To the Graduate Council:

I am submitting herewith a dissertation written by Georgia Lizabeth Self entitled "Photodegradation of Thermally Bonded Polyester Nonwovens." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Home Economics.

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PHOTODEGRADATION OF THERMALLY BONDED POLYESTER NONWOVENS

A Dissertation

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Doctor of Philosophy

Degree

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Georgia Lizabeth Self

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ABSTRACT

Durable polyester nonwoven fabrics have a finite lifetime determined by a number of factors. Important among these is photodegradation, where prolonged exposure to sunlight causes damage to the chemical linkages of the polymers resulting in the loss of desirable characteristics.

The purpose of this study was to investigate the degradation resulting from exposure to the ultraviolet component of sunlight in terms of changes in molecular weight, polydispersity, and physical performance behavior of thermally bonded polyester nonwovens. Fabrics representative of the nonwoven interlining market were made according to an initial determination of optimal base/binder fiber composition and bonding conditions. Samples were exposed to ultraviolet light in the xenon-arc Weatherometer for 100 to 400 hours in 50 hour increments. Flexural rigidity, tenacity, and elongation were analyzed before and after exposure, and viscosity, gel permeation chromatography, and differential scanning calorimetry were measured after exposure to determine the effect of exposure to ultraviolet light on the nonwoven fabric.

Overall, a decrease in all average molecular weight averages and an increase in polydispersity were observed. Chain scission reactions appeared to predominate; however, some evidence exists to support a degree of crosslinking between 200 and 300 hours of exposure to ultraviolet light. Mechanical properties of flexural rigidity, tenacity, and

extension followed trends exhibited by molecular weight, decreasing overall.

Additional investigation is recommended to determine the contribution of base fiber, binder fiber and bond strength to the failure of mechanical properties. Longer exposure time periods are needed to more realistically assess damage, as well as investigations using layered systems such as draperies to more adequately reflect actual end use testing.

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CHAPTER I

INTRODUCTION

Within the past 30 years, nonwoven fabrics have become an integral part of contemporary life, largely as a result of such cost efficient benefits as absorbency, resilience, strength, flame retardancy, washability, and convenience. A variety of methods for producing nonwoven fabrics have been in existence for some time, and end uses for those products have expanded rapidly. Continued growth and development in the market have led to evaluation and characterization of the end use product in an attempt to improve performance without increasing the cost of production and use. The nonwoven product market is still young enough that characterization of product behavior in many cases is still underway.

In particular the response of durable nonwoven products to sunlight exposure has come under investigation. Exposure to sunlight is known to have a degradative effect on most natural fibers and the problem has not been overcome with the development of man-made fibers (Wall & Frank, 1971). The effect is particularly important for the performance of durable products, expected to function effectively over a period of time. In the case of nonwoven interlinings, the performance behavior greatly influences consumer satisfaction with the total apparel product. Degradation of the durable nonwoven interlining, a component of the garment, may well have a detrimental effect on the garment performance and on consumer satisfaction as well.

The term nonwoven is applied to fabrics that are made directly from fiber without the intermediate step of yarn preparation. A nonwoven fabric is defined as a textile structure produced by bonding and/or interlocking of fibers, accomplished by mechanical, chemical, thermal, or solvent means, and combinations thereof. Paper or fabrics constructed by weaving, knitting or tufting are not included in the definition (ASTM, 1980). Nonwoven fabrics may be produced through a number of processes, including dry-lay, wet-lay, spunbonded, spunlaced, solvent bonded, point bonded, needlepunched and apertured techniques. Each type of bonding has distinctive features that determine the shape, form and properties of the nonwoven product. With the exception of spunbonding which involves the production of fabric directly from the polymer, virtually all nonwoven fabrics undergo a rather standard sequence of steps. These include (a) preparation of the fiber, (b) web formation, (c) web bonding, and in some methods, (d) drying and curing (Britton, 1983; Joseph, 1984).

Nonwoven fabrics are typically classified as durable or disposable based on end use. Durable nonwovens are expected to function throughout the life of a continuous use product. Apparel interlinings and interfacings, geotextiles, and carpet backings are typical examples of durable nonwovens. Disposable nonwovens are used in or as products that are typically discarded after a single use, like diapers, filters, or medical/surgical nonwovens, or after several uses, like wiping cloths.

