Valentine, Schwope, Royer, Frank, and Nielsen (1989) have recommended that, in characterizing the barrier properties of fabrics to be used as protective clothing against pesticide penetration, penetration test methods be used instead of permeation test methods. Methods for measuring liquid penetration through a fabric most commonly involve challenging the surface of the fabric with the test liquid and measuring the liquid breakthrough time and/or the amount of liquid transferred to an underlying surface. The ASTM Standard Test Method for Resistance of Protective Clothing Materials to Penetration by Liquids (F 903-90) is not frequently used by textile researchers, because it does not permit quantitative comparison between fabrics. Results from this test method are reported as 'pass/fail' based on whether the liquid breakthrough occurs through the fabrics or not (Branson and Sweeney, 1991).

Minor, Schwartz, Buckles, Wulkow, Marks, and Fielding (1961) have proposed four mechanisms of liquid penetration in textiles: capillary penetration, pressure penetration, impact penetration, and evaporation-condensation penetration. Each of these mechanisms is discussed below.

Capillary Penetration

Capillary penetration is defined by Minor et al. (1961) as penetration promoted primarily by capillarity. Capillarity may be defined as the "action by which the surface of a liquid, where it is in contact with a solid (as in a capillary tube), is elevated or depressed depending on the relative attraction of the molecules of the liquid for each other and for those of the solid" (Webster Ninth New Collegiate Dictionary, 1988). Liquid transport in fibrous networks is influenced by capillary action (Gupta, 1988). The factors influencing capillary action in fibrous networks are fluid characteristics (surface tension and viscosity), fiber surface energy and morphology, interaction of fluid with the fiber surface (contact angle) and size, volume and orientation of the pores in the fibrous network.

A review of the literature indicated that three concepts have been discussed in capillary penetration of a liquid through a textile to an underlying substrate. They are wetting, wicking and liquid retention. Each of these is briefly discussed below.

Wetting

Wetting is the displacement from a surface of one fluid by another (Shaw, 1980). It may involve the displacement of a gas (air) by a liquid at the surface of a solid. In a study of liquid transfer through cotton fabrics, Mecheels, Demeler, and Kachel (1966) found that if the surface of the fabric was wettable, then a significant amount of capillary penetration occurred. Fox and Zisman (1950) showed that the extent to which a liquid would wet a surface depended on the surface tension of the liquid. A liquid of very high surface tension would not wet the surface at all and would form an almost spherical drop. Liquids of successively lower surface tension would form increasingly flatter drops, until a liquid with sufficiently low surface tension would flatten out completely (contact angle 0) and spread over the surface. They found that the cosine of the contact angle, plotted against the surface tension of the liquid gave a straight line, and from the plot, the surface tension of a liquid required to give a zero contact angle, could be determined. This point was called the critical surface tension of that surface.

Critical surface tensions are usually determined for smooth surfaces such as films. Since fabrics have geometric structures as well as capillaries and pores that are not flat and smooth, it was proposed by Kawase, Misono, Fujii, and Minagawa (1990) that in the measurement of wettability for textile assemblies an apparent critical penetration tension (Y_c^{app}) be defined by the surface tension of a liquid that can just penetrate the textile. For fine filament mesh they found that the values of Y_c^{app} were practically independent of the geometric structure of the fabric, and very close to the critical surface tensions obtained by the Fox and Zisman (1950) plots.

Cassie and Baxter (1945) examined the wettability of porous surfaces. They deduced that the apparent receding contact angle for water on a rough surface is given by

$$\cos \Theta_w = f_1 * \cos \Theta_r - f_2$$

where Θ_w is the apparent receding contact angle, f_1 is the total area of the solid-liquid interface, Θ_r is the solid-water receding contact angle and f_2 is the total area of the liquid-air interface. They found that the porosity of a fabric had a significant effect on the contact angle formed at the surface of a fabric.

Washburn (1921) examined the dynamics of capillary flow through horizontal capillaries where the effects of gravity are negligible, and deduced that the rate at which a liquid moves in a horizontal capillary (under its own capillary pressure) of a porous substance is given by

$$dL/dt = (Yr/4Ln) * \cos(\Theta)$$

where (dL/dt) is related to the rate of the movement of the liquid in the horizontal capillary, (r) is the capillary radius, (Y) is the surface tension of the liquid, (n) is the viscosity of the liquid, (L) is the length already filled by the liquid, and (Θ) is the contact angle between the fiber and the liquid. From the equation it follows that an increase in 'Y' or 'r', or a decrease in 'Θ' will cause an increase in the rate of liquid transport in the horizontal capillaries.

Raheel and Gitz (1985) have applied the Washburn (1921) equation to explain the wetting action of a liquid on a fabric surface using the drop absorbency test. They assume that in the wetting action of a liquid on a fabric surface, there is a horizontal transport of the liquid where the effect of gravity can be neglected, and therefore, the Washburn equation for flow in horizontal capillaries may be applicable. Based on his equation, the authors propose that a fabric with a larger interyarn capillary radius, would be associated with a higher rate of wetting. However, it may be noted that in the wetting action of a liquid on a fabric surface as done in the drop absorbency test, there is an inplanar (horizontal) as well as transplanar (vertical) flow of the liquid taking place. Therefore, the Washburn equation may not be truly applicable. Furthermore, since the fabric is a porous material, the contact angle between the liquid and the fabric will be affected by the porosity of the material (Cassie and Baxter, 1945). Therefore, it is essential that the contact angle between the liquid and the fabric be determined before the Washburn (1921) equation is applied to wetting.

Minor et al. (1961) found that capillary penetration was influenced by the weight of the liquid per unit area of the wetted fabric (surface density). Higher surface density is associated with an increase in the penetration of the liquid through the fabrics. The authors also found that liquids that wetted rapidly, attained a low surface density rapidly, thereby resulting in less penetration.

Wicking

Capillary penetration is also dependent on a fabrics ability to 'wick' a liquid. Chandler and Zeronian (1979) define 'wicking' as the migration of a liquid through the interfiber or interyarn capillaries of a fabric. As a result of surface tension, there is a balancing pressure difference across any given curved surface of a liquid, with the pressure being greater on the concave side. For a given curved surface of radius of curvature (r) and surface tension of the liquid (Y), the pressure difference (ΔP) across the surface is given by the Young-Laplace equation (Shaw, 1980)

$$\Delta P = 2Y\cos(\Theta)/r$$

It is this pressure difference that causes a liquid to rise through the capillaries resulting in wicking action.

Raheel and Gitz (1985) found that fabrics having larger interfiber and interyarn capillary radii (looser weaves and lower yarn twists) had greater ease of wettability as measured by drop absorbency, while fabrics having smaller interfiber and interyarn capillary radii (denser weaves and higher yarn twists) had higher rates of wicking in a vertical strip test. They found that vertical wicking of carbaryl and chloramben in cotton broadcloth, cotton twill and cotton poplin fabrics decreased with apparent increases in capillary radius. The authors suggested that the Washburn equation did not hold true in gravimetric wicking and that larger capillary radii may not promote movement of liquids as opposed to smaller capillary radii. The authors suggested that fabrics of a closely woven structure will transport more pesticide solution to the skin than would fabrics made up of a loosely woven structure. The reason ascribed for this was that closely woven fabrics had smaller capillary radii, which became even smaller due to swelling by water. Therefore, there was an increase in the wicking action for closely woven structures because of their smaller radii. Such findings do not support the requirements of a protective garment as suggested by the Federal Register (1974), which requires the garment to have a close weave. It may be noted that in their study, Raheel and Gitz (1985) did not actually measure penetration but, concluded that a greater amount of wicking obtained in a vertical strip test maybe associated with a greater amount of penetration of the pesticide solution.

Minor, Schwartz, Wulkow, and Buckles (1959) found that a liquid in a nonuniform capillary system moves from a larger capillary to a smaller capillary provided the contact angle between the fiber and the liquid is less than 90°. In a layered system, if the middle layer has larger capillary radii than the upper layer, the amount of penetration in the middle layer will be less than if the middle layer had a smaller capillary radii than the upper layer.

Wehner, Miller, and Rebenfeld (1987) found that thickness and porosity of a fabric could affect the penetration of a liquid through a fabric. Liquid absorption by the fabric, led to a decrease in the interfiber capillary spaces thereby reducing the average capillary diameter. They also found that air permeability of a fabric could be an important indicator of the decrease in the capillary diameter. A lower capillary diameter was associated with lower air permeability for fabrics of approximately the same thicknesses.

Liquid Retention

Retention of a liquid in the interfiber or interyarn capillary spaces of a fabric influences the amount of capillary penetration of a liquid to a substrate. If a fabric can retain greater amounts of a liquid in its capillary spaces, then a lesser amount of the liquid reaches the underlying substrate (Crouse, DeJonge, and Calogero, 1990).

For a given liquid the two factors that influence retention of a liquid in a fibrous network are capillary diameter and pore volume (Gupta, 1988). The capillary diameter affects the capillarity force, while the pore volume determines the total liquid holding capacity of the structure. Capillary diameter and pore volume are affected by the fiber type (density), fiber fineness (denier), web manufacturing process (fiber orientation and degree of entanglement), and pressure under which the web is tested.

Morton and Hearle (1962) have discussed the retention of water in the interfiber and interyarn capillary interstices of the fabric. They defined the fractional water retention in the capillary spaces of a fabric by the relationship

$$r = m / M$$

where r is the fractional water retention, m is the mass of the water retained in the capillary spaces and M is the mass of the fibers in the fabric. They found that the amount of water retained in the capillary spaces was influenced by the nature of the packing of the fibers. Less water was held by randomly oriented viscose fibers than was by parallel ones in a fiber web.

Pressure Penetration

Miller (1990) has discussed forced penetration of liquids through fibrous networks. The relationship that is used to describe forced flow (pressure penetration) through porous media is given by Darcy's Law

$$dV / dt = (KA / \eta x) * \Delta P$$

where, dV/dt is the volumetric rate of penetration, K is the penetration constant for a given material, A is the area of the fabric surface under consideration, η is the viscosity of the liquid, x is the linear distance of penetration and ΔP is the external force.

Minor et al. (1961) found that pressure penetration was influenced by the following factors: type of fabric, type of liquid, drop size, time between applying the liquid and applying pressure to the wet spot (wicking time), pressure applied, time of application of pressure (expelling time), and the nature of the substrate. They found that penetration increased with increasing drop size though the relationship was not linear. Below a certain minimum critical drop size, no penetration occurred. If the time between applying the liquid on the fabric and placing the weight on the fabric was increased, then the amount of penetration that took place decreased, due to a decrease in the surface density (weight of liquid per unit area of wetted fabric surface). It was found that increasing the pressure applied on the liquid or the time of application of pressure resulted in an increase in the amount of penetration that took place, but the relationship was not linear.

In the case of pressure penetration, pressure applied on the liquid which has been placed on the surface of the fabric causes collapse of the nap fibers between the fabric and substrate. Minor et al. (1961) showed that, if the pressure applied was sufficient to collapse the nap fibers, then liquid could be forced from the fabric to the substrate.

Crouse, DeJonge and Calogero (1990) examined the effect of capillary and pressure penetration mechanisms through Sontara (woodpulp/polyester, spunlace nonwoven) and SMS (polypropylene, spunbond/melt blown/spunbond nonwoven composite). Their results indicated that unfinished and fluorochemical-treated fabrics provided protection against capillary penetration, but in pressure penetration the performance of the two unfinished fabrics was significantly better than that of the fluorochemical treated fabrics. The reason ascribed for this was that the finishes may seal off the capillary spaces between the fibers, and limit their ability to serve as a reservoir to store pesticides.

Impact Penetration

Capillary and pressure penetration methods are static methods of penetration because the momentum of the liquid droplet before it enters the fabric is zero. Impact penetration differs from the other types of penetration in the sense that the liquid droplets have an appreciable amount of momentum before they strike the fabric, and penetration of the liquid occurs primarily due to the impact between the liquid droplet and fabric surface (Minor et al, 1961).

Leonas (1991) describes the mechanism of impact penetration. In impact penetration the force with which the droplet strikes the fabric surface is dependent on Newton's Second Law (force = mass x acceleration). If the liquid strikes the fabric with greater force, it will penetrate to a greater distance in the fabric. If the liquid also acts as a carrier, substances suspended or dissolved in the liquid (such as pesticides) will also move through the fabric.

Minor et al. (1961) found that impact penetration was dependent on the following factors: liquid viscosity, drop size, and fabric cover. It was found that decreasing the viscosity of the liquid increased the amount of liquid that penetrated through impact penetration. For any given liquid, an optimum drop size existed at which impact penetration was maximized. Impact penetration decreased with increasing fabric cover. The authors also found that impact penetration took place almost instantaneously, if at all, and that there was a relatively poor correlation between air permeability and impact penetration.

Evaporation-Condensation Penetration

The evaporation-condensation mechanism of penetration is influenced by the volatility of the liquid (Segal, Philips, Loeb, and Clayton, 1958). If the liquid is highly volatile, then penetration is dependent on the volatility of the liquid, and not the surface tension of the liquid as in the case of capillary penetration. The evaporation-condensation mechanism of penetration is similar to permeation as defined by the ASTM Subcommittee F23.30 on Chemical Resistance, a subcommittee of ASTM Committee F-23 on Protective Clothing.

Pesticide Penetration Studies

A review of published literature indicates that pesticide penetration of fabrics is dependent on fabric variables, pesticide variables, and procedural variables. Research related to each of these variables is briefly discussed.

Fabric Variables

Fabric variables that have been examined in pesticide penetration studies include fiber composition, structure or geometry, fabric finishes and contaminates in the fabrics (particulate soil and perspiration). Studies of fiber content indicate that 100% cotton woven fabrics offered better protection against pesticide penetration than 100% polyester and 50% polyester/50% cotton fabrics of similar woven constructions (Freed, Davies, Peters, and Parveen, 1980; Lillie, Livingstone, and Hamilton, 1981; Leonas, 1991). The reason ascribed for the lower levels of penetration of 100% cotton fabrics was that cotton had better absorbency properties and therefore, more amounts of pesticide could be stored by it.

Leonas (1991) examined the effect of fabric weave (twill, plain) on capillary penetration of cotton fabrics using the pesticide Blandex. The twill fabric provided greater resistance to penetration than the plain woven fabric. In contrast Raheel and Gitz (1985) found that a twill weave cotton fabric had higher amounts of penetration of the pesticide than a cotton broadcloth of plain weave construction but attributed this to difference in fabric count and yarn size, which would influence capillary size.

Easter and Nigg (1992) have reviewed the work done on fabrics that have been tested for pesticide penetration. They concluded that regular nonwoven-Tyvek (a spunbonded polyethylene) and fluorochemical-treated woven and nonwoven fabrics exhibited lower levels of pesticide penetration as compared to 100% cotton and cotton-polyester blends. Unfinished, synthetic fiber, woven fabrics exhibited the highest level of penetration of pesticides. Some of the studies Easter and Nigg reviewed will be briefly described.

Staiff, Davis and Steven (1982) compared the penetration resistance of spunbonded polyethylene to that of light-weight cotton woven fabrics. They concluded that of the fabrics tested, only polyethylene-coated spunbonded olefin and rubberized cotton provided adequate protection against concentrated pesticide formulations. Light weight materials (four types of spunbonded olefin and a water repellent cellulosic) were penetrated by more pesticide than would penetrate rubberized materials.

Branson, Ayers and Henry (1986) evaluated the barrier effectiveness to pesticide penetration of seven fabrics using four pesticides. Three laminated fabrics containing polytetrafluoroethylene membranes, a 100% spunbonded polyethylene, a 65%polyester/35% cotton blend, a cotton denim, and a cotton chambray were used. The pesticides used were guthion, paraquat, parathion and dinoseb. Significant differences were found for fabric, pesticide, and the two way interactions. Chambray shirt fabric and denim jean fabric were not effective barriers against the pesticides tested. The laminated fabrics and the spunbonded polyethylene provided better protection than the 65% polyester/35% cotton, chambray, and denim fabrics.

Similarly, Leonas, Easter, and DeJonge (1989) found that polyethylene-coated Tyvek and Saranax-coated Tyvek provided the best protection against pesticide penetration as compared to unfinished Tyvek or denim fabrics. Hobbs, Oakland, and Hurwitz (1986) evaluated aerosol spray penetration of six nonwoven and five woven fabrics and concluded that the nonwoven fabrics offered better protection against aerosol spray penetration than the woven fabrics they had used.

Several researchers have investigated the influence of various types of functional finishes on the resistance offered by the fabrics to pesticide penetration. Fluorochemical soil repellent finishes have been shown to improve the resistance offered to pesticide penetration (Freed et al., 1980; Orlando, Branson, Ayers, and Leavitt, 1981; Laughlin, Easley, Gold, and Hill, 1986). Water repellent and soil release finishes have also been found to inhibit pesticide penetration, however, durable-press treated fabrics have been found to allow more penetration than untreated fabrics (Leonas and DeJonge, 1986).

Raheel (1991a) examined the effects of particulate soil on pesticide transmission through sixteen fabrics. The dust particles blocked the interstices (pores) in the fabrics, thus interrupting capillary flow through the fabrics, and also acted as a reservoir, absorbing a substantial amount of pesticide, and reducing the total amount of pesticide that penetrated through the fabrics. The author concluded that dust-soiled garments may trap pesticides to some degree and provide some measure of dermal protection.

Raheel (1991b) also examined the effects of perspiration on pesticide penetration. The author found that fabrics wet with perspiration had higher penetration than dry fabrics. The increase in pesticide penetration, was attributed to a reduction in the liquid (pesticide) holding capacity of the fabric system.

Pesticide Variables

Pesticide characteristics that influence the amount of penetration of pesticide through fabrics are volume, active ingredient, and formulation. Branson et al. (1986) found pesticide volume to be critical in determining the amount of penetration that took place. They applied 25, 50 and 75 μl of pesticide on a 3.81 cm x 3.81 cm (1.5" x 1.5") fabric specimen. The authors found that, in general, as volume of pesticide applied on the fabric increased, the barrier effectiveness of fabrics decreased i.e., penetration increased. However, the relationship between the amount of penetration of the pesticide and the volume of pesticide applied on the fabric was not linear. Effects of volume may be related to the concept of surface density as described by Minor et al. (1961).