Nonwoven fabrics have experienced phenomenal growth over the past ten years not only within established markets but also in

additional new markets. In 1984, $1.56 billion in nonwoven products were consumed in the United States, up over the $585 million consumed in 1974. Of this, $870 million was fabric used in disposable applications and $690 million in durable end uses. Durable nonwoven fabrics' sales expanded at a 7% average while nonwovens for disposable applications grew at a 14% annual rate between 1974 and 1984. Nonwoven consumption growth is currently forecast at 11% per year through 1990. Disposables and durables are expected to grow at about the same rate, with the growth outlook varying among end use applications. The fastest growing major application is predicted to be geotextiles and roofing, while the slowest growing major end use will be carpet components and interlinings. Currently, nonwovens are approaching a two-thirds penetration of the apparel interlining market compared to perhaps 40% ten years ago. In terms of dollars, durable nonwoven consumption in interlinings applications totaled $115 million in 1984, up over $65 million in 1975.

Currently, thermally bonded nonwoven products represent 10% of the total nonwovens market. Thermally bonded nonwovens are desirable due to (a) ease of production, (b) performance characteristics comparable to 100% cotton products, (c) reduced capital equipment leading to increased productivity, and (d) versatility involved in the capability to obtain a greater range of end products from the same equipment line. The thermal bonding process is only about ten years old in the United States, and it is desirable in that it does not present environmental problems like chemical content in water, effluents in air,

and high energy or water consumption. Thermally bonded nonwovens producers can shop competitively for fibers. By 1990, dry staple processes including thermally bonded processes are expected to hold 19% of the total nonwovens market (Trueman, 1985).

In the durable nonwovens market, progress is primarily technology-driven. Wovens, knits, and other substrates are replaced by nonwovens because they can be engineered to provide a superior cost/performance match to end use requirements. The convenience of use factor present in the disposable business is not applicable to the durable product market.

The substitution of nonwovens in some important durable end use applications has been quite slow due to the lack of technology to provide materials with the necessary cost advantages or performance superior to wovens or knits. For example, nonwovens still do not have the required performance level to be used as interlinings in the more expensive suits, coats, and dress shirts as well as a number of home furnishings applications. In addition, durable nonwoven usage is subject to changes in general economic activity. The volume of materials shipped into home furnishings, apparel and automotive end uses has fluctuated as these businesses have fluctuated (Starr, 1984).

Until recently, nearly all carded nonwovens were made from staple rayon fiber. However, in the 1970s the nonwoven industry enjoyed substantial growth. Staple rayon capacity was not increasing and production had started to decline. In contrast, polyester staple increased tenfold in capacity. The nonwoven consumption of polyester staple

increased noticeably in the early 1970s, primarily due to the use of polyester in durable nonwoven applications.

The initial motivation for the use of polyester fibers in the disposable carded nonwovens was due to a concern that there would be an insufficient rayon supply to meet the growing requirements of the nonwoven industry. The second major incentive for using polyester fiber was the projected short term pricing parity with rayon, and polyester's anticipated long term price advantage over rayon due to technical advances that resulted in a reduced cost of manufacture for polyester.

In apparel interlining applications, polyester has several advantages over rayon. Most properties are retained when wet, and the greater break elongation allows for conformability in use. Polyester's low hot water shrinkage is a major advantage for its use in interlinings, and increased thickness and flexibility over rayon give the perception of greater softness (Brown, Plant, & Vanderselt, 1978).

Like all synthetic polymeric materials, durable polyester nonwovens have a finite lifetime determined by a number of factors. Important among these is photodegradation, where prolonged exposure to sunlight causes damage to the chemical linkages of the polymers resulting in loss of desirable characteristics (Horsfall, 1981). Because interlinings and interfacings must last through the entire life of the garment, they must be durable and able to withstand washing and drycleaning. A balance of several other properties is additionally important. These include tensile and tear strength, drape, abrasion

resistance, dimensional stability to wear, and sewability. A loss in any of these desirable characteristics would increase consumer dissatisfaction with the product.

It is the purpose of this study to examine the influence of exposure to ultraviolet light on the physical performance and chemical nature of thermally bonded polyester nonwoven fabrics suitable for use in apparel interlinings or interfacings.

I. OBJECTIVES

1. To determine the effects of exposure to ultraviolet light at 121°F (49°C) and 58% relative humidity on the physical performance behavior of thermally bonded polyester nonwoven fabrics.

2. To determine the effects of exposure to ultraviolet light on the molecular weight and the polydispersity of the polyester fiber in the thermally bonded nonwoven product.

3. To predict the exposure time length at which the mechanical properties of the nonwoven fabric are adversely affected due to degradation by ultraviolet light.

II. HYPOTHESES

1. There will be a significant difference in the physical performance behavior of thermally bonded polyester nonwoven fabrics before and after exposure to ultraviolet light.

2. There will be a significant difference in the molecular weight and polydispersity of the polyester fiber in the thermally bonded nonwoven product before and after exposure to ultraviolet light.

III. ASSUMPTIONS

1. The polyester staple base and binder fibers used are representative of those used in commercial manufacturing.

2. The equipment and instrumentation used provide valid methods for processing and testing the nonwoven fabrics.

3. The thermally bonded polyester nonwovens produced and tested are representative of those used in consumer textile and apparel products.

4. Little information is available concerning the degradation behavior of thermally bonded polyester nonwoven fabrics.

IV. LIMITATIONS

Based on recommendations of Wyatt (1980):

1. Only one base/binder fiber combination is used.

2. The concentration of thermoplastic binder fiber is limited to 30% by weight of binder to base fiber.

In the preliminary portion of this study:

3. The optimum bonding time was determined to be and thus is limited to 30 seconds; bonding temperature is limited to 111.11 lbs/in^2 (765.55 kPa).

4. The optimum bonding temperature was determined to be and is limited to 375°F (190°C).

5. Exposure times are limited to six: 100 hours, 200 hours, 250 hours, 300 hours, 350 hours, and 400 hours.

V. DEFINITIONS

Unless otherwise indicated, all definitions are found in the INDA "Guide to Nonwoven Fabrics" (1978).

Base fibers: Fibers that compose the main structure of the nonwoven web (Guide, INDA, 1978).

Binder fibers: Fibers having a relatively low softening point compared to other fibers in the web, and which, upon application of heat and pressure, act as an adhesive.

Bonding: The process of combining fibers into sheets, webs or battings by means of adhesives, plastics, entanglement or heat.

Carding: A process in the manufacture of fibrous webs in which the staple is opened, cleaned, aligned and formed.

Cross direction: The axis perpendicular to the nonwoven's motion in the final forming step, and within the plane of the substance.

Machine direction: The axis parallel to the nonwoven's motion in the final forming step, and within the plane of the substance.

Thermally bonded fabric: A nonwoven formed of a base fiber and a thermoplastic fiber. The web is hot-calendared or embossed at the softening point of the thermoplastic fiber to form the interfiber bonds.

Photodegradation: Damage to the chemical linkages of polymers upon prolonged exposure to ultraviolet light (Horsfall, 1981).

CHAPTER II

REVIEW OF LITERATURE

I. POLYESTER

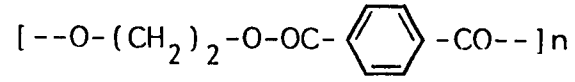
Polyester are defined as "organic polymers of regular linear structure characterized by the possession of repeat units of ester groups forming integral components of the backbones of the molecular chains" (Hillier, 1967). The general formula can be written as

$$[--O-R-O-OC-R'-CO--]n \quad \text{or} \quad [--O-R-CO--]n$$

Polyesters were the first polymers to be described in the classical work of Carothers. However, as fiber forming materials, the early polyesters that Carothers made suffered from two defects. They were too readily hydrolyzed and lacked the chemical stability characteristic of nylon. The chains were not rigid enough to form crystalline structures with a high degree of intermolecular bonding. In addition, their melting points were too low to resist normal ironing temperature used by consumers (Moncrieff, 1975).