Branson and Rajadhyaksha (1988) found that the active ingredient in a pesticide can affect the amount of penetration that takes place. They found that Gore-Tex fabric was not a good barrier to full-strength emulsifiable concentrate malathion with xylene as an additional active ingredient.

Laughlin, Easley, Gold, and Hill (1986) investigated pesticide formulation as a variable and found that encapsulated methyl parathion penetrated to a lesser extent than methyl parathion as wettable powder or emulsifiable concentrate and that emulsifiable-concentrate-formulated methyl parathion, penetrated to a greater extent than the wettable powder.

Procedural Variables

Procedural variables that have been shown to influence the amount of penetration of pesticides through fabrics are time of exposure, method of application and nature of substrate. Shaw and Hill (1991) examined the effect of exposure time on the penetration of pesticides. They examined two pesticides (diazinon and chlorpyrifos), four exposure times (0, 10, 20 and 30 minutes) and four fabrics of varying fiber contents (nylon, acrylic, and two types of polyester). The fabrics were treated with a water repellent finish. It was found that there was no significant difference between the 10, 20, and 30 minute exposure times, but there was a significant difference when the 10, 20, and 30 minute exposure times were each compared to the 0 minute exposure time. It was recommended that a 10 minute exposure time be used for the pipette drop method for applying pesticide on water repellent fabrics.

Leonas (1991) examined the effect of using the drop and spray method of contaminating 100% cotton (twill and plain weave) and 50% cotton/50% polyester fabrics using the pesticide Blandex. In the drop method a known volume of pesticide is applied on the fabrics using a pipette. This method is thought to simulate the type of exposure received during mixing, clean up, or spills of pesticide solutions. The spray system is designed to simulate exposure that might be received during the application of pesticides. In the spray system the velocity and pressure of the spray can be controlled. The drop method of exposure resulted in a significantly higher percent of pesticide penetration than the spray method.

A review of the literature revealed no standard substrate for measuring penetration. Instead various substrates have been used. Bhat and Perenich (1990) used four dosimeter backing materials (alpha-cellulose, 8-ply gauze, cotton T-shirt, Whatman paper # 42) to measure penetration of chlorpyrifos and pyremethrin. They found that the four dosimeter materials were significantly different from each other. The lowest 'mean percent penetration' was obtained with 8-ply gauze, and the highest with alpha-cellulose which is similar in structure to a cellulose-based blotter paper. Leonas (1991) used a 50% cotton/ 50% polyester blend T-shirt fabric to measure the penetration of the pesticide Blandex®. Raheel (1991a, 1991b) used 100% cotton knit T-shirt to measure the penetration of carbaryl and atrazine.

Different substrates have different values of wettability and form different capillary networks with the overlying fabric. Therefore, different substrates will give different absolute values of penetration (Minor et al, 1961).

Minor et al. (1961) have discussed the mechanism of transfer of liquid from a fabric to an underlying surface. When a fabric rests on a substrate, the nap fibers on the surface of the fabric in contact with the substrate tend to act as pillars or pedestals separating the denser portions of the fabric from the substrate (Figure 1). When the fabric and the substrate are pressed together, the nap fibers collapse, allowing greater contact between the fabric and the substrate, resulting in an effective capillary system between the fabric and the substrate (Figure 2). For transfer of the liquid to take place, it is essential that the substrate make contact with the liquid that is in the main continuous mass of liquid in the fabric.

Minor et al. (1961) have discussed the mechanism of penetration for single layered systems (where the fabric and the substrate comprised one layer). They found that, for rapid and extensive penetration to occur, the substrate should consist of a finer-pored system than the fabric, and should be wettable. The above mechanism of penetration can be extended to two or more layered systems. A two layered system may be obtained by placing two fabrics over the substrate or by having a single fabric which is a two layer laminate. In two-layered systems (Figure 3), the middle layer first acts as a substrate for the top layer and then as a fabric transferring liquid to the bottom layer. Likewise the above analogy can be extended to other multi-layered systems.

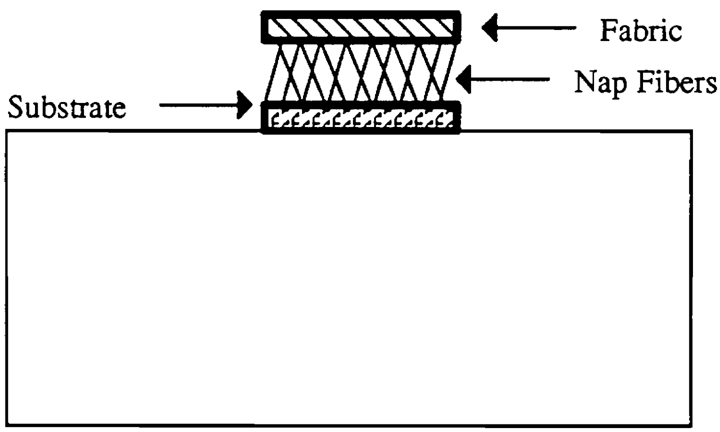


Figure 1. Fabric-Substrate interface in a one layer system.

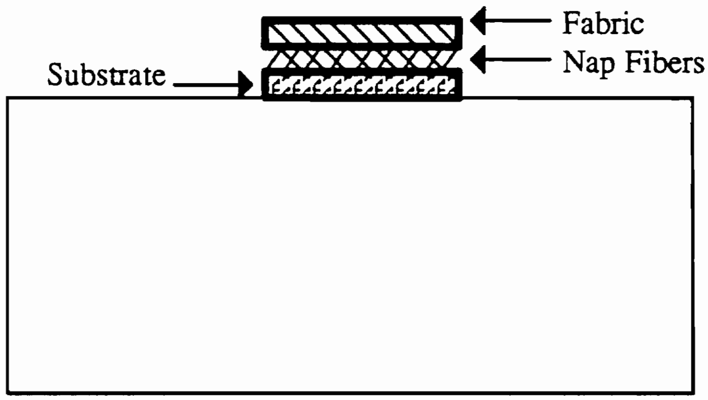


Figure 2. Collapse of nap fibers at the Fabric-Substrate interface

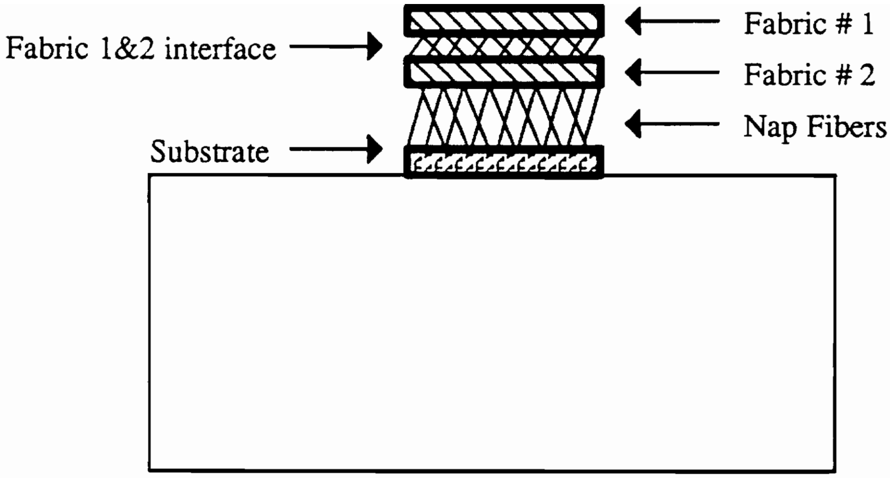


Figure 3. Two layered system of Fabric-Substrate.

Nonwoven Fabrics

In the reviews of pesticide protective clothing by Branson and Sweeney (1991) and Easter and Nigg (1992), the authors concluded that certain nonwoven fabrics offer better protection against pesticide penetration than typical unfinished work clothing fabrics. An understanding of the physical structure of nonwoven fabrics may be important in understanding the mechanisms of liquid penetration through them. Below is a brief discussion about the formation and properties of nonwoven fabrics.

Nonwoven fabrics are made by assembling fibers/filaments into a web, which is subsequently bonded (Wagner, 1988). Web formation is accomplished by three techniques: dry laid method, wet laid method, and polymer-laid method (spunbonding) (Meirhofer, 1987).

Web Formation

The dry laid method involves the conversion of fiber to web by the use of garnets, cards or air lay systems. The use of cards tends to orient the webs as carding action separates and aligns the fibers. To impart isotropic properties in the web, the fibers need to be oriented randomly. Random orientation of the fibers can be achieved by cross lapping of a unidirectional web. Air flow can also be used to randomize the fiber orientation (Meirhofer, 1987).

The wet laid method of producing nonwovens is often used for the manufacture of paper-like products. Wood fibers having a fiber length of about 1-2mm are commonly used. This process where the fibers are dispersed in water and are then collected on a moving screen or a wire. In order to obtain a uniform web, the fibers must contain sufficient water around them so that they can assume a random orientation (Meirhofer, 1987).

Polymer-laid nonwoven fabrics are produced by the direct conversion of a polymer to a web (Meirhofer, 1987; Hoyle, 1989). The polymer is melted and extruded into filaments that are subsequently collected on a wire and bonded. A variation of the spunbonding technique is the process of melt blowing. Melt blown fabrics are produced when a polymer is melted and extruded through a die. Immediately after extrusion the molten polymer is caught in two converging hot air streams, which rapidly draw the polymer into very fine filaments of 0.01-0.10 dtex. The filaments cool rapidly owing to the entrainment of atmospheric cold air and then break up into fibers of variable length, but of the order of several inches. The fibers are then collected as in the air lay process (Smith, 1988).

Bonding

Bonding in nonwoven fabrics is done using three basic processes: mechanical bonding, chemical bonding, and thermal bonding. Mechanical bonding can be done by: needle punching, stitchbonding, and hydraulic-entanglement. Chemical bonding can be achieved by latex bonding, saturation bonding, print bonding, spray bonding, foam bonding, solution bonding, and partial solvation bonding. Thermal bonding can be done by area bond hot calendaring, point bond hot calendaring, embossing hot calendaring, through-air oven bonding, ultrasonic bonding, and radiant heat bonding (Hoyle, 1989).

Bonding in dry laid fabrics can be achieved by several means. A common technique used is resin (latex) bonding. Another common technique used in the entanglement of fibers is hydro-entanglement (hydraulic-entanglement) to produce spun laced fabrics. Bonding of wet-formed nonwovens is usually done with latex, but thermal bonding can be done when thermoplastic fibers are used. Thermal bonding is used to produce spunbonded fabrics (Hoyle, 1989).

Bonding has a great influence on the properties of the nonwoven fabric and usually the requirements of the end product determine the choice of bonding agent. In thermal bonding using calendaring, the temperature of the heated rollers is 20-30 °C above the melting point of the thermoplastic fiber and fusion of the thermoplastic fiber with the web results in a significant increase in the strength of the web. The efficacy of the bonding process in thermal bonding, is influenced by the volume of the web and the proportion of the thermoplastic fibers it contains. A larger proportion of thermoplastic fibers will result in a better bonding of the web (Lunenschloss and Albrecht, 1985).

CHAPTER III

STATEMENT OF THE PROBLEM

Theoretical Framework

Fabrics (clothing) serve as a barrier between agricultural workers and pesticides (Leonas and DeJonge, 1986). Research on pesticide penetration of fabrics has consistently shown nonwoven fabrics to be more effective barriers than woven fabrics, but these fabrics are often considered thermally uncomfortable (Easter and Nigg, 1992). Experimental trilaminate fabrics with a cotton core and melt-blown polypropylene surfaces have been developed at the University of Tennessee, Knoxville, TN, for the Southern Regional Research Project S-250. These fabrics may have potential for use in protective clothing.

Minor et al. (1961) postulate that penetration of a liquid through a fabric occurs by the following methods: capillary, pressure, impact and evaporation-condensation. The evaporation-condensation method of penetration as suggested by Minor et al. (1961), is closely related to permeation and not penetration as defined by the ASTM Subcommittee F-23 on Protective Clothing. Ehntholt et al. (1989) recommended that, in characterizing barrier properties, penetration test methods be used.

Capillary penetration of a liquid through a fabric has been shown to depend on the wettability (Mecheels et al., 1966), wickability (Raheel and Gitz, 1985) and retention or liquid holding capacity of a fabric (Freed et al., 1980; Lillie et al., 1981). Wetting of a fabric surface is influenced by the surface tension of the liquid (Fox and Zisman, 1950; Kawase et al., 1990), and fabric surface geometry (Baxter and Cassie, 1945). Raheel and Gitz (1985) found faster rates of wetting as measured by drop absorbency and less vertical wicking in woven fabrics with yarn characteristics suggesting larger capillary radii.

Application of pressure on the liquid surface has been shown to increase the quantity of the liquid penetrating through a fabric (Minor et al., 1961; Crouse et al 1990). For a given liquid and drop size, pressure penetration has been shown to depend on the pressure applied on the liquid placed on the fabric surface, the time between application of pressure and placing the liquid on the fabric surface, and the time of application of pressure (Minor et al., 1961).

Impact penetration differs from capillary and pressure forms of penetration because the liquid in impact penetration has a much greater momentum when it strikes the fabric surface than in either capillary or pressure penetration. Impact penetration depends on the force with which the liquid impacts the fabric, liquid viscosity, drop size and fabric cover (Minor et al., 1961; Leonas, 1991).

Pesticide penetration through fabrics has been shown to depend on fabric, pesticide and procedural variables. If type of pesticide, nature of substrate, exposure time, and method of application are kept constant, pesticide penetration depends primarily on fabric characteristics and the volume of pesticide applied on the fabrics. Several studies (Freed et al., 1980; Lillie et al., 1981; Leonas et al., 1991) have indicated that increasing the amount of cotton in woven fabrics increases the ability of fabrics to absorb and store pesticide, and therefore results in less penetration taking place.

Branson et al. (1986) found that an increase in the volume of pesticide applied to the fabric resulted in an increase in penetration. This supports Minor et al., (1961) findings that the weight of the liquid per unit area of the wetted fabric (surface density) influences penetration.

Minor et al. (1961) discussed the transfer of a liquid from a fabric surface to an underlying substrate. For transference of the liquid from the fabric to the substrate, it is essential that the substrate be in contact with the liquid that is in the main continuous mass of the fabric and that the substrate be wettable. Penetration of a liquid through a laminate can be thought to be an extension of a "one-layer system" composed of a fabric and a substrate (Minor et al., 1961). Likewise, a cotton/polypropylene nonwoven trilaminate can be considered to form "a three layer system".

Research Problem Statement

The purpose of this research was to investigate and compare the liquid transport properties of cotton nonwoven laminates of varying cotton/polypropylene fiber content (80:20, 60:40, 40:60, by weight) and a 100% polypropylene fabric. Capillary, pressure, and impact penetration mechanisms were investigated as well as other measures of fabric wetting, wicking, and liquid retention. Chlorpyrifos was the pesticide selected for study. A water/surfactant solution of surface tension close to that of the selected pesticide was used in some tests to determine whether it could be used to simulate liquid transport characteristics of the pesticide. The effect of volume-of-liquid-applied on capillary and pressure penetration was also evaluated. A 100% polyethylene fabric which is commonly used in pesticide protective clothing (Tyvek) was also tested to provide a reference for performance levels of the experimental fabrics.

Objectives

O1: To compare pesticide and water/surfactant penetration and retention of test fabrics using capillary penetration at three volumes.

O2: To determine the effects of pressure on water/surfactant penetration and retention of the test fabrics at three volumes.

O3: To determine the effects of impact on water/surfactant penetration of the test fabrics.

O4: To determine wetting (drop absorbency) and wicking of the test fabrics using water, water/surfactant, and pesticide.

O5: To determine the air permeability, water and oil repellency of the test fabrics.

O6: To characterize the test fabrics for selected mechanical properties.

Research Hypotheses

The following research hypotheses were generated based on prior empirical results and the theoretical framework.

H1: In the capillary penetration of the pesticide solution, the 100% polypropylene will show the greatest amount of penetration, and trilaminates with increasing cotton content will result in less capillary penetration taking place. On increasing the volume, there will be an increase in the amount of penetration that takes place.

H2: In the capillary penetration of the water/surfactant solution, the 100% polypropylene will show the greatest amount of penetration, and increasing cotton content will result in less capillary penetration taking place. On increasing the volume, there will be an increase in the amount of penetration that takes place. On comparing capillary penetration of pesticide solution with the water/surfactant, there will be a high degree of correlation between the penetration values for the pesticide and the water/surfactant solutions.

H3: In the retention of the pesticide solution by the test fabrics during capillary penetration, the 100% polypropylene will show the least amount of retention of the pesticide solution and increasing cotton content will result in greater amounts of pesticide retained by the fabrics. On increasing volume, there will be an increase in the amount of pesticide retained by the fabrics.

H4: In the retention of the water/surfactant solution by the test fabrics during capillary penetration, the 100% polypropylene will show the least amount of retention of the water/surfactant solution and increasing cotton content will result in greater amounts of water/surfactant retained by the fabrics. On increasing volume, there will be an increase in the amount of water/surfactant retained by the fabrics.

Rationale:

The rationale for hypotheses 1-4 is as follows: A fabric with a greater ability to retain a liquid will allow less liquid to penetrate to the underlying substrate. In woven fabrics, higher cotton content resulted in lower amounts of penetration due to the ability of cotton to store greater amounts of liquid-pesticide (Freed et al. 1980; Lillie et al., 1981). Therefore, it is hypothesized that increasing cotton content in nonwoven fabrics may result in a greater ability of the fabric to retain a liquid and may result in lower amounts of penetration.