Polyesters having worthwhile properties were discovered in Whinfield's investigation of the special properties of the polyester based on terephthalic acid (Hillier, 1967). Whinfield found that the inclusion of an aromatic nucleus in the chain increased the chemical stability and raised the melting point (Moncrieff, 1975). The resonance behavior of the aromatic nucleus lowers the energy and stabilizes the molecule. In addition, the aromatic nucleus allows for better

packing and improved bonding. The structure of Whinfield's aromatic polyester has the following formula:



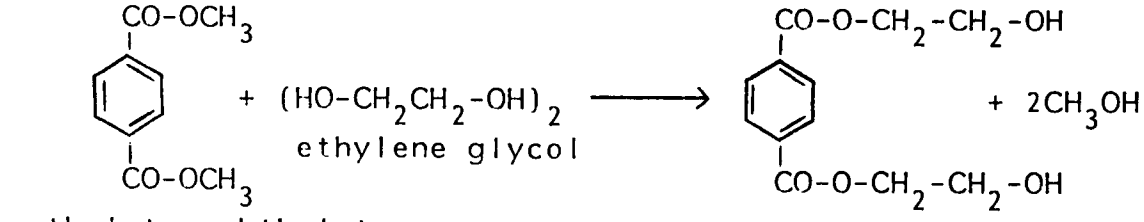
Synthesis of Polyethylene Terephthalate

Polyester is manufactured by mixing dimethyl terephthalate with a slight excess of ethylene glycol, heating to 150°C to 210°C, and adding a suitable catalyst such as sodium or magnesium methoxide or zinc borate (Trotman, 1975). Catalysts are added to promote both ester interchange and polymerization. They are usually added together at the beginning of the ester interchange reaction when uniform dispersion is easiest (Hillier, 1967).

A small amount of titanium dioxide is commonly added to deluster the fibers. The amount added varies with the degree of dullness desired. About 0.5% is sufficient for a normal, dull fiber. Titanium dioxide is added carefully to prevent aggregation of the delustrant particles during polymerization. Such aggregation hinders extrusion.

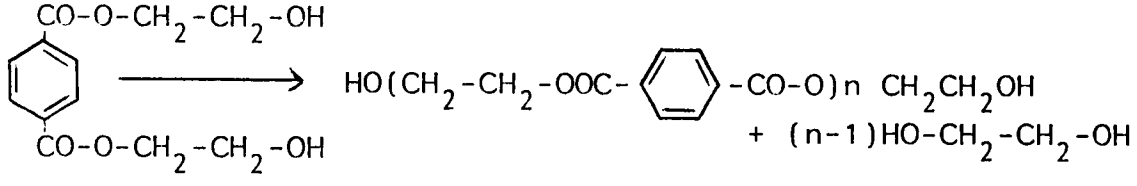
Phosphorus compounds may also be added to inactivate the ester interchange catalysts at the end of that reaction or to prevent their deposition as insoluble salts of terephthalic acid (Hillier, 1967).

The synthesis of polyethylene terephthalate proceeds by a reversible ester exchange which goes to completion by removal of the methanol through a fractionating column (Trotman, 1975):



methyl terephthalate

Only a small degree of polymerization takes place during this reaction. The monomer is transferred to an autoclave and the temperature is raised to 280°C. Condensation takes place as follows:



The removal of ethylene glycol is facilitated by the reduction of the autoclave pressure to below 0.1 mm Hg. The viscosity of the mixture rises as polymerization proceeds. Upon the completion of polymerization, the molten product is removed from the autoclave in a thin stream. It is cooled, broken into chips, and packed in sealed containers (Hillier, 1967; Trotman, 1975).

Polymer Properties

If quenched quickly from the melt stage, polyethylene terephthalate is an amorphous, glassy solid having a density of 1.33 g/cc. Upon heating, a second-order transition is observed at 67°C, and above 100°C crystallization occurs, reaching a maximum rate above 180°C. At this point the polymer becomes opaque, and with further heating, melting occurs at 260°C. The density of the crystalline

polymer will increase with an increasing degree of heat treatment of the sample (Hillier, 1967).