Branson et al. (1986) found that an increase in the volume of pesticide applied to the fabric resulted in an increase in the amount of penetration. An increase in the volume of pesticide or water/surfactant applied to the fabric will result in an increase in the surface density (weight of liquid per unit area of fabric) of the liquid on the fabrics, thereby resulting in an increase in the amount of penetration of the liquid-pesticide or water/surfactant (Minor et al., 1961).

In comparing the capillary penetration of the pesticide to the water/surfactant, it is hypothesized that there will be a high degree of correlation between the penetration values for the pesticide and a water/surfactant solution of approximately the same surface tension. Since capillary penetration is influenced by the surface tension of the liquid, it is hypothesized that liquids of the same surface tension will penetrate similarly through the fabrics.

H5: In the pressure penetration of the water/surfactant, there will be no significant difference in the penetration values of the 100% polypropylene and the cotton laminates. An increase in the cotton content from 40% to 80% will result in no significant difference in the penetration values of the water/surfactant. On increasing volume, there will be an increase in the amount of penetration of the water/surfactant for pressure penetration.

H6: In the pressure penetration of the water/surfactant, there will be no significant difference in the retention values of the 100% polypropylene and the cotton laminates. An increase in the cotton content from 40% to 80% will result in no significant difference in the penetration values of the water/surfactant. On increasing volume, there will be an increase in the amount of penetration of the water/surfactant for pressure penetration.

H7: There will be an increase in the amount of water/surfactant penetrating through the fabrics for pressure penetration as compared to capillary penetration.

Rationale:

The rationale for hypotheses 5-7 is as follows: Crouse et al. (1990) found that at a pressure of 1 psi, the fabrics would be saturated by the pesticide solution and would not be able to resist penetration of the pesticide from taking place. Therefore, it is hypothesized that there would not be much difference in the amount of penetration or retention of the water/surfactant on increasing the cotton content. An increase in volume will result in an increase in the amount of penetration because the saturated fabrics will not be able to hold additional water/surfactant solution. Therefore, any additional water/surfactant solution will penetrate to the underlying substrate.

Crouse et al. (1990) also found that there was greater than a 10 fold increase in the amount of pressure penetration that took place when compared to capillary penetration for the pesticide Dicofol. Therefore, it is hypothesized that there will be a greater amount of penetration in the case of pressure penetration when compared to capillary penetration.

H8: There will be no significant difference in the amount of impact penetration for the 100% polypropylene and the cotton laminates

Rationale:

Since the impact penetration test involves 500 ml of liquid, the 100% polypropylene and the cotton laminates would be totally saturated with the water/surfactant and therefore, would not be able to resist penetration from taking place. Therefore, there will not be any difference in the impact penetration values for the 100% polypropylene and the cotton laminates.

H9: There will be no significant difference in the fabrics in terms of the wetting times as measured by the drop absorbency test.

Rationale:

Since the upper surface of all the fabrics (except the 100% polyethylene) is a layer of polypropylene, no difference is expected in the wetting times for the 100% polypropylene and the cotton laminates.

H10: There will be a significant difference in the distance wicked by the fabrics when distilled water is compared to the water/surfactant or the pesticide solution. However, there will be no significant difference in the distance wicked by the fabrics when comparing the water/surfactant to the pesticide solution.

Rationale:

The Young-Laplace equation (Shaw, 1980) states that an increase in the surface tension of the liquid will result in an increase in the distance wicked by the fabrics. Since, the surface tension of the water/surfactant solution is lower than that of the distilled water, it is expected that there will be difference in the wicking response for the two liquids. Since the surface tension of the water/surfactant is the same as that of the pesticide solution, no difference is expected in the wicking response of these two solutions.

H11: An increase in the cotton content will result in an increase in the air permeability of the fabrics.

Rationale:

An increase in cotton content in the core of the trilaminates may result in less effective binding of the web thus increasing porosity which may be evidenced by an increase in air permeability (Lunenschloss and Albrecht, 1985).

H12: An increase in the cotton content will result in an increase in the static absorption of the laminates. An increase in the cotton content will result in no difference in the water spray rating and oil repellency rating of the fabrics.

Rationale:

Static absorption of the cotton laminates will increase on increasing the cotton content due to cotton's ability to absorb a liquid. The water spray rating and oil repellency rating would remain the same because all the fabrics have the 100% polypropylene on the top layer which would be expected to behave in a similar manner to the water spray and oil repellency tests.

Assumptions

The following assumptions have been made in conducting the research.

1. It is assumed that the fabrics are reasonably consistent through the lot with respect to thickness, weight, and other physical properties and that any variations in these properties that may exist in the fabrics are of random occurrence.

2. It is assumed that there is no significant variation in the concentration of the pesticide solution and that the pesticide solution is homogenous.

3. It is assumed that machine and operators errors are of a random nature and have no significant effect on the results.

4. It is assumed that all instruments used for this research yield reliable results.

Limitations

The results are not generalizable to fabric, pesticide, and procedural parameters beyond those used in the study.

CHAPTER IV

MATERIALS AND METHODS

This chapter is divided into seven sections: (1) materials used, (2) evaluation of penetration mechanisms, (3) evaluation of wetting and wicking, (4) evaluation of air permeability and other sorption properties (water and oil repellency), (5) fabric characterization, (6) pretests, and (7) hypothesis testing. The procedure for extraction and quantification of the pesticide is discussed in the evaluation of penetration mechanisms.

Materials

Fabrics

The fiber contents of the nonwoven fabrics used in this study were as follows: 100% polyethylene, 100% polypropylene, and 80:20, 60:40, and 40:60 cotton:polypropylene (by weight). The 100% polyethylene supplied by Dupont (Tyvek®), was produced using the spunbonded process. The 100% polypropylene and the cotton laminates were produced at the University of Tennessee for the Southern Regional Research Project (S-250). The cotton nonwoven fabrics comprised three layers which involved a layer of dry laid cotton fibers sandwiched between two layers of melt blown polypropylene. The three layers were thermally bonded using the embossing hot calendaring technique. The 100% polypropylene was manufactured using the melt-blown technique for producing nonwoven fabrics, however it was not was thermally bonded using the embossing hot calendaring technique. The nominal weights of the 100% polypropylene and the cotton-laminates were 84.8 g/m^2 (2.5 oz/sq. yd). By holding process parameters and fabric weight constant, researchers at the University of

Tennessee attempted to ensure that variability in the properties of the fabrics were attributable to the differences in fiber content.

Substrate

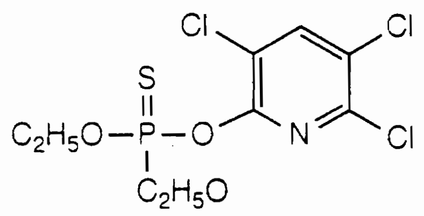
The substrate used in this study was a standard blotter paper (AATCC Order No. 8344) as prescribed for use in AATCC Test Methods 21, 35, 42 and 70. The substrate was cut to the same dimensions as the fabric specimens. The substrate specimens were placed on top of an aluminum foil (Reynolds® 665 Heavy Duty Aluminum Wrap) backing during penetration testing.

Pesticide

The pesticide used in the study was chlorpyrifos. The pesticide solution was diluted from 42.8% a.i. (active ingredient) to 1.25% a.i. (typical field strength) by adding distilled water. Chlorpyrifos was chosen because of its high toxicity and extensive usage as an insecticide in corn fields. Chlorpyrifos is an organophosphorus insecticide used to control ectoparasite of cattle, sheep, and poultry; as a soil insecticide for vegetables, cereals, and tobacco; and as a foliar insecticide for deciduous fruit, cereals, fodder crops, cotton, some vegetables, tobacco and rice (Worthing, 1979). The chemical structure, nomenclature, properties, and toxicity information for chlorpyrifos are shown in Figure 4.

Surfactant

The manufacturer of the pesticide disclosed that a nonionic surfactant was used as part of the inert ingredients of the pesticide. The specific name and concentration of the surfactant



Chlorpyrifos

Nomenclature
Common Name: chlorpyrifos
IUPAC Name : O,O-diethyl O-(3,5,6-trichloro-2-pyridyl) phosphothioate
Trade Marks: 'Dursban' and 'Lorsban'

Properties
Melting Point : 42.5-43°C
Vapor Pressure: 1.87 x 10^{-5}
Solubility : 2 mg/l water at 35°C

Toxicity
LD_{50} : for rats 135-163 mg/kg
LD_{50} : for guinea-pigs 500 mg/kg
LD_{50} : for rabbits 1000-2000 mg/kg

Figure 4. Structure, nomenclature, properties and toxicity of chlorpyrifos.

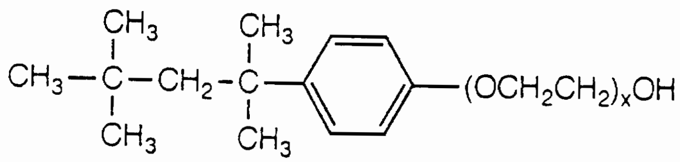
is proprietary information that the manufacturer would not disclose. Therefore, the selection of the surfactant for this research was based on finding a nonionic surfactant which would lower the surface tension of distilled water to that of the pesticide solution. The nonionic surfactant used in this study was Triton X 100®. The chemical structure of Triton X 100® is given in Figure 5. The water/surfactant solution contained 100 μl of the surfactant in 30 ml of distilled water.

Evaluation of Penetration Mechanisms

Volume of the Challenge Liquids

Field studies by Davies, Enos, Barquet, Morgade, Peters, and Danauskas (1982) indicated that the amount of chlorpyrifos deposited on the surface of a 65/35 polyester/cotton varied from 49.63 to 57.83 $\mu g/cm^2$ (2881.7 - 3357.9 μg on a 7.6 cm x 7.6 cm specimen). These values were obtained during the application of chlorpyrifos in citrus groves in Orange County, Florida. A 1.25% a.i. solution of 4E (4 lbs/gal) of chlorpyrifos contains 13998.3 μg/ml of pesticide. For a fabric specimen of 7.6 cm x 7.6 cm as used in the present study it was determined that the volume equivalent of the amount of chlorpyrifos contamination found by Davies et al. ranged from 205 to 240 μl. For this study a volume of 300 μl was used to represent application level exposure.

Since spills of pesticide may result in higher levels of pesticide on clothing, a volume of 500 μl of pesticide was included to represent more severe exposure levels. A volume of 100 μl was chosen to represent milder forms of exposure such as could occur from workers re-entering fields that have been sprayed with pesticides for inspection or harvesting activities. The application of 100, 300, and 500 μl of the pesticide solution would effectively result in



Triton X 100

Figure 5. Structure of Triton X 100® (Nonionic Surfactant)

the application of a total of 1399.83, 4199.49, and 6999.15 μg a.i. of the pesticide on the test specimens respectively. This amounts to applying 24.2, 72.7 and 121.2 $\mu g/cm^2$ on the specimens respectively. It may be noted the volumes represented are only nominal volumes. Actual volumes depend on the accuracy of the measuring equipment.

Preparation of Test Fabric-Substrate Assembly

To maintain consistency with other studies, test specimens, collector substrates, and aluminum foil backings were cut in 7.6 cm x 7.6 cm (3" x 3") squares. Variation in placement of the test fabric on the substrate may result in different capillary networks at the fabric-substrate interface and thereby influences capillary penetration of the assembly (Minor et al., 1961). To minimize the variability at the fabric-substrate interface, a protocol for placement of the fabric on the substrate was established. The blotter paper substrate was placed on aluminum foil. The test fabric specimen was dropped on to the substrate, from a height of 2.5 cm (1"). A pressure of 1 psi was applied on the assembly for 30 s and was then removed. The test fabric-substrate assembly was then allowed to recover for 30 s before it was challenged by the test liquid. The times of 30 s, each, were arbitrarily chosen.

Capillary Penetration

Capillary penetration was determined using the technique described by Leonas (1991). The predetermined volume (100, 300 or 500 μl) of chlorpyrifos or water/surfactant was dropped from a height of 1 cm over the center of the test fabric/substrate assembly, using a Pipetman P1000® pipette, and was allowed to remain on the fabric surface for 10 minutes as suggested by Shaw and Hill (1991). After 10 minutes any excess water/surfactant or pesticide was rolled off in to a beaker. The fabric was separated from the substrate and analyzed immediately.

Pressure Penetration

Pressure penetration was determined using the technique used by Crouse et al. (1990). Volumes of 100, 300 or 500 μl of water/surfactant were dropped onto specimens using the same procedure as for capillary penetration. A pressure of 1 psi was applied on the drop using a glass slab, for a period of 10 minutes. A pressure of 1 psi was used because such pressure could easily occur when a worker leans against a tractor or rests his arm on his leg (Crouse et al, 1990).

Impact Penetration

Impact penetration was determined using AATCC 42-1989 Water Resistance: Impact Penetration Test (AATCC, 1992). In this test five hundred ml of water/surfactant were dropped from a height of two feet against the taut surface of the fabric placed over the standard blotter paper. The dimensions of the fabric and the blotter were 18 cm x 33 cm (7" x 13") and 15 cm x 23 cm (6" x 9") respectively.

Quantification of Penetration and Retention of Liquids

In the case where water/surfactant was used to challenge the fabrics, the change in weight of the blotter paper was used to determine the amount of penetration that occurred. The change in weight of the fabric specimen was used to determine retention of water.

In the case of chlorpyrifos contamination of the fabrics, the amount of pesticide penetration and the amount of pesticide retained in the fabrics, was measured by hexane extraction of the substrate and of the fabric specimen respectively, followed by analysis of the extract through gas chromatography. In order to determine the amount of pesticide in the extract, standard concentrations of 0.02, 0.04 and 0.13 μg/ml were prepared by diluting 1.25 % a.i. chlorpyrifos in pesticide grade hexane. The standard solutions were chosen so that the response lay within the limits of the gas chromatograph (GC). One microliter from the standard solutions was injected into a Shimadzu GC-14A Chromatograph® interfaced with a Shimadzu C-R4A Chromatopac®. The column used was a Crossbonded 65% dimethyl - 35% diphenyl siloxane and the detector used was a Ni63 electron capture detector (ECD). The injection port, detector and oven temperatures were 250, 325, and 250°C respectively. The flow gas used was nitrogen. A graph was plotted using peak height and concentration (Figure 6). Since the graph between peak height and concentration is linear, concentrations can be determined for an unknown sample whose peak height is known.

A blank solution was extracted from each of the five test fabrics and the substrate using the extraction procedure described above. The purpose of the blanks was to identify peaks which may interfere with the detection of chlorpyrifos. No such peaks were found. The solution in the 250 ml volumetric flask (obtained after extraction) was diluted as required till a response was obtained which lay in the range of the standard curve. One microliter of the diluted extract from the test fabric or the substrate was then injected into the GC and the concentration of the pesticide (μg/ml) in the test fabric or the substrate, was obtained by comparing the average of three readings for peak height obtained from the GC to the standard

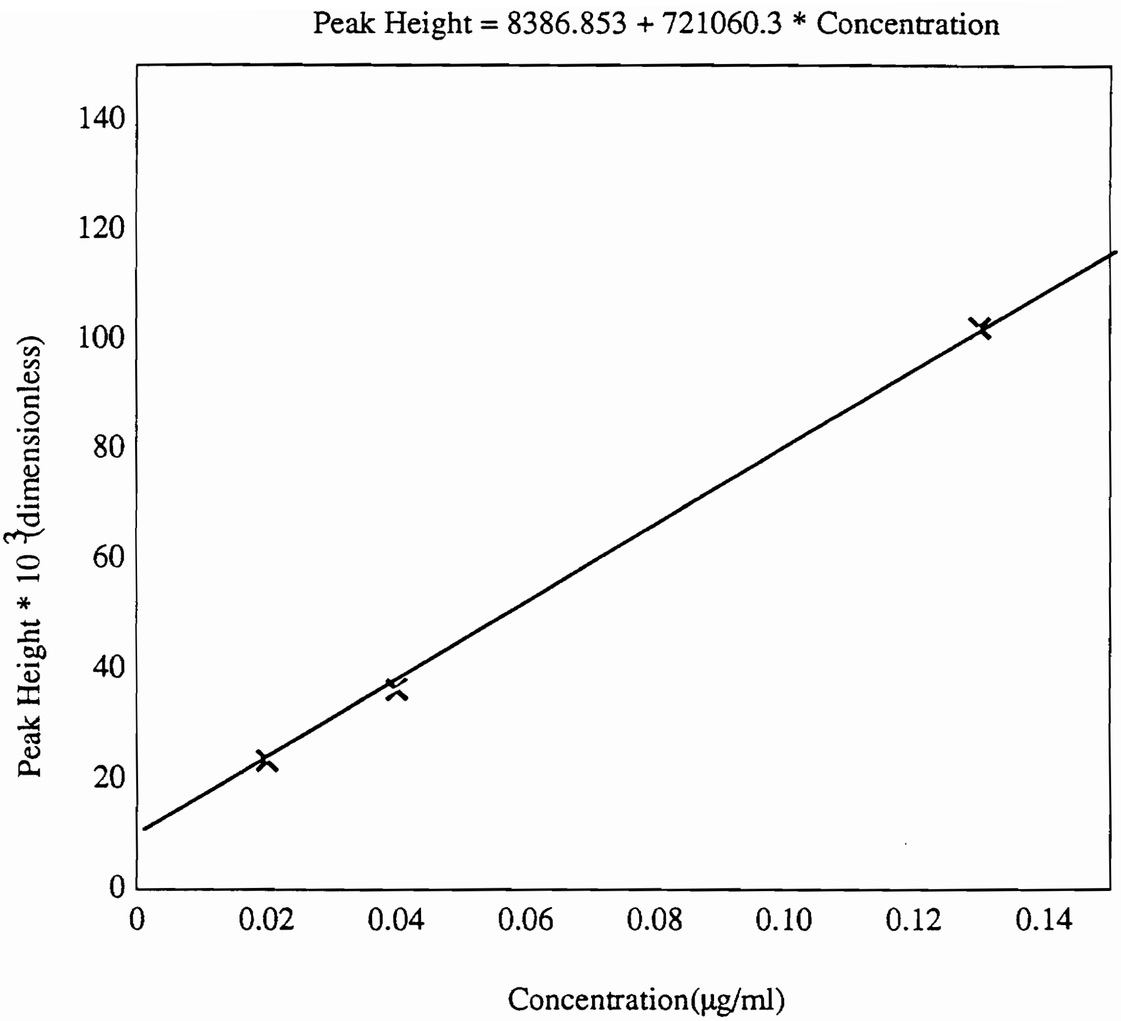


Figure 6. Calibration Curve

curve. The weight of pesticide recovered from the fabric or the substrate was calculated using the formula

$$W\ (\mu g) = C\ (\mu g/ml) * 250\ (ml) * D$$

where, W = weight of the pesticide (μg), C = concentration (μg/ml), D = dilution ratio (dimensionless). The average extraction efficiency was 77%.