Daubeny, Bunn, and Brown (1954) evaluated the crystal structure of polyethylene terephthalate from x-ray diffraction studies. The unit cell is triclinic, and the molecular chains extend almost fully along the carbon axis. The repeat distance is 10.75 Å, compared to 10.9 Å calculated for a fully extended chain. The chains are slightly tilted with respect to the fiber axis. The aliphatic parts ($-CH_2-CH_2-$) adopt a trans configuration, and the packing of the molecules is very tight. The chains are arranged so that aromatic rings and other structural elements lie on a plane perpendicular to the fiber axis.

Polyethylene terephthalate is insoluble in most solvents. However, chloroform will dissolve the amorphous material at temperatures below 0°C. Crystalline material will reprecipitate if the solution is warmed to room temperature (Hillier, 1967).

Fiber Manufacture

Fibers of polyethylene terephthalate are made by melt spinning (Trotman, 1975). Two features distinguish polyester from the manufacture of other synthetic fibers by melt extrusion. Extremely dry conditions are necessary during extrusion, because at the temperature of the melt the rate of hydrolytic degradation is high. In addition, the viscosity of the molten material is high, requiring higher pressures in the region above the spinneret and resulting in the extrusion of a more rigid filament (Hillier, 1967). The emerging filaments are quite

unoriented, weak, and capable of being stretched four to five times their length (Trotman, 1975).

Properties of Polyethylene Terephthalate Fiber

The properties of polyester fiber are dependent upon the molecular weight of the polymer and the conditions under which the yarn is manufactured. A wide range of yarn properties can be achieved by altering the drawing route of the initial amorphous melt-spun yarn (Hillier, 1967).

The tenacity and elongation at break can be varied over a considerable range by controlling the draw ratio. High tenacity, normal tenacity and staple fiber are all made from the same polymer drawn to different degrees after spinning. Generally, highly oriented (high draw ratio) yarns exhibit the highest tensile strength. This property also increases with increases in the average molecular weight of the polymer (Hillier, 1967). The highly drawn yarn usually results in lower elongation capabilities. Thus, higher tenacity yarn is drawn to a greater extent than normal tenacity yarn. Fibers intended for use as staple are usually drawn less than the continuous filament to allow for higher extensibility in the product (Moncrieff, 1975).

Hillier (1967) reports that the tensile properties of polyethylene terephthalate yarns are maintained after prolonged periods of heating. A 22% strength loss was found after 64 hours heating in air at 175°C. The heat shrinkage is linearly related to temperature, being about 4% for a highly drawn yarn at 100°C and 16% at 200°C. Tenacity has

been found to be little affected by relaxation temperatures as high as 200°C. However, load extension behavior is modified, initial modulus is reduced, and extensibility is increased after such heat relaxation. The load/extension properties are much less affected as the yarn is held to a fixed length or subjected to small stretch during the heat treatment.

Polyester fibers absorb very small amounts of water, and the regain at 65% RH and 20°C is 0.4% (Hillier, 1967; Trotman, 1975). Even at 100% RH the moisture regain is only 0.6 to 0.8% (Moncrieff, 1975). Moisture has been found to have very little effect on the mechanical properties of this fiber. However, the low moisture regain is conducive for producing undesirable static electricity (Moncrieff, 1975).

Polyester fibers have immediate and/or delayed recovery from stretch, compression, bending shear, and wrinkling. The initial modulus of polyester is high (Moncrieff, 1975), higher than almost all other fibers (Hillier, 1967). This has been ascribed to the high bending rigidity of the fiber. The fiber exhibits nonlinear and time-dependent elastic behavior. Creep will occur under load with delayed recovery upon removal of the load.

Polyester fibers have a specific gravity of 1.38. When compared to rayon (1.54), polyester provides 10 to 14% greater coverage at equal denier and opacity (Mayer, 1973). Amorphous fibers exhibit lower density than highly oriented crystalline fibers. The density of amorphous polyester is 1.33 g/cc. This density increases with

orientation and crystallinity to values of 1.38-1.40 g/cc. The density of a perfectly crystalline polyester has been calculated to be 1.455 g/cc. In general, the better the packing of the molecules, the higher the density (Moncrieff, 1975).