The extraction of the pesticide was done by cutting the fabric or the blotter into nine pieces measuring approximately 2.5 cm x 2.5 cm, and placing the pieces in a 250 ml Erlenmeyer flask. One hundred ml of pesticide grade hexane was then added to the flask. The corked flask was shaken and the pressure was released three times before placing the flask in a shaker (Fisher Shaking Water Bath, Model 129) at 120 oscillations/minute for 30 minutes. The solution was then decanted from the Erlenmeyer flask into a 250 ml volumetric flask through a funnel containing anhydrous sulfate that had been washed in petroleum ether. Fifty ml of pesticide grade hexane was added to the Erlenmeyer flask and the flask was shaken for a minute before the liquid was decanted into the Erlenmeyer flask. Another 50 ml of pesticide grade hexane was added to the Erlenmeyer flask, which was again shaken for a minute before the liquid was decanted into the volumetric flask. Pesticide grade hexane was also used to rinse the inside of bottle, the neck of the flask and the anhydrous sodium sulfate, and the rinse was added to the volumetric flask until it reached its capacity.

In the case of impact penetration, the amount of penetration was measured by the increase in weight of the blotter in grams. The average result for three test specimens was reported. No attempt was made to determine the amount of water/surfactant retained by the fabric because of the nature of the test.

Evaluation of Wetting and Wicking

Wetting (Drop Absorbency)

Drop absorbency was measured using AATCC 79-1986 Absorbency of Bleached Woven Cloth (AATCC, 1992). A drop of water was allowed to fall on a 20 cm x 20 cm (8" x 8") fabric specimen from a height of 1 cm, the fabric specimen being held taut by an embroidery hoop with a diameter of 15.2 cm (6"). The time required for the drop to lose its specular reflectance was measured using a stop watch. The average time for ten readings was reported. Drop absorbency was also determined using water/surfactant.

Wicking

Fabric wicking of distilled water, water/surfactant solution, and the 1.25 % a.i. pesticide solution was measured according to the technique used by Raheel and Gitz (1985). A 2.5 cm x 15.2 cm (1" x 6") specimen strip was marked at 1 cm intervals using a water soluble ink. The specimen was weighted using a sinker, suspended vertically such that 1 cm of the specimen was immersed in the test solution. Wicking height was determined after 1, 5, and 10 minutes. The average of five readings was taken for the specimens in the machine direction in the cross direction.

Evaluation of Air Permeability and Other Sorption Properties

Air Permeability

Air permeability was measured using the ASTM D 737-75(1980) Test Method for Air Permeability of Textile Fabrics (ASTM, 1992). Air permeability was measured using a U.S. Testing Air Flow Tester, Model 9025. The specimen size used was 25 cm x 25 cm (10" x

10") and results were reported for an average of 7 specimens in cfm / ft^2. The pressure differential between the fabric surfaces was 1.3 cm (0.5") of water.

Water Repellency

Water repellency was measured using AATCC 21-1978 Water Repellency: Static Absorption Test and by the AATCC 22-1989 Water Repellency: Spray test (AATCC, 1992). In the static absorption test, a weighed 7.6 cm x 7.6 cm (3" x 3") specimen was immersed in a hydrostatic water head of 8.9 cm (3.5") for 20 minutes using a sinker. After 20 minutes the fabric was squeezed in a laboratory padder (Atlas Laboratory Wringer®) at a surface speed of 2.5 cm/min, and the percentage change in weight of the specimen was calculated to obtain the total amount of water absorbed by the specimen. The average of three replications was reported. In the spray test the specimen size was 18 cm x 18 cm (7" x 7"), and three replications were conducted. The fabric was rated according to the prescribed photographic standard.

Oil Repellency

Oil repellency was measured using AATCC 118-1989 Hydrocarbon Resistance Test (AATCC, 1992). The test specimen size was 20 cm x 20 cm (8" x 8") and the fabrics were rated according to the highest-numbered test liquid which would not wet the fabric within a period of 30 seconds. If a fabric was wet by Liquid #1, it was assigned the value 0.

Fabric Characterization

All fabric samples were conditioned for at least 24 hours in standard atmospheric conditions of 70° ± 2° F and relative humidity of 65 ± 2% before tests were conducted. Specimens for the tests were selected in a random manner after excluding 3" from the selvedges of the fabric.

Fabric Weight

Fabric weight was calculated using the ASTM D 3776-85 Standard Test Method for Mass Per Unit Area (Weight) of Woven Fabric (Option C) (ASTM, 1992). Option C requires that a number of small specimens be taken such that the combined area of the specimens is at least 130 cm^2 (20 in^2). Three specimens each of area 58.1 cm^2 (9 in^2) were randomly selected from the fabric. Fabric weigh in g/m^2 was determined using the formula

$$W\ (g/m^2) = M\ (g)\ /\ A\ (m^2)$$

where W is the fabric weight in g/m^2, M is the mass of the sample determined (g), and A is the area of the fabric specimen (cm^2).

Thickness

Thickness was calculated using the ASTM D 1777-64 (1975) Test Method for Measuring Thickness of Textile Materials (ASTM 1992). Thickness was measured using a Federal Thickness Tester made by Custom Scientific Inc. The average of 10 results is reported. The area of the presser foot was 1 sq.inch and the pressure applied was 3.59 N/m^2 (2 oz/sq.inch). The thickness of the specimen was recorded in inches five seconds after applying the load on the fabric specimen.

Breaking load and Elongation

Breaking load and elongation was measured using the ASTM D 5035-90 Standard Test Method for breaking force and elongation of textile fabrics (strip force) (ASTM, 1992). Breaking load and elongation were calculated using an Instron Tensile Tester (Table Model 1130). Six specimens measuring 15 cm x 15 cm (6" x 1") were tested in the machine direction and in the cross direction of the fabric. The load capacity used was 50000 gf, the crosshead speed was 0.508 cm/s and the chart speed was 1.016 cm/s (i.e. ratio of the crosshead to chart speed was 1:2).

The average breaking load for the six specimens was calculated by taking the average of the maximum force (gf) exerted on the specimens. The average breaking elongation for the six specimens was calculated by taking the average of the percentage increase in length of the specimens from the initial gauge length setting to the point of maximum force on the specimen.

Tear Strength

Tear strength was measured using the trapezoidal tearing strength procedure described in ASTM D 1117-80 Standard Methods for Testing Nonwoven Fabrics (ASTM, 1992) and the same machine as was used to measure breaking load and elongation. Five test specimens measuring 15.2 cm x 7.6 cm (6" x 3") were tested in the machine direction and in the cross direction of the fabrics. Tearing strength was calculated by taking the average of the load values for the maxima and minima peaks. The load cell used was 5000 gf.

Stiffness

Stiffness was measured using the ASTM D 1388-64(1975) Test Method for Stiffness of Fabrics. Option A - Cantilever Test was done on a FRL Cantilever Stiffness Tester (ASTM, 1992). Four specimens of size 2.5 cm x 15.2 cm (1" x 6") were cut in the machine and cross directions of the fabrics. Overhang length was calculated as specified by the test method. Flexural rigidity was calculated by the equation

$$G = W \times (O/2)^3$$

where:

G = flexural rigidity in mg.cm

W = weight of the fabric in mg/cm^2

O = overhang length in cm

Preliminary Testing

A preliminary test conducted with distilled water (surface tension 73.2 dynes/cm) revealed that the fabric surfaces of all the fabrics except the 80:20 cotton:polypropylene were not wettable. As a result of the fabric surfaces being non-wettable, almost no capillary penetration occurred for all fabrics except the 80:20 cotton:polypropylene fabric.

It was found from the manufacturer of the pesticide that the pesticide solution contained a nonionic surfactant as part of its inert ingredients which lowered the surface tension of the pesticide solution to 32.8 dynes/cm. Therefore, in order to obtain similar levels of surface tension as the pesticide solution, a nonionic surfactant (Triton X 100) was added to reduce the surface tension of water to that of the pesticide solution. Surface tension measurements on Triton X 100 indicated that the surface tension of a 0.1 ml solution of Triton X 100 dissolved in 30 ml of distilled water had the value 32.5 dynes/cm.

In the search to determine a nonionic surfactant that would produce similar levels of surface tension as the pesticide solution, one of the nonionic surfactant tested was Dowfroth 250 Polypropylene Glycol (PPG). Surface tension measurements revealed that the critical micellar concentration of PPG was 39.9 dynes/cm.

Surface tension measurements were made using a Dynamic Contact Angle Analyzer (DCA 322). The receding contact angle was used in determining the surface tension of the liquid.

Hypothesis Testing

Statistical analysis was performed using the SAS software developed by the SAS Institute, Cary, NC. Statistical differences between the means for the test fabrics was calculated using a General Linear Model (GLM) at a significance level of $p \leq 0.05$. Post hoc analysis was accomplished by Duncan's Multiple Groupings.

To test the research hypotheses, null hypotheses were developed. Each null hypothesis is given below with the statistical analysis used.

NH1: There is no significant difference in the penetration values of the pesticide solution in capillary penetration by fabric and by volume for the test fabrics. Statistical analysis performed was Two-way ANOVA with interaction. The independent variables were fabric and volume and the dependent variable was penetration by the pesticide. Post hoc analysis was Duncan's Multiple Grouping.

NH2: There is no significant difference in the penetration values of the water/surfactant solution in capillary penetration by fabric and by volume for the test fabrics. Statistical analysis performed was Two-way ANOVA with interaction. The independent variables were fabric and volume and the dependent variable was penetration by the water/surfactant. Post hoc analysis was Duncan's Multiple Grouping. To determine a relationship between penetration of pesticide and penetration of water/surfactant, Pearson's correlation coefficient was determined between penetration of pesticide and water/surfactant at the three volumes.

NH3: There is no significant difference in the retention values of the pesticide solution in capillary penetration by fabric and by volume for the test fabrics. Statistical analysis performed was Two-way ANOVA with interaction. The independent variables were fabric and volume and the dependent variable was retention of the pesticide by the fabric. Post hoc analysis was Duncan's Multiple Grouping.

NH4: There is no significant difference in the retention values of the water/surfactant solution in capillary penetration by fabric and by volume for the test fabrics. Statistical analysis performed was Two-way ANOVA with interaction. The independent variables were fabric and volume and the dependent variable was retention of the water/surfactant by the fabric. Post hoc analysis was Duncan's Multiple Grouping. To determine a relationship between the retention of pesticide and water/surfactant, Pearson's correlation coefficient was determined between retention of pesticide and water/surfactant at the three volumes.

NH5: There is no significant difference in the penetration values of the water/surfactant solution in pressure penetration by fabric and by volume for the test fabrics. Statistical analysis performed was Two-way ANOVA with interaction. The independent variables were fabric and volume and the dependent variable was penetration by the water/surfactant. Post hoc analysis was Duncan's Multiple Grouping.

NH6: There is no significant difference in the retention values of the water/surfactant solution in pressure penetration by fabric and by volume for the test fabrics. Statistical analysis performed was Two-way ANOVA with interaction. The independent variables were fabric and volume and the dependent variable was retention of the water/surfactant by the fabric. Post hoc analysis was Duncan's Multiple Grouping.

NH7: There is no significant difference in the penetration values of the water/surfactant solution between capillary and pressure penetration. Statistical analysis performed was multivariate analysis of variance (MANOVA). The independent variable was fabric and the dependent variables were penetration and retention of the water/surfactant by the substrate and fabric, respectively.

NH8: There is no significant difference in the penetration values of the water/surfactant solution in impact penetration, for the test fabrics. Statistical analysis performed was One-way ANOVA. The independent variable was fabric and the dependent variable was impact penetration. Post hoc analysis was Duncan's Multiple Grouping.

NH9: There is no significant difference in the wetting times for the fabrics using distilled water, water/surfactant and the pesticide solutions. Statistical analysis performed was One-way ANOVA. The independent variable was fabric and the dependent variable was wetting time. Post hoc analysis was Duncan's Multiple Grouping.

NH10: There is no significant difference in the wicking times for the fabrics using distilled water, water/surfactant, and the pesticide solutions. Statistical analysis carried out was Three-way ANOVA with interaction. The independent variables were liquid, position, and fabric. The dependent variable was wicking time. Post hoc analysis performed was Duncan's Multiple Grouping.

NH11: There is no significant difference in the air permeability values for the test fabrics. Statistical analysis performed was One-way ANOVA. The independent variable was fabric and the dependent variable was the air permeability. Post hoc analysis was Duncan's Multiple Grouping.

NH12: There is no significant difference in the static absorption values for the test fabrics. Statistical analysis performed was One-way ANOVA. The independent variable was fabric and the dependent variable was static absorption by the fabrics. Post hoc analysis performed was Duncan's Multiple Grouping.

CHAPTER V

RESULTS AND DISCUSSION

This chapter has been organized into four parts. The first part contains the results of the analyses of the penetration mechanisms, the second part contains the results of the analyses of wetting and wicking and their relationship to capillary penetration of the pesticide, the third part contains the results of air permeability and other sorption properties (water and oil repellency), and the fourth part contains the results of fabric characterization.

Analyses of Penetration Mechanisms

Capillary Penetration of fabrics by the pesticide solution: Hypothesis 1.

It was hypothesized that the 100% polypropylene would show the greatest amount of capillary penetration by the pesticide solution and that trilaminates with increasing cotton content would show less capillary penetration. It was also expected that increasing the volume of chlorpyrifos pipetted on to the center of the specimen would increase the amount of penetration.

The 100% polyethylene fabric showed no penetration (less than 5 $\mu g/cm^2$) with the pesticide solution for any of the three volumes. Therefore, the 100% polyethylene fabric was used to provide a baseline reference but was not included in statistical analysis.

A two way analysis of variance (ANOVA) with interaction was conducted using fabric and volume as independent variables and pesticide penetration as the dependant variable. Fabric, volume and fabric*volume (interaction) effects were determined. The post hoc analysis performed was Duncan's Multiple Grouping.

Result of the ANOVA (Table I) indicate that fabric, volume, and fabric*volume interaction are all significant at the 5% significance level. Therefore, the null hypothesis that there would be no significant difference in the capillary penetration of the pesticide by fabric or by volume was rejected. Duncan's Multiple Grouping for the main effects of fabric and volume are given in Table II. The 80:20 cotton:polypropylene (C:P) fabric exhibited significantly higher levels of penetration than the other fabrics. There were no significant differences between the other two cotton:polypropylene laminates and the 100% polypropylene fabric (PP). As expected an increase in volume was associated with an increase in the penetration of the pesticide (Table II).

Since the fabric*volume interaction was significant Duncan's Multiple Grouping was also determined for the fabrics at each volume (Table III). At a volume of 100 μl there was no significant difference between the fabrics. However, at volumes of 300 and 500 μl, the 80:20 cotton:polypropylene fabric exhibited significantly higher pesticide penetration than the other fabrics. There was no significant difference between the other fabrics at any of the volumes considered.

The research hypothesis for the capillary penetration of the pesticide solution was not supported. It was found that the 100% polypropylene fabric did not exhibit the greatest amount of penetration of the pesticide solution. Trilaminates on increasing cotton content exhibited no difference in penetration at lower volumes but at higher volumes ($>$ 100 μl) the trilaminate with the highest cotton content (80:20 cotton:polypropylene) exhibited the greatest amount of penetration of the pesticide solution. Therefore, it was concluded that an increase in the cotton content did not necessarily indicate a decrease in the penetration of the pesticide

Table I

<u>Analysis of variance of capillary penetration by pesticide.</u>

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	55523171.8	5047561.1	53.70	0.0001
Error	24	2255754.6	93989,8		
Corrected Total	35	57778926.4			

R-Square = 0.960959
CV = 13.51916
Root MSE = 306.578
Mean = 2267.73

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Fabric	3	2427934.6	809311.5	8.61	0.0005
Volume	2	51638572.3	25819286.1	274.7	0.0001
Fab*Vol	6	1456664.9	242777.5	2.58	0.0449

Table II

Duncans Multiple Groupings for capillary penetration of pesticide by fabric and by volume.

Duncan Grouping	Mean (μg)	N	Fabric
A	2710.4	9	80:20 C:P
B	2173.5	9	60:40 C:P
B	2139.3	9	40:60 C:P
B	2047.7	9	100% PP

Duncan Grouping	Mean (μg)	N	Volume
A	3706.3	12	500
B	2322.7	12	300
C	774.2	12	100

Note. Means with the same letter are not significantly different a $p<0.05$

Table III

Results of capillary penetration of pesticide for each fabric by volume.

100 μl

Fabric	Mean (μg)	Standard Deviation (μg)
100% polypropylene	754.34 [a]	55.54
40:60 cotton:polypropylene	727.12 [a]	99.43
60:40 cotton:polypropylene	769.50 [a]	135.07
80:20 cotton:polypropylene	845.72 [a]	153.88
100% polyethylene	0	0

300 μl

Fabric	Mean (μg)	Standard Deviation (μg)
100% polypropylene	2197.71 [b]	315.54
40:60 cotton:polypropylene	2170.91 [b]	82.25
60:40 cotton:polypropylene	2214.36 [b]	239.75
80:20 cotton:polypropylene	2707.88 [a]	69.79
100% polyethylene	0	0

500 μl

Fabric	Mean (μg)	Standard Deviation (μg)
100% polypropylene	3191.01 [b]	196.48
40:60 cotton:polypropylene	3519.78 [b]	811.70
60:40 cotton:polypropylene	3536.72 [b]	451.39
80:20 cotton:polypropylene	4577.67 [a]	55.57
100% polyethylene	0	0

Note. Means in the same column (for each volume) with the same superscript are not significantly different at $p < 0.05$.

solution. With increasing volume, it was found that there was an increase in the penetration of the pesticide solution.

Capillary Penetration of fabrics by the water/surfactant solution: Hypothesis 2.

For the capillary penetration of the water/surfactant solution, it was hypothesised that the 100% polypropylene would show the greatest amount of penetration, and increasing cotton content would result in less capillary penetration taking place. With increasing volume there would be an increase in the amount of penetration that takes place. On comparing capillary penetration of pesticide solution with the water/surfactant there would be a high degree of correlation between the capillary penetration values for the pesticide and the water/surfactant solutions.

The results of a Two-way ANOVA (Table IV) indicate that volume was the only significant variable in the capillary penetration of the water/surfactant solution. The interaction between fabric and volume and fabric itself were not significant variables. The null hypothesis that there is no significant difference between the fabrics for the capillary penetration of the water/surfactant solution was accepted.

Duncan's Multiple Grouping for the water/surfactant penetration by volume (Table V) indicated, as expected, that increasing volume resulted in increased penetration. Table VI shows the results of capillary penetration test for each fabric at each volume.

Research hypothesis for the capillary penetration of the water/surfactant solution was not supported. The trilaminates on increasing cotton content did not exhibit higher penetration of the water/surfactant solution. The 100 % polypropylene fabric did not have the highest penetration of the water/surfactant.

Table IV

Analysis of variance of capillary penetration by water/surfactant.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	0.83008	0.07546	34.27	0.0001
Error	24	0.05285	0.00220		
Corrected Total	35	0.88294			

R-Square = 0.940138
CV = 11.89518
Root MSE = 0.04693
Mean = 0.39452

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Fabric	3	0.00853	0.00284	1.29	0.2999
Volume	2	0.80734	0.40367	183.3	0.0001
Fab*Vol	6	0.01420	0.00236	1.08	0.4047

Table V

Duncans Multiple Grouping for capillary penetration of water/surfactant by volume

Duncan Grouping	Mean (g)	N	Volume
A	0.57569	12	500
B	0.39891	12	300
C	0.20895	12	100

Note. Means with the same letter are not significantly different a $p<0.05$

Table VI

<u>Results of capillary penetration of water/surfactant for each fabric by volume.</u>

100 μl

Fabric	Mean (g)	Standard Deviation (g)
100% polypropylene	0.2340	0.0062
40:60 cotton:polypropylene	0.1974	0.0359
60:40 cotton:polypropylene	0.2294	0.0058
80:20 cotton:polypropylene	0.2359	0.0359
100% polyethylene	0.0034	0.0011

300 μl

Fabric	Mean (g)	Standard Deviation (g)
100% polypropylene	0.4213	0.0099
40:60 cotton:polypropylene	0.3912	0.0067
60:40 cotton:polypropylene	0.3512	0.0664
80:20 cotton:polypropylene	0.4310	0.0154
100% polyethylene	0.0034	0.0009

500 μl

Fabric	Mean (g)	Standard Deviation (g)
100% polypropylene	0.5979	0.0059
40:60 cotton:polypropylene	0.5616	0.0178
60:40 cotton:polypropylene	0.5521	0.0185
80:20 cotton:polypropylene	0.5922	0.0072
100% polyethylene	0.0023	0.0015

Pearson's correlation coefficients were determined between the capillary penetration by the pesticide solution and penetration by the water/surfactant solution (Table VII). It was found that there was a reasonably high degree of correlation at low volumes indicating that there may be a relationship between the penetration of the pesticide and penetration of the water/surfactant through the fabrics. Since the surface tensions of the two solutions were the same it appears that surface tension influences penetration through the fabrics.

Retention in capillary penetration of fabrics by the pesticide solution : Hypothesis 3.

Hypothesis 3 proposed that the 100% polypropylene fabric would show the least amount of retention of the pesticide solution and increasing cotton content would result in greater amounts of pesticide solution retained by the fabrics. With increasing volume, there would be an increase in the amount of pesticide retained by the fabrics.

The results of a Two-way ANOVA (Table VIII) indicates that there were significant differences in the retention values of the pesticide solution by fabric, and volume, but the interaction between fabric and volume was not significant. Based on the results, the null hypothesis was rejected and it was concluded that there were significant differences in the retention values of the pesticide solution for the test fabrics.

Duncan's Multiple Grouping for the amount of pesticide retained by the fabrics (Table VIII) indicates that there were significant differences between the amount of pesticide retained by the 80:20 cotton:polypropylene fabric and the other cotton laminates. It was found that the 80:20 cotton:polypropylene fabric retained significantly less pesticide than the other cotton laminates. On increasing volume, significantly larger amounts of pesticide were retained by the fabrics. Table IX gives the mean retention values for each fabric at each volume.

Table VII

Pearson's correlation coefficients between capillary penetration of pesticide and water/surfactant.

100 μl

Fabric	Pesticide (μg)	Water/Surfactant (g)
100% polypropylene	754.34	0.2340
40:60 cotton:polypropylene	727.17	0.1974
60:40 cotton:polypropylene	769.50	0.2294
80:20 cotton:polypropylene	845.72	0.2359

Pearson's R = 0.6826

300 μl

Fabric	Pesticide (μg)	Water/Surfactant (g)
100% polypropylene	2197.71	0.4213
40:60 cotton:polypropylene	2170.91	0.3912
60:40 cotton:polypropylene	2214.36	0.3512
80:20 cotton:polypropylene	2707.88	0.4310

Pearson's R = 0.5736

500 μl

Fabric	Pesticide (μg)	Water/Surfactant (g)
100% polypropylene	3191.01	0.5979
40:60 cotton:polypropylene	3519.78	0.5616
60:40 cotton:polypropylene	3536.72	0.5521
80:20 cotton:polypropylene	4577.67	0.5922

Pearson's R = 0.2352

Table VIII

Analysis of variance for retention of pesticide in capillary penetration.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	13294855.6	1208623.2	10.27	0.0001
Error	24	2823397.8	117641.6		
Corrected Total	35	16118253.4			

R-Square = 0.824832
CV = 38.82901
Root MSE = 342.989
Mean = 883.332

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Fabric	3	3132609.4	1044203.1	8.88	0.0004
Volume	2	8895759.8	4447879.7	37.81	0.0001
Fab*Vol	6	1266486.8	211081.1	1.79	0.1429

Duncans Multiple Groupings for retention of pesticide by fabric and by volume.

Duncan Grouping	Mean (μg)	N	Fabric
A	1201.4	9	100% PP
A	1039.9	9	40:60 C:P
A	880.2	9	60:40 C:P
B	411.8	9	80:20 C:P

Duncan Grouping	Mean (μg)	N	Volume
A	1514.8	12	500
B	835.2	12	300
C	300.0	12	100

Table IX

<u>Results of retention of pesticide in capillary penetration for each fabric by volume.</u>

100 μl

Fabric	Mean (μg)	Standard Deviation (μg)
100% polypropylene	292.90	68.51
40:60 cotton:polypropylene	413.44	197.43
60:40 cotton:polypropylene	331.86	84.20
80:20 cotton:polypropylene	161.78	105.01
100% polyethylene	397.57	121.52

300 μl

Fabric	Mean (μg)	Standard Deviation (μg)
100% polypropylene	1186.76	261.17
40:60 cotton:polypropylene	939.53	95.84
60:40 cotton:polypropylene	874.98	218.23
80:20 cotton:polypropylene	339.64	90.20
100% polyethylene	646.79	175.34

500 μl

Fabric	Mean (μg)	Standard Deviation (μg)
100% polypropylene	2124.64	415.41
40:60 cotton:polypropylene	1766.71	763.21
60:40 cotton:polypropylene	1433.82	665.38
80:20 cotton:polypropylene	733.92	225.26
100% polyethylene	2721.06	556.19

The research hypothesis was not supported. The 100% polypropylene fabric did not exhibit the least amount of retention of the pesticide solution. Increasing cotton content in the trilaminates was associated with a decrease in the amount of pesticide retained in the fabrics. As expected, however, with increasing volume there was an increase in the amount of pesticide retained by the fabrics.

On comparing the results of retention of the pesticide to the results of penetration of the pesticide, it was observed that fabric with significantly higher retention exhibited significantly lower penetration. The 80:20 cotton:polypropylene fabric exhibited the maximun penetration and minimum retention of both the pesticide and the water/surfactant solutions. This can be seen on comparing the Duncan's Multiple Grouping for the fabrics.

Retention of water/surfactant in capillary penetration: Hypothesis 4.

Hypothesis 4 proposed that the 100 % polypropylene fabric would show the least amount of retention of the water/surfactant solution and increasing cotton content would result in greater amounts of water/surfactant retained by the fabrics. It was expected that with increasing volume there would be an increase in the amount of water/surfactant retained by the fabrics.

Results of a Two-way ANOVA (Table X) indicated that fabric and volume were significant factors and their interaction was not. Based on the results the null hypothesis was rejected.

Duncan's Multiple Grouping (Table XI) for the retention of water/surfactant indicated that the 80:20 cotton:polypropylene fabric retained significantly lesswater/surfactant solution than the other trilaminate fabrics. The 100% polypropylene retained an intermediate amount

Table X

Analysis of variance on retntion in the capillary penetration by water/surfactant

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	0.01468	0.00133	2.08	0.0648
Error	24	0.01540	0.00064		
Corrected Total	35	0.03008			

R-Square = 0.488020
CV = 55.59270
Root MSE = 0.02533
Mean = 0.04557

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Fabric	3	0.00680	0.00226	3.54	0.0298
Volume	2	0.00460	0.00230	3.58	0.0434
Fab*Vol	6	0.00327	0.00054	0.85	0.5445

Table XI

Duncans Multiple Grouping for retention in the capillary penetration of water/surfactant

Duncan Grouping	Mean	N	Fabric
A	0.05998	9	60:40 C:P
A	0.05547	9	40:60 C:P
A,B	0.04223	9	100% PP
B	0.02460	9	80:20 C:P

Duncan Grouping	Mean	N	Volume
A	0.05561	12	500
A	0.05133	12	300
B	0.02978	12	100

Note. Means with the same letter are not significantly different a $p < 0.05$

of water/surfactant and was not significantly different from any of the trilaminates. Post hoc analysis for volume indicated no significance in retention for 300 and 500 μl, but at 100 μl significantly less retention occured.

Table XII gives results of retention evaluations for each volume. On comparing the results of retention of water/surfactant to the penetration of water/surfactant, it was found that even though the 80:20 cotton:polypropylene fabric exhibited significantly greater amounts of penetration of the water/surfactant than the other fabrics, it did not differ significantly from the other fabrics in terms of retention of the water/surfactant.

The research hypothesis was not supported by the results. The 100% polypropylene did not retain significantly lower amounts of water/surfactant than the other fabrics. Increasing cotton content in the trilaminates did not result in an increase in the amount of water/surfactant retained by the fabrics.

Pearson's correlation coefficients were determined between the retention of pesticide and water/surfactant in capillary penetration (Table XIII). It was found that there was a reasonably high degree of correlation at all volumes indicating that there may be a relationship between the retention of the pesticide and penetration of the water/surfactant in the fabrics. Since the surface tensions of the two solutions were the same it appears that surface tension influences retention in the fabrics.

The results of hypotheses 1-4 for capillary penetration and retention of fabrics do not support the findings of previous studies using woven fabrics. In those studies an increase in the cotton content of fabrics resulted in a decrease in the capillary penetration of the pesticide solution (Freed et al., 1980; Lillie et al., 1981; and Leonas, 1991). In the present study, the

Table XII

Results of retention of water/surfactant in capillary penetration for each fabric by volume.

100 μl

Fabric	Mean (g)	Standard Deviation (g)
100% polypropylene	0.0234	0.0024
40:60 cotton:polypropylene	0.0568	0.0267
60:40 cotton:polypropylene	0.0251	0.0021
80:20 cotton:polypropylene	0.0138	0.0001
100% polyethylene	0.0277	0.0042

300 μl

Fabric	Mean (g)	Standard Deviation (g)
100% polypropylene	0.0476	0.0076
40:60 cotton:polypropylene	0.0512	0.0071
60:40 cotton:polypropylene	0.0798	0.0642
80:20 cotton:polypropylene	0.0267	0.0015
100% polyethylene	0.0476	0.0056

500 μl

Fabric	Mean (g)	Standard Deviation (g)
100% polypropylene	0.0566	0.0022
40:60 cotton:polypropylene	0.0584	0.0257
60:40 cotton:polypropylene	0.0750	0.0454
80:20 cotton:polypropylene	0.0333	0.0049
100% polyethylene	0.0512	0.0121

Table XIII

<u>Pearson's correlation coefficients between retention of pesticide and water/surfactant in capillary penetration.</u>

100 μl

Fabric	Pesticide (μg)	Water/Surfactant (g)
100% polypropylene	292.90	0.0234
40:60 cotton:polypropylene	413.44	0.0568
60:40 cotton:polypropylene	331.86	0.0251
80:20 cotton:polypropylene	161.78	0.0138

Pearson's R = 0.8786

300 μl

Fabric	Pesticide (μg)	Water/Surfactant (g)
100% polypropylene	1186.76	0.0076
40:60 cotton:polypropylene	939.53	0.0071
60:40 cotton:polypropylene	874.98	0.0642
80:20 cotton:polypropylene	339.64	0.0015

Pearson's R = 0.5140

500 μl

Fabric	Pesticide (μg)	Water/Surfactant (g)
100% polypropylene	2124.64	0.0022
40:60 cotton:polypropylene	1766.71	0.0257
60:40 cotton:polypropylene	1433.82	0.0454
80:20 cotton:polypropylene	733.92	0.0049

Pearson's R = 0.5632

40:60 cotton:polypropylene and 60:40 cotton:polypropylene blends gave penetrationa and retention results which are not significantly different from the 100% polypropylene. The 80:20 cotton:polypropylene blend had higher penetration and lower retention. This may be due to the fact that the binding of the layers in 80:20 cotton:polypropylene was not as good as in the other trilaminates due to the greater bulk of the cotton layer. It appears that there is an associational relationship in the penetration and retention of the pesticide and water/surfactant solutions for capillary penetration. It may be possible to extend this relationship to other penetration mechanisms such as pressure and impact penetration.

Pressure Penetration of fabrics by the water/surfactant solution: Hypothesis 5.

It was hypothesized that, in the pressure penetration of the water/surfactant, there would be no significant difference in the penetration values of the 100% polypropylene and the cotton laminates, and an increase in volume would result in an increase in the amount of penetration of the water/surfactant for pressure penetration.

The results of the Two-way ANOVA (Table XIV) indicate that interaction between fabric and volume was not significant but fabric and volume were found to be significant at $p \leq 0.05$. Based on the results the null hypothesis was rejected.

Duncan's Multiple Grouping for the penetration values of water/surfactant for pressure penetration (Table XV) indicate that there were no significant differences in the pressure penetration values for the 80:20 and 40:60 cotton:polypropylene fabrics. No significant differences were found between the 100% polypropylene and the 60:40 cotton:polypropylene fabric. However, there were significant differences between the 80:20 and 40:60 cotton:polypropylene fabrics as compared to the 100% polypropylene and the 60:40

Table XIV

Analysis of variance on pressure penetration by water/surfactant

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	0.645226	0.05865	179.3	0.0001
Error	24	0.00784	0.00032		
Corrected Total	35	0.65307			

R-Square = 0.987981
CV = 4.288814
Root MSE = 0.01808
Mean = 0.42168

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Fabric	3	0.00560	0.00186	5.71	0.0043
Volume	2	0.63809	0.31904	975.4	0.0001
Fab*Vol	6	0.00153	0.00025	0.78	0.5930

Table XV

Duncans Multiple Grouping for pressure penetation of water/surfactant by fabric and by volume.

Duncan Grouping	Mean (g)	N	Fabric
A	0.43438	9	40:60 C:P
A	0.43370	9	80:20 C:P
B	0.41161	9	100% PP
B	0.40701	9	60:40 C:P

Duncan Grouping	Mean (g)	N	Volume
A	0.58103	12	500
A	0.42884	12	300
B	0.25515	12	100

Note. Means with the same letter are not significantly different a $p<0.05$

cotton:polypropylene fabrics. No significant difference in the penetration was found when the volume was increased from 300 to 500 μl, but significant differences were found at a volume of 100 μl as compared to the other volumes. It may be noted that while there was virtually no capillary penetration of either the pesticide or the water/surfactant solutions, there was appreciable pressure penetration of the water/surfactant solution through the 100 % polyethylene fabric (Table XVI). It is possible that some of the penetration occured due to the transport of the solution over the edges of the fabric.

The research hypothesis was not supported. Significant differences were found between the fabrics. An increase in volume from 100 to 300 μl resulted in a significant difference in pressure penetration, but an increase in volume from 300 to 500 μl did not result in an increase in penetration.

Retention in pressure penetration of the fabrics by the water/surfactant : Hypothesis 6

It was hypothesized that, in the pressure penetration of the water/surfactant, there would be no significant difference in the retention values of the 100% polypropylene and the cotton laminates, and increasing volume would result in an increase in the amount of penetration of the water/surfactant.

The results of the ANOVA (Table XVII) indicate that fabric, volume and the interaction between fabric and volume are all significant at $p \leq 0.05$. Based on the results the null hypothesis was rejected.