The effects of chemical reaction that may occur with polyester are likely to be very specific depending on the reagent and on the structure of the fiber undergoing the reaction (Hillier, 1967). Hydrolysis is a key reaction, with a rapid attack by water occurring at elevated temperature.

Polyester exhibits good resistance to weak acids even at the boiling temperature, to strong acids at cold temperatures, to weak alkalies, and to oxidizing agents such as bleaches. It is less resistant to strong alkalies (Moncrieff, 1975). There are two modes of attack by alkalies. Substances such as caustic soda, sodium silicate, etc., attack only the surface of the fiber and have no effect on the strength of the fiber with the exception of loss due to dissolution of the fiber surface. Ammonia and organic bases do penetrate the structure and degradation produces general strength loss (Hillier, 1967). Most alcohols, ketones, soaps, detergents and drycleaning agents do not react chemically with polyester (Moncrieff, 1975).

Polyester is soluble in hot m-cresol, trifluoroacetic acid, ortho-chlorophenol, a mixture of 7 parts of trichlorophenol and 10 parts (by weight) of phenol, and a mixture of 2 parts of tetrachloroethane and 3 parts (by weight) of phenol (Moncrieff, 1975).

Polyester fibers decompose when they melt in air and thus the melting point depends somewhat on the method of measurement. Polyester melts on the average at about 250°C. Sticking temperature occurs at 205°C (Moncrieff, 1975).

Polyester exhibits good resistance to biological attack. The fiber loses strength when exposed to light for long periods, primarily due to absorption of light in the near ultraviolet range (300-330 nm). Resistance to full sunshine is fairly good, while resistance behind glass is excellent. A marked decrease in tensile strength and elongation occurs upon irradiation with γ-rays from cobalt 60. There appears to be no crosslinking induced and little or no hydrogen is evolved.

Generally, polyester does not propagate a flame, due to local melting of the fabric which drops away. However, in blends which do support a flame, polyester is combustible (Moncrieff, 1975).

Polyester Fibers for Nonwovens

Polyester currently makes up to 25 to 27% of the total fiber going into nonwoven fabrics in the United States (Joseph, 1984). The initial motivation for the use of polyester fibers in disposable carded nonwovens was due to a concern that there would be an insufficient rayon supply to meet the growing requirements of the nonwoven industry. Polyester's anticipated long-term price advantage over rayon, largely due to technical advances, was the second major incentive for using polyester fiber (Brown, Plant & Vanderselt, 1978; Seidel, 1978).

The nonwoven consumption of polyester staple increased noticeably in the early 1970s, primarily due to the use of polyester in

durable nonwoven applications. Substantial use of polyester in the disposable nonwoven sector began in the mid 1970s and was largely responsible for polyester's success in the nonwovens industry (Brown, Plant, & Vanderselt, 1978; Seidel, 1978). More recently, polypropylene has dominated the thermal bonding market, but the polyester fiber producers have made great strides in using the same thermal method to produce a better nonwoven product of polyester.

Polyester fiber is usually sold to nonwovens manufacturers as a staple product in various deniers from 1.5 to 5, and in staple lengths of 1.5 to 4 inches. In nonwovens applications, polyester has a number of advantages over other synthetic fibers. The primary advantages of polyester include strength and an ability to meet certain medical requirements for sterilization.

Products with much higher thickness can be attained with the use of polyester fiber, due to the fiber's reduced wettability and higher wet modulus. Both properties aid in retention of crimp during processing.

The elongation of adhesively bonded polyester nonwovens is considerably greater than that of many other nonwovens. Compared to a representative rayon nonwoven, a polyester nonwoven has twice the elongation value. Polyester's toughness is significantly greater than a comparable rayon product as a result of both higher tenacity and elongation.

A major consideration for use in interlinings is shrinkage behavior. The low hot-water shrinkage for the polyester nonwoven is a

primary advantage for its use in apparel. In addition, increased thickness and flexibility add to the softness of the product. Polyester is measurably and noticeably whiter than rayon.

The wicking characteristics and the ability to control wetting give the polyester nonwoven a major advantage over other synthetic fibers. Polyester also maintains its fiber spacing in the presence of water. The polyester nonwoven can be designed to allow liquid to pass through without allowing the liquid to wick back into the fabric (Brown, Plant, & Vanderselt, 1978).