Duncan's Multiple Grouping by fabric for the retention of water/surfactant in pressure penetration (Table XVIII) indicated that 80:20 cotton:polypropylene retained the least water/surfactant while the 100 % polypropylene retained significantly greater amounts of the

Table XVI

<u>Results of pressure penetration of water/surfactant.</u>

100 μl

Fabric	Mean (g)	Standard Deviation (g)
100% polypropylene	0.2478	0.0126
40:60 cotton:polypropylene	0.2627	0.0168
60:40 cotton:polypropylene	0.2506	0.0022
80:20 cotton:polypropylene	0.2596	0.0034
100% polyethylene	0.2223	0.0249

300 μl

Fabric	Mean (g)	Standard Deviation (g)
100% polypropylene	0.4202	0.0109
40:60 cotton:polypropylene	0.4387	0.0131
60:40 cotton:polypropylene	0.4163	0.0072
80:20 cotton:polypropylene	0.4401	0.0138
100% polyethylene	0.3898	0.0421

500 μl

Fabric	Mean (g)	Standard Deviation (g)
100% polypropylene	0.5669	0.0036
40:60 cotton:polypropylene	0.6018	0.0172
60:40 cotton:polypropylene	0.5541	0.0435
80:20 cotton:polypropylene	0.6014	0.0271
100% polyethylene	0.5108	0.0232

Table XVII

Analysis of variance on retntion in the pressure penetration by water/surfactant

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	0.01887	0.00171	78.3	0.0001
Error	24	0.00052	0.00002		
Corrected Total	35	0.01939			

R-Square = 0.972910
CV = 10,46140
Root MSE = 0.00468
Mean = 0.04473

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Fabric	3	0.00276	0.00092	42.0	0.0001
Volume	2	0.01406	0.00703	321.2	0.0001
Fab*Vol	6	0.00204	0.00034	15.5	0.0001

Table XVIII

Duncans Multiple Grouping for retention in the pressure penetration of water/surfactant

Duncan Grouping	Mean (g)	N	Fabric
A	0.05743	9	100% PP
B	0.04550	9	60:40 C:P
B	0.04318	9	40:60 C:P
C	0.03278	9	80:20 C:P

Duncan Grouping	Mean (g)	N	Volume
A	0.07016	12	500
B	0.04205	12	300
C	0.02196	12	100

Note. Means with the same letter are not significantly different a $p<0.05$

water/surfactant as compared to the trilaminate fabrics. With increasing volume, it was found that there was an increase in the amount of water retained by the fabrics.

Duncan's Multiple Grouping's for each fabric at the three volumes (Table XIX) indicated that there were no significant differences in the retention values at a volume of 100 μl, but at higher volumes the 80:20 cotton:polypropylene fabric retained significantly lower amounts of the water/surfactant solution. Water/surfactant solution from the 100% polyethylene that was present on the surface of the fabric was drained off before the retention was determined.

The research hypothesis was only partly supported. At low volumes there were no significant differences in the retention of the water/surfactant but at higher volumes the 80:20 cotton:polypropylene fabric exhibited lower retention than the other fabrics. On increasing volume the amount retained by the fabrics did increase.

Comparison between Capillary and Pressure Penetration: Results of Hypothesis 7.

It was hypothesized that there would be an increase in the amount of water/surfactant penetrating through the fabrics for pressure penetration as compared to capillary penetration. In order to test the null hypothesis a multivariate analysis of variance (MANOVA) was performed using the penetration and retention of the water/surfactant as dependent variables. The independent variable was the method of penetration.

The result of the MANOVA (Table XX) indicate that there were no significant differences in the capillary and pressure penetration of the water/surfactant solution for the fabrics. On performing ANOVA on each of the dependent variables, it was found that both

Table XIX

<u>Results of retention of water/surfactant in pressure penetration for each fabric by volume.</u>

100 μl

Fabric	Mean (g)	Standard Deviation (g)
100% polypropylene	0.0209 [a]	0.0035
40:60 cotton:polypropylene	0.0238 [a]	0.0042
60:40 cotton:polypropylene	0.0236 [a]	0.0022
80:20 cotton:polypropylene	0.0195 [a]	0.0009
100% polyethylene	0.0471	0.0077

300 μl

Fabric	Mean (g)	Standard Deviation (g)
100% polypropylene	0.0567 [a]	0.0037
40:60 cotton:polypropylene	0.0328 [b]	0.0098
60:40 cotton:polypropylene	0.0469 [a]	0.0044
80:20 cotton:polypropylene	0.0317 [b]	0.0015
100% polyethylene	0.0406	0.0410

500 μl

Fabric	Mean (g)	Standard Deviation (g)
100% polypropylene	0.0947 [a]	0.0024
40:60 cotton:polypropylene	0.0730 [b]	0.0073
60:40 cotton:polypropylene	0.0659 [b]	0.0052
80:20 cotton:polypropylene	0.0471 [c]	0.0031
100% polyethylene	0.0310	0.0273

Note. Means in the same column (for each volume) with the same superscript are not significantly different at $p \leq 0.05$.

Table XX

Multivariate analysis of variance for the effect of method of penetration testing on penetration and retention of the water/surfactant solution by test fabrics.

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks Lambda	0.98710	0.4505	2	69	0.6392
Pillai's Trace	0.01289	0.4505	2	69	0.6392
Hotelling Lawley Trace	0.01305	0.4505	2	69	0.6392
Roy's Greatest Root	0.01305	0.4505	2	69	0.6392

penetration and retention were not significant based on the method of penetration (Table XXI).

Based on the results, the null hypothesis was accepted and it was concluded that there were no significant difference between capillary and pressure penetration of the water/surfactant. The research hypothesis was not supported. The results of the pressure penetration of water/surfactant did not support the findings of Crouse et al. (1990), who stated that application of pressure may cause the fabrics to be saturated with the liquid, and therefore would not be able to resist the penetration of the liquid. The results also do not support the findings of Minor et al. (1961) who proposed that the application of pressure on the fabrics may have resulted in a collapse of the nap fibers at the interface of the fabric and the substrate, causing the liquid to be forced from the fabric to the substrate.

Impact penetration of the fabrics by the water/surfactant: Hypothesis 8.

It was hypothesized that there would be no significant difference in the impact penetration values for the cotton laminates and the 100% polypropylene fabrics. A One way analysis of variance (ANOVA) was used to test the hypothesis.

The results of the ANOVA and Duncan's Multiple Grouping on impact penetration of the water/surfactant are given in Table XXII. The results indicate that there were significant differences in the impact penetration values of the water/surfactant for the test fabrics. Therefore, the null hypothesis was rejected. The results of Duncan's Multiple Grouping indicate that there was no significant differences in the impact penetration values of cotton laminates, but there were significant differences in the impact penetration values between the 100% polypropylene and the cotton laminates. The 100% polypropylene exhibited

Table XXI

Analysis of variance of retention on the comparison between capillary and pressure penetration of the water/surfactant solution.

Dependent Variable: Penetration

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.00001	0.00001	0.02	0.8935
Error	70	0.04948	0.00070		
Corrected Total	71	0.04949			

Dependent Variable: Retention

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.01327	0.01327	0.61	0.4392
Error	70	1.53601	0.02194		
Corrected Total	71	1.54929			

Table XXII

Results of impact pentration

Fabric	Mean (g)	Standard Deviation (g)
100% polypropylene	10.46 [b]	3.19
40:60 cotton:polypropylene	19.26 [a]	0.64
60:40 cotton:polypropylene	17.65 [a]	2.40
80:20 cotton:polypropylene	20.53 [a]	1.18
100% polyethylene	0.01	0.01

Note. Means in the same column (for each volume) with the same superscript are not significantly different at $p<0.05$.

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Between Groups	4	872.9090	218.2272	61.9315	0.0001
Within Groups	10	35.2369	3.5237		
Total	14	908.1458			

significantly lower amounts of impact penetration of water/surfactant than the cotton laminates. The 100% polyethylene fabric exhibited virtually no impact penetration.

On comparing the results of impact penetration of the 100% polyethylene fabric to that of capillary and pressure penetration, we find that there is virtually no capillary or impact penetration for the 100% polyethylene fabric. However, there was a substantial amount of pressure penetration through the 100% polyethylene fabric, suggesting that pressure penetration may result in the most severe form of penetration taking place. For the other fabrics, it was found that while there was no significant difference between the capillary or pressure penetration of the water/surfactant through the fabrics, there were significant differences between the impact penetration of the water/surfactant between the 100 % polypropylene and the cotton laminates, indicating greater water repellency.

Analyses of Wetting and Wicking and their Relationship to Capillary Penetration of the Pesticide

Wetting of the fabrics using distilled water, water/surfactant and the pesticide solution: Hypothesis 9.

It was hypothesized that there would be no significant difference in the wetting times of the fabrics to the three liquids. Wetting response was measured for distilled water, water/surfactant, and the pesticide solutions.

The results for wetting (drop absorbency) are given in Table XXIII. The values for drop absorbency of distilled water were greater than 600 seconds for all the fabrics except for the 80:20 fabric which was wetted by distilled water in approximately 10 seconds. Since the values of drop absorbency for distilled water was greater than 600 seconds for most of the

Table XXIII

Results of wetting (drop absorbency).

Fabric	Drop Absorbency		
	Water (sec)	Water/Surfactant (sec)	Pesticide (sec)
100% polypropylene	>600	1.47 [a]	2.14 [a]
40:60 cotton:polypropylene	>600	0.81 [b]	1.17 [b]
60:40 cotton:polypropylene	>600	0.57 [c]	1.09 [b]
80:20 cotton:polypropylene	10.58	0.34 [d]	0.43 [c]
100% polyethylene	>600	>600	>600

Note. Means in the same column (for each volume) with the same superscript are not significantly different at $p<0.05$.

Analysis of Variance (Water/Surfactant)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Between Groups	3	7.17	2.3900	67.5729	0.0001
Within Groups	36	1.2733	0.0354		
Total	39	8.4433			

Analysis of Variance (Pesticide)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Between Groups	3	14.8053	4.9351	123.1508	0.0001
Within Groups	36	1.4426	0.0401		
Total	39	16.2479			

fabrics, and were greater than 600 seconds for the 100% polyethylene fabric for all three liquids, these results were not included in the statistical analysis. The statistical analysis done on the drop absorbency values of the water/surfactant and the pesticide solutions was One-way ANOVA, followed by Duncan's Multiple Grouping. The result of the ANOVA and Duncan's Multiple Grouping for the drop absorbency of water/surfactant and the pesticide are also given in Table XXIII.

There were significant differences in the drop absorbency values for the fabrics using water/surfactant and the pesticide solutions. Duncan's Multiple Grouping revealed that the 80:20 cotton:polypropylene fabric had the fastest wetting time while the 100% PP had the slowest wetting time. It should be noted, however, that mean wetting times for all the trilaminates and polypropylene were less than 3 seconds for the water/surfactant and for the pesticide.

The results obtained from the drop absorbency test for the water/surfactant were related to the Washburn (1921) equation according to which

$$dL/dt = (Yr/4Ln) * \cos(\Theta)$$

Since Y, L and n are fixed for a given liquid and a given amount of liquid, the rate of liquid transferred depends on the capillary radius and the contact angle Θ. Since, no measurements were made on the contact angle between the fabric and the liquids, it is not possible to say if a higher rate of wetting was directly proportional to the capillary radius. In their discussion on the applicability of the Washburn (1921) equation to the drop absorbency test, Raheel and Gitz (1985) assume that a higher rate of wetting (lower wetting time) as measured by the drop absorbency test is associated with a larger capillary radius. From their discussion, it would appear that the 100% polypropylene fabric would have the smallest capillary radii, and the

80:20 cotton:polypropylene fabric would have the largest capillary radii. Based on the results of the drop absorbency and the Washburn (1921) equation, the 80:20 cotton:polypropylene fabric, should have the largest capillary radii. However, the 80:20 cotton:polypropylene fabric also exhibited the greatest amount of penetration of the pesticide solution. Raheel and Gitz (1985) proposed that a larger capillary radii would be associated with less penetration, because a larger capillary radii would be able to store greater amounts of the pesticide solution in it. This was found not to be true. However, the reader is cautioned that capillary radii were not measured in either our study or theirs. Pore size measurements and air permeability may be a better indicator of the interfiber capillary radii.

Wicking of the fabrics using distilled water, water/surfactant, and pesticide solutions: Hypothesis 10.

It was hypothesised that there would be a significant difference in the distance wicked by the fabrics when distilled water is compared to the water/surfactant or the pesticide solution. However, there will be no significant difference in the distance wicked by the fabrics when comparing the water/surfactant to the pesticide solution.

The results for wicking are given in Table XXIV. In order to test the null hypothesis for wicking, a Three-way ANOVA with interaction was used to determine the effect of fabric, liquid (water, pesticide and water/surfactant), position (machine direction and cross direction) and their interactions. It may be noted that the 100 % polyethylene fabric did not exhibit any wicking at any of three times using any of the three liquids and was not included in the analysis. The average of the distance wicked after 1, 5, and 10 minutes was considered in the analysis. The results in Table XXV indicate that the liquid*fabric*position interaction was

Table XXIV

<u>Wicking response of water, water/surfactant, and pesticide after 1, 5, and 10 minutes.</u>

Machine Direction

Fabric	Water 1 (cm)	Water 5 (cm)	Water 10 (cm)	Water+Surfactant 1 (cm)	Water+Surfactant 5 (cm)	Water+Surfactant 10 (cm)	Pesticide 1 (cm)	Pesticide 5 (cm)	Pesticide 10 (cm)
100% polypropylene	0	0	0	2.8	5.2	6.6	2.6	5.8	8.2
40:60 cotton:polypropylene	3.4	7.6	9.6	5.2	8.2	9.8	5.0	8.6	10.4
60:40 cotton:polypropylene	5.2	8.2	8.4	5.8	9.8	11.6	6.2	10.0	12.0
80:20 cotton:polyporpylene	5.4	6.8	7.2	5.4	8.6	10.0	6.2	9.0	10.2
100% polyethylene	0	0	0	0	0	0	0	0	0

Cross Direction

Fabric	Water 1 (cm)	Water 5 (cm)	Water 10 (cm)	Water+Surfactant 1 (cm)	Water+Surfactant 5 (cm)	Water+Surfactant 10 (cm)	Pesticide 1 (cm)	Pesticide 5 (cm)	Pesticide 10 (cm)
100% polypropylene	0	0	0	2.6	5.0	6.6	2.8	5.8	8.2
40:60 cotton:polypropylene	3.2	7.4	9.0	4.0	8.0	10.4	4.0	8.0	9.6
60:40 cotton:polypropylene	4.8	7.8	8.0	5.2	9.2	11.0	5.6	9.2	11.2
80:20 cotton:polyporpylene	6.0	7.2	7.2	5.4	9.0	10.6	6.0	8.8	10.0
100% polyethylene	0	0	0	0	0	0	0	0	0

Table XXV

Results of fabric, liquid and position and their interaction for wicking.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Liq	2	371.55	185.77	289.99	0.0001
Fab	4	4531.67	1132.92	1768.48	0.0001
Pos	1	4.06	4.06	6.33	0.0132
Liq*Fab	8	314.52	39.31	61.37	0.0001
Fab*Pos	4	9.23	2.31	3.60	0.0083
Liq*Pos	2	1.41	0.70	1.10	0.3364
Liq*Fab*Pos	8	2.21	0.28	0.43	0.9000

not significant, but liquid*fabric and the fabric*position interactions were significant. Further analysis was required to test for the effect of liquid and position for each fabric. A linear contrast between the wicking response for distilled water and water/surfactant, and water/surfactant and pesticide was performed to ascertain the effect of surface tension on the wicking response of the fabrics. Post hoc analysis was Duncan's Multiple Grouping.

The results (Table XXVI) indicate that there were differences in wicking for distilled water and water/surfactant for all the fabrics, indicating that surface tension played a crucial role in determining the wicking response of the fabrics. There were no significant differences in the wicking response of the cotton laminates for water/surfactant and pesticide, however there was a difference in the wicking response for 100% polypropylene fabric. The pesticide and water/surfactant wicked to a greater height than distilled water. It is unclear why there were differences in the wicking heights for the 100% polypropylene when considering the pesticide and water/surfactant solutions.

The effect of position (wicking along the length/width of the fabric) was also examined by the analyses. The results in Table XXVII indicate that there were significant differences between the distance wicked by position for the 40:60 cotton:polypropylene, and the 60:40 cotton:polypropylene. There were no significant differences between the distance wicked by position for the 80:20 cotton:polypropylene and the 100% polypropylene fabrics. Normally, one would expect that there be significant differences in the distance wicked by position because the fibers in a nonwoven fabric are preferentially aligned in one direction (machine direction of production - length). However, these results suggest that the fibers for the 80:20 cotton:polypropylene fabric and the 100% polypropylene fabric were more randomly oriented than the other cotton laminates.

Table XXVI

Effect of liquid by fabric on wicking.

Fabric 1 (100% polypropylene)

Liquid	Mean (cm)	Observation	Duncan's Grouping
Pesticide	5.567	30	A
Water/Surfactant	4.800	30	B
Distilled Water	0.000	30	C

Fabric 2 (40:60 cotton:polypropylene)

Liquid	Mean (cm)	Observation	Duncan's Grouping
Pesticide	7.600	30	A
Water/Surfactant	7.600	30	A
Distilled Water	6.700	30	B

Fabric 3 (60:40 cotton:polypropylene)

Liquid	Mean (cm)	Observation	Duncan's Grouping
Pesticide	9.033	30	A
Water/Surfactant	8.800	30	A
Distilled Water	7.067	30	B

Fabric 4 (80:20 cotton:polypropylene)

Liquid	Mean (cm)	Observation	Duncan's Group
Pesticide	8.400	30	A
Water/Surfactant	8.167	30	A
Distilled Water	6.633	30	B

Note. Means with the same letter are not significantly different a $p < 0.05$

Table XXVII

Effect of position by fabric on wicking.

Fabric 1 (100% polypropylene)

Position	Mean (cm)	Observation	Duncan's Group
Length	3.467	45	A
Width	3.444	45	A

Fabric 2 (40:60 cotton:polypropylene)

Position	Mean (cm)	Observation	Duncan's Group
Length	7.533	45	A
Width	7.067	45	B

Fabric 3 (60:40 cotton:polypropylene)

Position	Mean (cm)	Observation	Duncan's Group
Length	8.600	45	A
Width	8.000	45	B

Fabric 4 (80:20 cotton:polypropylene)

Position	Mean (cm)	Observation	Duncan's Group
Length	7.667	45	A
Width	7.800	45	A

Note. Means with the same letter are not significantly different a $p<0.05$

Table XXVIII

Results of air permeability.

Fabric	Mean (cfm/ft^2)	Standard Deviation (cfm/ft^2)
100% polypropylene	18.80 [a]	1.88
40:60 cotton:polypropylene	13.16 [b]	1.01
60:40 cotton:polypropylene	15.13 [c]	0.92
80:20 cotton:polypropylene	38.36 [d]	2.01
100% polyethylene	≤0.01	-

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Between Groups	3	2776.9582	925.6527	391.4753	0.0001
Within Groups	24	56.7486	2.3465		
Total	27	2833.7068			

Based on the results for wicking, the null hypothesis was rejected and it was concluded that there were significant differences in the wicking responses for the test fabrics using the three liquids. The research hypothesis was supported.

Analyses of Air Permeability and other Sorption Properties

Air Permeability of the fabrics: Hypothesis 11.

It was hypothesized that an increase in the cotton content would result in an increase in the air permeability of the fabrics. Air permeability of the 100% polyethylene fabric could not be determined on the instrument used because the air permeability of the 100% polyethylene fabric was below the detectable limit of the instrument used.

The results of the ANOVA (Table XXVIII) indicated that there were significant differences in the air permeability values of the four test fabrics. Duncan's Multiple Grouping (Table XXVIII) revealed that the 80:20 cotton:polypropylene fabric had the greatest air permeability among the cotton laminates and the 100% polypropylene.

Air permeability was related to capillary size by Wehner et al. (1987). It was found that a higher air permeability was related to a larger interfiber capillary spaces. Based on the air permeability results, it would appear that the 80:20 cotton:polypropylene fabric will have the largest interfiber capillary radii.

On comparing the results of air permeability to the capillary penetration of the pesticide solution, it is seen that a higher air permeability is associated with a higher amount of penetration of the pesticide solution. However, this relationship is not always true because, there were significant differences in the air permeability values for 100% polypropylene and the 40:60 and 60:40 cotton:polypropylene fabrics, but there were no significant difference in the penetration values between them.

Based on the results, the null hypothesis was rejected, and it was concluded that there were significant differences in the air permeability values for the test fabrics. The research hypothesis was supported. It does appear that the air permeability was higher for the 80:20 cotton:polypropylene fabric due to a less effective binding of the cotton layer in the trilaminate.

Water and oil repellency of the fabrics: Hypothesis 12.

It was hypothesized that an increase in the cotton content will result in an increase in the static absorption of the laminates. An increase in the cotton content will result in no difference in the water and oil spray rating of the fabrics. Statistical analysis of the water spray rating and the oil repellency data was limited because the data obtained from these tests is in the form of ranks. In the water spray rating test a value of 100 indicates complete resistance to wetting while a rating of 0 indicates complete wetting.

ANOVA was done on the static absorption values to see if there were significant differences in the static absorption values for the test fabrics. Post hoc analysis done Duncan's Multiple Grouping.

The ANOVA for the static absorption test (Table XXIX) indicated that there were significant differences in the static absorption values for the test fabrics. Duncan's Multiple Grouping indicated that the 80:20 cotton:polypropylene had the largest static absorption values, indicating that it had the greatest ability to absorb water.

Based on the results, the null hypothesis was rejected, and it was concluded that there were significant differences in the in the static absorption values of the test fabrics. On comparing the static absorption values to the retention of pesticide in the fabrics in capillary penetration, it was found that the 80:20 cotton:polypropylene fabric, which had the highest static absorption values, retained the least amount of pesticide. On the contrary the 100% polypropylene fabric, which had the least static absorption value, retain significantly greater amounts of pesticide than the 80:20 cotton:polypropylene fabric. These results appear to be contrary to what was found for woven fabrics, where it was found that on increasing the cotton content, there was an increase in the resistance offered to penetration by pesticides i.e. greater retention of the pesticide in the fabric, which suggests that there may be differences in the way by which a pesticide moves through a woven fabric as compared to a nonwoven fabric.

For the water spray rating (Table XXIX), it was found that the 80:20 cotton:polypropylene fabric had the lowest rating of 50, followed by the 60:40 cotton:polypropylene fabric, which had a rating of 70. There was no difference in the water spray ratings of the 100% polyethylene, 100% polypropylene and the 40:60 cotton:polypropylene fabric, all of which had water spray ratings of 90. For the spray rating in the water repellency test, it was found that as the spray rating decreased (i.e. the fabric became less water repellent), there was a decrease in the resistance offered to the penetration by the pesticide. This maybe because a lower rating signifies greater amount of wetting on the fabric surface. Since, wetting of a fabric surface is important for capillary penetration to occur, it is possible that the spray rating maybe a good indicator of a fabrics ability to resist penetration by pesticide.

Table XXIX

<u>Results of water repellency.</u>

Fabric	Water Repellency	
	Spray Test Rating	Static Absorption (%)
100% polypropylene	90	0.63 [c]
40:60 cotton:polypropylene	90	199.82 [b]
60:40 cotton:polypropylene	70	434.49 [b]
80:20 cotton:polypropylene	50	554.60 [a]
100% polyethylene	90	2.93

Note. Means in the same column (for each volume) with the same superscript are not significantly different at $p<0.05$.

The results for oil repellency are given in Table XXX. All the fabrics except the 100% polyethylene were wetted by 'Liquid #1' (Kaydol, surface tension 32.49) and were assigned the value 0. The 100% polyethylene was wetted by 'Liquid #7' (Octane) and was given the value 6.

The surface tensions of the various liquids used in the oil repellency test were also measured in an attempt to determine the surface free energies of the fabrics. Since 80:20 cotton:polypropylene fabric was wetted by distilled water (surface tension 73.2 dynes/cm), it was concluded that the surface free energy of the 80:20 cotton:polypropylene was greater than 73.2 dynes/cm. Distilled water did not wet any of the other fabrics. Therefore, the surface free energies of the other fabrics must be lower than 73.2 dynes/cm. The 40:60 and the 60:40 were wet by water containing Dowfroth 250 Polypropylene Glycol (15 μl of polypropylene glycol in 30 ml of water), which is a nonionic surfactant (surface tension 39.9 dynes/cm), but the 100% polypropylene and the 100% polyethylene were not. Therefore, it was concluded that the 40:60 and the 60:40 cotton:polypropylene fabrics have surface free energies greater than 39.9 dynes/cm but less than 73.2 dynes/cm. All fabrics except the 100% polyethylene were wetted by water containing Triton X 100 (surface tension 32.5 dynes/cm). Therefore, the 100% polypropylene had a surface free energy greater than 32.5 dynes/cm but less than 39.9 dynes/cm. The 100% polyethylene was wetted by 'Liquid # 7' (surface tension 21.5 dynes/cm), but was not wetted by 'Liquid # 6' (Decane, surface tension 23.8 dynes/cm). Therefore, the surface free energy of the 100% polyethylene was between 21.5-23.8 dynes/cm. Thus the various fabrics could be ranked on the basis of their surface free energies. The results of the surface free energies are summarized in Table XXX.

Table XXX

Results of oil repellency.

Fabric	Oil Repellency	
	Rating	Free Energy (dynes/cm)
100% polypropylene	0	39.9>F>32.5
40:60 cotton:polypropylene	0	73.2>F>32.5
60:40 cotton:polypropylene	0	73.2>F>32.5
80:20 cotton:polypropylene	0	F>73.2
100% polyethylene	6	21.5>F>23.8

Note. The letter F represents the surface free energy

The research hypothesis was partly supported. An increase in the cotton content resulted in an increase in the static absorption. Differences were found in the water spray ratings of the fabric but, no differences were found in the oil spray ratings of the fabrics.

Results of Fabric Characterization

Fabric Weight

The results for fabric weight are given in Table XXX. The fabric weight calculated in g/m^2 indicated that the cotton laminates and the 100% polypropylene were close to the desired value of 84.765 g/m^2. The variation in weights between the cotton laminates and the 100% polypropylene may arise due to inaccuracy in the production process of these fabrics. One way ANOVA on the test fabrics revealed no significant difference in fabric weight for the 100% polypropylene and the cotton laminates. The weight of the 100% polyethylene was 44.42 g/m^2, and was significantly less than that of the other fabrics.

Fabric Thickness

The fabric thickness for the various fabrics are given in Table XXXI. One way ANOVA followed by post hoc Duncan's Multiple Grouping on fabric thickness revealed that there were no significant difference in the thickness values between the 100% polypropylene, 60:40, and 80:20 cotton:polypropylene fabrics, but the 40:60 cotton:polypropylene fabric was significantly less thicker than the other cotton laminates and the 100% polypropylene fabric. The 100% polyethylene fabric was the thinnest fabric. The increase in thickness from the 40% cotton to the 80% cotton fabric, could be due to the greater bulk of cotton the cotton core.

Table XXXI

Results of fabric weight and thickness.

Fabric	Weight (g/m^2)	Thickness (mm)
100% Polypropylene	88.156 [a]	0.607 [a]
40:60 cotton:polypropylene	83.748 [a]	0.551 [b]
60:40 cotton:polypropylene	88.495 [a]	0.589 [a]
80:20 cotton:polypropylene	84.069 [a]	0.610 [a]
100% polyethylene	44.42	0.127

Note. Means in the same column (for each volume) with the same superscript are not significantly different at $p < 0.05$.

Breaking Load and Elongation

The results of breaking load and elongation are given in Table XXXII. The results indicate that the breaking load in general was greater in the machine direction of the fabrics than in the cross direction. However, in case of the 100% polyethylene, breaking load was greater in the cross direction than in the machine direction. On increasing the cotton content from 40% to 80%, it was observed that there was a decrease in the breaking load. The 100% polyethylene had the greatest breaking load.

Breaking elongation in general did not follow a trend opposite to breaking load as might have been expected. In the machine direction of the fabric, breaking elongation decreased as the cotton content was increased from 40% to 80%. In the cross direction, breaking elongation increased when the cotton content was increased from 40% to 60% but decreased when the cotton content increased from 60% to 80%. For the 100% polyethylene, breaking elongation was greater in the cross direction of the fabric than along the machine direction the fabric.

Tear Strength

The results for tearing strength are given in Table XXXIII. Tear strength was found to decrease on increasing cotton content from 40% to 80%. Tear strength was less in the cross direction of the fabric as compared to the machine direction of the fabric, except for the 100% polyethylene where the results were reversed. Tear strength of the 100% polypropylene was greater than any of the cotton laminates, but was less than that of the 100% polyethylene.

Table XXXII

Results of tensile strength and breaking elongation in the machine direction (MD) and coss direction (CD).

Fabric	Tensile Strength MD (gf)	CD (gf)	Breaking Elongation MD %	CD %
100% polypropylene	2180	1700	11.28	38.83
40:60 cotton:polypropylene	2520	1290	10.07	17.7
60:40 cotton:polypropylene	1840	1080	13.54	26.22
80:20 cotton:polyproylene	1090	700	9.20	25.35
100% polyethylene	4890	5160	6.08	11.63

Table XXXIII

Results of tear strength in the machine and cross directions.

Fabric	Tear Strength MD (gf)	CD (gf)
100% polypropylene	570	470
40:60 cotton:polypropylene	430	250
60:40 cotton:polypropylene	360	350
80:20 cotton:polypropylene	320	320
100% polyethylene	1590	2180

Stiffness

The results for stiffness are given in Table XXXIV. Stiffness was found to be greater in the machine direction of the fabric than in the cross direction of the fabrics except for the 100% polyethylene. Stiffness decreased on increasing the cotton content from 40% to 80%. The 100% polyethylene was less stiff than the other fabrics.

Table XXXIV

Results of Stiffness in the Machine Direction (MD) and in the Cross Direction (CD).

Fabric	Stiffness (mg.cm) MD	Stiffness (mg.cm) CD
100% Polypropylene	2.52	1.51
40:60 cotton:polypropylene	3.09	1.33
60:40 cotton:polypropylene	2.52	1.05
80:20 cotton:polypropylene	1.51	0.87
100% polyethylene	0.57	0.61

CHAPTER VI

SUMMARY, CONCLUSIONS AND IMPLICATIONS

Summary

The objectives of this research were: (1) to compare pesticide and water/surfactant penetration and retention of test fabrics using capillary penetration at three volumes, (2) to determine the effects of pressure on water/surfactant penetration and retention of the test fabrics at three volumes, (3) to determine the effects of impact on water/surfactant penetration of the test fabrics, (4) to determine the effects of wetting (drop absorbency) and wicking of the test fabrics using water, water/surfactant and pesticide (5) to determine the air permeability, water and oil repellency of the test fabrics, and (6) to characterize the test fabrics for physical/mechanical properties.

In the analysis of the first objective, capillary penetration and retention of the pesticide was measured by extracting the pesticide from the fabric or the substrate (standard blotter paper), and determining the concentration of the extract using gas chromatography. Results from preliminary testing indicated that capillary penetration of a liquid depended upon the ability of the liquid to wet a fabric surface. Since, distilled water (surface tension 73.2 dynes/cm) did not wet the fabric surface of four out of five of the fabrics, the surface tension of distilled water was lowered to the level of the surface tension of the pesticide solution (32.8 dynes/cm) by adding a nonionic surfactant (Triton X 100, surface tension 32.5 dynes/cm). Capillary penetration and retention for water/surfactant was determined by measuring the weight change of the substrate and the fabric. Statistical analysis done on the data was ANOVA followed by post hoc Duncan's Multiple Grouping.

In the analysis of the second objective, a pressure of 1 psi was applied on the water/surfactant solution, after it was dropped on the fabric surface from a height of 1 cm. The amount of penetration and retention of water/surfactant was calculated by determining the change in weight of the substrate. MANOVA was carried out on the data obtained from the penetration and retention of water/surfactant using capillary and pressure penetration test methods, to see if there was a significant difference between capillary and pressure penetration.

In the analysis of the third objective, impact penetration of the fabric was measured after 500 ml of water/surfactant was dropped on the fabric surface from a height of two feet. The change in weight of the substrate (blotter paper) was used as a measure of impact penetration.

In the analysis of the fourth objective, wetting and wicking responses of the fabrics was measured using distilled water, water/surfactant, and pesticide. Wetting was measured using the drop absorbency test. In order to measure wicking, the fabrics were marked at 1 cm intervals, and were weighted down using a sinker. The fabrics were then immersed 1 cm in the liquid and the distance moved up by the liquid was recorded after 1, 5, and 10 minutes.

Differences between the wetting responses of the fabrics was determined by Analysis of Variance. A General Linear Model (GLM) was used to determine the effect of fabric (all the test fabrics), liquid, (water, pesticide and water+surfactant) position (length and width) and their interactions on the wicking response of the fabrics. Linear contrasts were done between distilled water and water/surfactant, and water/surfactant and liquid-pesticide, in order to determine the effect of surface tension on wicking.

In the analysis of the fifth objective, air permeability, water repellency (spray test and static absorption) and oil repellency were measured using standard ASTM and AATCC test methods. ANOVA was used to determine if there were significant differences in the air permeability and the static absorption values for the test fabrics. The results of air permeability were related to the capillary and impact penetration of the pesticide solution. The result of the water repellency tests were related to the capillary penetration of the pesticide solution.

In the analysis of the sixth objective, standard ASTM test were used to measure fabric weight, thickness, breaking load and elongation, tear strength and stiffness. Measurements were made in the machine as well as cross directions of the fabrics, for breaking load and elongation, tear strength, and stiffness.

Conclusions

Twelve research hypotheses were formulated based on previous research and the theoretical framework. Below is a summary of the results for each hypothesis.

Research hypothesis 1 was that in the capillary penetration of the pesticide solution, the 100% polypropylene would show the greatest amount of penetration, and trilaminates with increasing cotton content would show less capillary penetration taking place. An increase in the volume of the pesticide was expected to increase penetration.

Research hypothesis 1 was not supported by the results. It was found that the 100% polypropylene fabric did not offer the least resistance to penetration by the pesticide solution. Increasing cotton content did not result in an decrease in the penetration of the pesticide or water/surfactant solutions. It was found that the 80:20 cotton:polypropylene fabric exhibited the least resistance to penetration by the pesticide solutions. On increasing volume, it was found that there was an increase in the penetration of the pesticide solution.

Research hypothesis 2 proposed that, in the capillary penetration of the water/surfactant solution, the 100% polypropylene would show the greatest amount of penetration, and increasing cotton content would result in less capillary penetration taking place. An increase in volume was expected to increase penetration. A high degree of correlation was expected between the penetration values for the pesticide and the water/surfactant solutions.

Research hypothesis 2 was not supported by the results. It was found that the 100% polypropylene fabric did not offer the least resistance to penetration by the water/surfactant solution. The 80:20 cotton:polypropylene fabric exhibited significantly greater penetration than the other fabrics at higher volumes. In general an increase in volume resulted in an increase in the amount of penetration of the water/surfactant. In comparing the capillary penetration of the pesticide to the water/surfactant, a reasonably high degree of correlation found at low volumes.

Research hypothesis 3 was that in the retention of the pesticide solution on the test fabrics, the 100% polypropylene would show the least amount of retention of the pesticide solution and increasing cotton content would result in more pesticide being retained by the fabrics. An increase in volume was expected to result in an increase in the amount of pesticide retained by the fabrics.