The greatest problem with regard to the use of the polyester nonwoven in apparel end uses is the lack of resiliency (Brown, Plant, & Vanderselt, 1978). The highly restricted fiber mobility and bond rotation lead to high bending rigidity and stiffness in the nonwoven product (Textile Industries, 1978).

II. THERMAL BONDING

Bonding in nonwoven fabrics can be achieved in a variety of ways, perhaps the oldest of which is evidenced by the felting of animal protein fibers exposed to heat, moisture, and pressure. That process has been developed and modified until, today, practically any textile fiber can be bonded into a cohesive web structure through any one or more of the following processes: adhesive bonding, spunbonding, wet bonding, mechanical bonding, laminating, chemical bonding, and extrusion bonding (Shimalla & Whitwell, 1976).

The most pronounced recent developments in nonwoven processes include (a) the growth of spunbonded and thermally bonded systems, (b) the trend toward greater machine widths, and (c) the increase in production rates (Floyd, 1984). The thermal bonding process is only about ten years old, and it has experienced growing acceptance in the United States. Although most webs are still chemically bonded, thermal bonding is expanding rapidly (Textile World, 1984). Thermally bonded nonwoven products represent about 10% of the current nonwovens market, with steady growth evident (Trueman, 1985).

Traditionally, thermally bonded nonwovens have been used in specialty types of products, and large volume markets have been dominated by latex bonded products. In 1981, 95% of the total binder market for nonwoven fabrics was comprised of latex binders which were applied by wet processes such as saturation, spraying, padding, and printing (Harris, 1982). Latex bonded nonwovens generally require 20 to 50 weight percent binder to meet performance requirements, and uniform distribution of binder throughout the structure is difficult. Fabric stiffness is easily increased by binder concentration on the surface and heavy deposition along the longitudinal fiber axis.

Latex binders are frequently chosen on the basis of torsional modulus, which, more than any other single binder characteristic, predicts hand and tensile strength of the bonded nonwoven. Torsional modulus is determined primarily by backbone composition which has the greatest influence on dry tensile strength and hand. It also influences elasticity, and to some degree, the absorption rate and capacity of the nonwoven.

Functionality in the binder is important in optimizing durability, resistance properties, wet tensile strength, elasticity and hand of nonwovens. It also helps to provide for efficient bonding on the nonwoven production line. Carboxylic acid functionality is commonly incorporated in binders to provide stability, hydrophilicity, self-thickening character, and/or sites for external crosslinking. Hydroxyl functionality can also be used, but it is less common. Amide functionality is more common, especially in the form of acrylamide (Laudadio, 1983).

Recent performance and marketing advantages coupled with developments in binder products and thermal bonding process technology have caused increased interest in thermal bonding. Tomioka (1981) states that thermal bonding is especially advantageous because it meets the three primary objectives of current nonwoven technology. First, thermal bonding is a rapid and simple bonding technology which can accommodate high speed web formation (Tomioka, 1981). Second, it can effectively be used with polypropylene fiber which provides a cost advantage over other fibers (Harris, 1982; Tomioka, 1981). And finally, thermal bonding is particularly attractive because it is an energy saving bonding method. Thermal bonding reduces energy costs by as much as seven to ten times that required in the wet bonding process simply because the removal of water is not necessary in thermal bonding (Purdy, 1983).

Thermal bonding offers additional basic advantages in production. It is a short, compact process requiring less plant space and offering

the potential of low conversion costs. The chemistry of the final product can be simplified when the product is binder free. Thermal bonding assures that the product can be further processed by thermal means (Floyd, 1984). The drying process and cost factor of bonding chemicals is eliminated (Textile World, 1984).

Other advantages are associated with thermal bonding as well. Thermally bonded nonwovens contain no chemical systems which could potentially cause toxic or allergenic reactions in the medical/surgical/health care/hygienic field (Textile Industries, 1982). Thermal bonding is cleaner and produces less waste and fewer waste disposal problems than do latex systems. A very uniform web is produced which generally yields high strength-to-weight ratios. Thermal bonding has the potential for product improvements (strength) and developments (comfort, more textile-like hand) which could increase competition in markets currently dominated by woven or knit structures (Harris, F., 1982).