Research hypothesis 3 was not supported. It was found that the 80:20 cotton:polypropylene fabric retained significantly less pesticide solution when compared to the other fabrics. The 100% polypropylene did not perform significantly differently from the

40:60 and 60:40 trilaminates. However, on increasing volume, there was an increase in the amount of pesticide retained by the fabric. In comparing the results of retention of the pesticide in the fabric to the amount of penetration of the pesticide to the underlying substrate, it was found that an increase in the retention of the pesticide on the fabric resulted in a decrease in the amount of pesticide that penetrated to the substrate.

Research hypothesis 4 proposed the 100% polyethylene would show the greatest amount of retention of the water/surfactant solution and increasing cotton content would result in more water/surfactant retained by the fabrics. With increasing volume, there will be an increase in the amount of water/surfactant retained by the fabrics.

Research hypothesis 4 was not supported. It was found that there were no significant differences in the retention values for the test fabrics. When volume increased, there was an increase in the amount of water/surfactant retained by the fabrics. On comparing the results for the retention of water/surfactant to the amount of penetration of the water/surfactant to the underlying substrate, it was found that even though there were significant differences in the penetration values of the water/surfactant, there were no significant differences in the retention values of the water/surfactant.

Research hypothesis 5 was that in the pressure penetration of the water/surfactant, there would be no significant difference in the penetration values of the 100% polypropylene and the cotton laminates. An increase in the cotton content from 40% to 80% was not expected to show significant differences in the penetration values of the water/surfactant. An increase in volume was expected to increase the penetration of the water/surfactant for pressure penetration.

Research hypothesis 5 was not supported. Significant differences were found between the fabrics. An increase in volume from 100 to 300 μl resulted in a significant difference in pressure penetration, but an increase in volume from 300 to 500 μl did not result in an increase in penetration.

Research hypothesis 6 was that in the retention of water/surfactant for pressure penetration, there would be no significant difference in the retention values of the 100% polypropylene and the cotton laminates. An increase in the cotton content from 40% to 80% would result in no significant difference in the penetration values of the water/surfactant. An increase in volume was expected to increase the penetration of the water/surfactant for pressure penetration.

Research hypothesis 6 was only partly supported. At low volumes there were no significant differences in the retention of the water/surfactant but at higher volumes the 80:20 cotton:polypropylene fabric exhibited lower retention than the other fabrics. On increasing volume the amount retained by the fabrics did increase.

Research hypothesis 7 was that there would be an increase in the amount of water/surfactant penetrating through the fabrics for pressure penetration as compared to capillary penetration.

Research hypothesis 7 was not supported. There were no significant differences in the capillary and pressure penetration of the water/surfactant solution for the fabrics. Neither penetration nor retention were found to be significant based on the method of penetration (capillary vs. pressure).

Research hypothesis 8 was that in comparing impact penetration for the fabrics, the 100% polyethylene fabric would show the least penetration. There would be no significant difference in the amount of impact penetration for the 100% polypropylene and the cotton laminates.

Research hypothesis 8 was partly supported. It was found that the 100% polyethylene fabric, offered significantly greater resistance to impact penetration than the other fabrics. It was found that there were no significant differences in the impact penetration values of the cotton laminates, but there were significant differences in the impact penetration values for the 100% polyethylene fabric and the cotton laminates.

Research hypothesis 9 proposed that there would be no significant difference in the fabrics in terms of the wetting times as measured by the drop absorbency test.

Research hypothesis 9 was not supported. It was found that the 80:20 cotton:polypropylene fabric had the fastest rate of wetting (lowest wetting time) while the 100% polyethylene fabric did not wet at all for all three test liquids.

Research hypothesis 10 proposed that there would be a significant difference in the distance wicked by the fabrics when distilled water is compared to the water/surfactant or the pesticide solution. However, there will be no significant difference in the distance wicked by the fabrics when comparing the water/surfactant to the pesticide solution.

Research hypothesis 10 was mostly supported. It was found that 100% polyethylene fabric exhibited no wicking of any of the solutions. There were no differences in wicking response for all the fabrics (except the 100% polypropylene) when comparing the water/surfactant to the pesticide solution, but there were significant differences in the wicking response of all the fabrics on comparing water/surfactant to the distilled water.

Research hypothesis 11 proposed that the 100% polyethylene fabric will have the lowest air permeability and increasing cotton content may result in an increase in the air permeability of the fabrics.

Research hypothesis 11 was partly supported. It was found that the 100% polypropylene fabric had the lowest air permeability, and an increase in the cotton content led to an increase in the air permeability of the fabrics.

Research hypothesis 12 proposed that an increase in the cotton content would result in an increase in the static absorption of the laminates. An increase in the cotton content will result in no difference in the water and oil spray rating of the fabrics.

Research hypothesis 12 was partly supported. It was found that increasing cotton content in the trilaminates did result in an increase in the static absorption. While differences were found in the water spray ratings of the fabrics, no differences were found in the oil spray ratings of the fabrics except for the 100% polyethylene fabric, which had the highest oil spray ratings, among the fabrics tested.

Implications

This research examined the liquid transport phenomena through nonwoven fabrics. It was found in this research that an increase in the cotton content resulted in an increase in the penetration of the pesticide, which was contrary to the findings on woven fabrics. Therefore, it is possible that the structure of the nonwoven fabrics may have a significant effect on the way the pesticide penetrates through the fabric. In this research only a few variables such as fiber content and volume of pesticide were considered. It is possible that other pesticide, fabric structure, and procedural variables may influence the penetration of the pesticide through the fabrics. These would need to be investigated more closely in the light that penetration through nonwoven fabrics occurs differently from those of woven fabrics.

It is hypothesized that there may be an interaction (physical/chemical reaction) between the pesticide and the fibers of the fabric, causing the pesticide to be adsorbed/absorbed to a greater extent on the polypropylene fibers than the cotton fibers. In order to fully understand the nature of the interaction of the pesticide with the fibers, it is suggested that the enthalpy change (ΔH) be determined for the interaction between the pesticide and polypropylene, and cotton fibers. From the measurements of ΔH, it can be determined if the pesticide had a preferential attraction for the polypropylene fibers over the cotton fibers or if there were certain other variables that may have caused there to be a difference in the amount of capillary penetration of the liquid pesticide on changing the cotton content.

Surface tension of a pesticide solution can determine if it will wet a fabric surface or not. It was found that if the fabric surface were not wettable, then there was virtually no penetration taking place. This suggests that the surface free energy of the fabrics be lowered by the application of some kind of fluorochemical finish.

Interfiber capillary radius was found to be important in determining the wetting and wicking responses of the fabrics. Raheel and Gitz (1985) applied the Washburn (1921) equation to the drop absorbency test which was used to measure wetting of fabrics. They concluded that a faster wetting rate is associated with a larger capillary radius. In this research it was found that the 80:20 cotton:polypropylene fabric had the fastest wetting rate, and therefore should have been associated with the largest capillary radius, if we are to assume the relationship suggested by Raheel and Gitz (1985). The air permeability of the 80:20 cotton:polypropylene fabrics was also significantly greater than the other laminates. From the research of Wehner et al. (1987) it also seems likely that the 80:20 cotton:polypropylene fabric would have the largest interfiber capillary radii. It is suggested that pore size measurements be done using a Porometer to establish that the 80:20 cotton:polypropylene fabric does indeed, have a greater interfiber capillary radius.

Raheel and Gitz (1985) found that an increase in interyarn capillary radius resulted in an increase in the wicking of the pesticide through fabrics. By their argument, the 80:20 cotton:polypropylene should exhibit the least amount of wicking and therefore, penetration of the pesticide. However, it was found that the 80:20 cotton:polypropylene fabric exhibited significantly greater amounts of wicking as compared to the other fabrics. Therefore, the results found in this research are contrary to those found by Raheel and Gitz. Further research is needed to investigate the relationships between wettability, wickability, and liquid penetration of textiles to determine whether the relationships proposed by Raheel and Gitz apply to a variety of fabric structures.

In general, this study indicates that the effects of adding a cotton core to nonwovens may or may not contribute the assumed benefits of cotton. However, these results should be considered in concert with studies being done by other members of the regional research project.

REFERENCES

AATCC (1992). In: Technical Manual of the American Association of Textile Chemists and Colorists, Research Triangle Park, NC: American Association of Textile Chemists and Colorists.

ASTM (1992). In: ASTM Annual Book of Standards, 15.07, Philadelphia, PA: American Society for Testing and Materials.

Bhat, S. A. and Perenich, T. (1990). Soiling and effectiveness of various dosimeter materials in pesticide penetration/retention studies on selected textiles. In: Book of Papers - 1990 International Conference and Exhibition, (pp. 29-33). Research Triangle Park, NC: American Association of Textile Chemist and Colorists.

Branson, D.H., Ayers, G.S., & Henry, M.S. (1986). Effectiveness of selected work fabrics as barriers to pesticide penetration. In: Barker, R.L., & Coletta, G.C.(Eds.), Performance of Protective Clothing, ASTM 900, (pp 114-120). Philadelphia, PA: American Society for Testing and Materials.

Branson, D.H. and Rajadhyaksha, (1988). Distribution of malathion on gore-tex fabric before and after sunlight exposure and laundering as determined by electron microscopy. In Mansdorf, S.Z., Sager, R., and Nielsen, S.P. (Eds.), Performance of Protective Clothing: Second Symposium, ASTM 989, (pp651-659). Philadelphia, PA: American Society for Testing and Materials.

Branson, D.H. and Sweeney, M. (1991). Pesticide personal protective clothing. Reviews of Environmental Contamination and Toxicology, 122, 81-109.

Cassie, A.B.D. and Baxter, S. (1944). Wettability of porous surfaces. Transactions of the Faraday Society, 40, 546-551.

Colbert, J.F. and May, M.A. (1985). Fluorochemicals-unique additives for nonwoven substrates. In Tappi Notes, 1985 Nonwoven Binders: Additives Chemistry and use Seminar, (pp29-34). Atlanta, GA: TAPPI press.

Chandler, J. and Zeronian, S.H. (1979). How finishes affect the moisture-related properties of cotton fabrics. Textile Chemist and Colorist, 11(3), 20-25.

Crouse, J.L., DeJonge, J.O., Calogero, F. (1990). Pesticide barrier performance of selected nonwoven fabrics in laboratory capillary and pressure testing. Textile Research Journal, 60, 137-142.

Davies, J.E., Enos, H.F., Barquet, A., Morgade, C., Peters, L.J., and Danauskas, J.X. (1982). Protective clothing studies in the field. Pesticide Residues and Exposure, 169-182.

Easter, E.P. and Nigg, H.N. (1992). Pesticide protective clothing. Reviews of Environmental Contamination and Toxicology, 129, 1-16.

Ehntholt, D.J., Bodek, I., Valentine, J.R., Schwope, A.D., Royer, M.D., Frank, U., and Nielsen, A.P. (1989). The effects of solvent type and concentration on the permeation of pesticide formulations through chemical protective glove materials. In Perkins, J.L. and Stull, J.O. (Eds.), Chemical Protective Clothing Performance in Chemical Emergency Response, STP 1037, (pp. 146-156). Philadelphia, PA: American Society for Testing and Materials.

Federal Register (1974) 39: 16888-16891.

Fox, H.W. and Zisman, W.A. (1950). The spreading of liquids on low energy surface I: polytetrafluoroethylene. Journal of Colloid Science, 5, 514-531.

Hobbs, N.E., Oakland, B.G., and Hurwitz, M.D. (1986). effects of barrier finishes on aerosol spray penetration and comfort of woven and disposable nonwoven fabrics for protective clothing. In Barker, R.L., & Coletta, G.C.(Eds.), Performance of Protective Clothing, ASTM 900, (pp 151-161). Philadelphia, PA: American Society for Testing and Materials.

Hoyle, A.G. (1989). Bonding as a nowoven design tool. Tappi Journal, 72(4), 109-112.

Kawase, T., Misono, K., Fujii, T., and Minagawa, M. (1990). Repellency of textile assemblies. Textile Research Journal, 60, 345-350.

Laughlin, J.M. (1986). Textiles and refurbishment: A human resources perspective. In Deacon, R.E. Huffman, W.E. (Eds.), Human Resources Research, 1887-1987 Proc. (pp 71-73). Ames: Iowa State University.

Laughlin, J.M., Easley, C.B., Gold, R.E., & Hill, R.M. (1986). Fabric parameters and pesticide characteristics that impact on dermal exposure of pesticides. In Barker, R.L., & Coletta, G.C.(Eds.), Performance of Protective Clothing, ASTM 900, (pp 136-150). Philadelphia, PA: American Society for Testing and Materials.

Laughlin, J.M., and Gold, R.E. (1989). Evaporation dissipation of methyl parathion from laundered protective apparel fabrics. Bulletin of Environmental Contamination and Toxicology, 42, 566-573.

Leonas, K.K., and DeJonge, J.O. (1986). Effect of functional finish barriers on pesticide penetration. In Barker, R.L., & Coletta, G.C.(Eds.), Performance of Protective Clothing, ASTM 900, (pp 177-186). Philadelphia, PA: American Society for Testing and Materials.

Leonas, K.K., Easter, E.P., and DeJonge, J.O. (1989). Effect of fabric characteristics on pesticide penetration through selected fabrics. Bulletin of Environmental Contamination and Toxicology, 43, 231-238.

Leonas, K.K. (1991). The mechanism of pesticide transmission through apparel fabrics: A comparison of drop and spray exposure methodologies. Archives of Environmental Contamination and Toxicology, 20, 427-431.

Lillie, T.H., Livingstone, J.M., and Hamilton, M.A. (1981). Recommendations for selecting and decontaminating pesticide applicator clothing. Bulletin of Environmental Contamination and Toxicology, 27, 716-723.

Lunenschloss, J. and Albrecht, W. (1985). Non-woven bonded fabrics. Sussex: Ellis Horwood Limited.

Maibach, H.I., Fieldman, R.J., Milby, T.W., and Serat, W.F. (1971). Regional variance in percutaneous penetration in man. Archives of Environmental Health, 23, 208-211.

Meirhoefer, A.W. (1987). Nonwovens for laminated and coated fabrics. Journal of Coated Fabrics, 16, 258-263.

Mecheels, J.J., Demeler, R.M., and Kachel, E. (1966). Moisture transfer through chemically treated fabrics. Textile Research Journal, 36, 375-384.

Miller, B. (1990). The penetration of liquids into fiber networks. In Rebenfield, L. (Ed.), Science and Technology of Fibers and Related Materials, (pp 403-415). New York, John Wiley and Sons.

Minor, F.W., Schwartz, A.M., Wulkow, E.A. and Buckles, L.C. (1959). The migration of liquids in textile assemblies. Textile Research Journal, 29, 931-939.

Minor, F.W., Schwartz, A.M., Buckles, L.C., Wulkow, E.A., Marks, M.P., and Fielding, G.H. (1961). The migration of liquids in textile assemblies. Part IV: Penetration of fabrics by liquids. Textile Research Journal, 31, 525-539.

Orlando, J., Branson, D., Ayers, G. and Leavitt, R. (1980). The penetration of formulated guthion spray through selected fabrics. Journal of Environmental Science and Health, B16(5), 617-628.

Raheel, M. and Gitz, E.G. (1985). Effect of Fabric geometry on resistance to pesticide penetration and degradation. Archives of Environmental Contamination and Toxicology, 14, 273-279.

Raheel, M. (1991a). Pesticide transmission in fabrics: Effect of particulate soil. Bulletin of Envronmental Contamination and Toxicology, 46, 845-851.

Raheel, M. (1991b). Pesticide transmission in fabrics: Effect of perspiration. Bulletin of Environmental Contamination and Toxicology, 46, 837-844.

Schwope, A.D. (1983). Chemical protective clothing. ASTM Standardization News, 11(7), 19-22.

Segal, L.S., Philips, F.J., Loeb, L., and Clayton, R.L. (1958). Oil and water repellent treatments for cotton with fluorochemicals. Textile Research Journal, 28, 233-241.

Shaw, D.J. (1980). Introduction to colloid and surface chemistry. London: Butterworths.

Shaw, A. and Hill, K.R. (1991). Effect of exposure time on the sorption of pesticide emulsifiable concentrates through microporus fabrics. Bulletin of Environmental Contamination and Toxicology, 46, 45-52.

Smith, P. (1988). Nonwoven products and processes. Textile Horizons, 8, (4), 27-36.

Staiff, D.C., Davis, J.E., Stevens, E.R. (1982). Evaluation of various clothing materials for protection and worker acceptability during application of pesticides. Archives of Environmental Contamination and Toxicology, 11, 391-398.

Washburn, E.W. (1921). Dynamics of capillary flow. Physical Review, Second Series, 17, 273-283.

Wagner, J.R. (1988). Nonwovens: The state of the art. Tappi Journal, 71(4), 115-121.

Webster's Ninth New Collegiate Dictionary (1988). Springfield, MA: Merrium-Webster Inc.

Wehner, J.A., Miller, B., and Rebenfeld, L. (1987). Moisture induced changes in fabric structure as evidenced by air permeability measurements. Textile Research Journal, 57, 247-256.

Wolfe, H.R., Durham W.F., and Armstrong, J.F. (1967). Exposure of workers to pesticides. Archives of Environmental Health, 14, (4) 622-633.

Worthing, C.R. (1979). The pesticides manual (6th ed). Suffolk: Lavenham Press.

VITA

Siddartha Sarin was born in New Delhi, India, on December 28, 1969. After graduating from Delhi Public School, R. K. Puram, New Delhi, India, he attended the Indian Institute of Technology, New Delhi, India, where he received his Bachelor's Degree in Textile Technology. For his baccalaureate thesis, he developed an algorithm for a dedicated software for the Instron 4202 Universal Tensile Tester. He also examined the structure-property relationships of silk fibers at various stages of degumming.

He came to the United States of America in Fall 1991 for his graduate study in Textile Science at Virginia Polytechnic Institute and State University. He worked as a graduate teaching assistant, and as a graduate assistant in the Department of Clothing and Textiles. he was a member of the Clothing and Textiles Graduate Student Assembly and served as the President of the Virginia Tech Chapter of the American Association of Textile Chemists and Colorists.

Siddartha Sarin