Thermal bonding may be accomplished using any of four different product types. These include (a) self-bonding fibers, (b) unicomponent or binder fibers, (c) binder powders, and (d) bicomponent or conjugate fibers.

The self-bonding fiber is normally used in 100% form (Barton, 1983). Webs are carded from staple fiber, and bonding occurs from fiber softening or collapse upon exposure to heat and pressure, usually provided by the engraved calendar roll. An example is the self-bonding rayon fiber (Allan, Miller, & Reif, 1972)I. Although solid

rayon fibers do not readily self-bond, certain fistular forms will collapse into flattened, flexible ribbons which develop extensive interfiber contact areas. The bond that results is sufficient to provide web cohesion.

Generally, webs produced from self-bonding fibers are comprised of about 20% bonded area, producing a soft, bulky, yet relatively strong nonwoven product. Currently, the majority of self-bonding fibers in use is found in the diaper cover sheet industry (Barton, 1983).

Unicomponent or binder fibers are essentially adhesives in fiber form. The chief characteristic of the fiber is that it should melt at a temperature lower than that of the base fiber in the web. Binder fibers usually comprise about 10 to 20 weight percent of the nonwoven fabric. Upon heating, the structure of the binder fiber completely melts and flows to crossover points in the nonwoven to form bonds (Barton, 1983). The formed bonds generally have a high level of adhesive mass associated with each bond (Harris, F., I, 1982). Several binder fibers are commercially available, including polyesters, polyamides, poly(vinyl)chloride and a series of copolymers from each homopolymer, polypropylene, and polyethylene.

Most binder fibers currently in use are polyester and polypropylene. Polypropylene has been the leading choice because of its lower softening temperature and lower price. However, polyester is gaining market share due to its softer hand, better coverage, and greater availability over polypropylene. Web coverage comparable to

polypropylene is attainable with 15% less fiber. Required bonding temperatures of polyester are close to those of polypropylene (Textile World, 1984).

Some problems do exist in using binder fibers in thermal bonding. For example, polypropylene shows great thermal shrinkage and cohesion. Upon melting, the bonding fibers tend to agglomerate, giving the resulting nonwoven an agglomerate structure (Tomioka, 1981). In addition, the bonding temperature range of polypropylene is quite narrow. Thus temperature control during the manufacturing process is difficult, often resulting in nonuniform nonwovens. Tensile strength and bulkiness of the nonwoven bonded with the unicomponent fiber is less than that bonded with the bicomponent fiber, due to the thermal shrinkage and agglomerate structure of the unicomponent product.

In spite of these potential hazards, a successful unicomponent binder fiber known as Kodel 410 has been developed by Eastman Chemicals (Harris, 1982). Kodel 410 is a totally amorphous copolyester binder. It is a crimped fiber with the following properties (Table I) that make it easy to process both in 100% form or in blends with other fibers (Harris, 1982). Experimental work with Kodel 410 has shown the fiber to have excellent adhesive properties. Any bond failure appears to be cohesive rather than adhesive.

Another commercially available unicomponent binder fiber has been specifically engineered by Celanese for use in nonwovens. Fortrel Type 450 functions effectively as a binder in 100% polyester webs and

TABLE I

PROPERTIES OF KODEL 410 BINDER FIBER

Property	Level
Linear density, d tex	2.8
Staple length, mm	38
Tenacity, mN/d tex	22.0
Modulus, mN/d tex	530
Elongation, %	40
Glass transition, °C	75
Sticking Temperature, °C	85
Shrinkage at 60°C, %	5
Shrinkage at 80°C, %	60
Crystallinity	none
Composition	Copolyester

in blends with natural or synthetic fibers. The resultant nonwoven structures are especially suited for specialty synthetic papers, filtration media, electrical insulation materials, thermoformed molded products, and other industrial products (Seidel, 1982).

A typical web blend is 50/50 binder/base fiber. Webs produced on cards, garnetts or air-laid systems are bonded by hot calendaring. Fiber diameter, type of structure, and percent binder fiber used determine the bonding temperature and pressure required. Physical properties of the fiber are shown in Table II (Seidel, 1982).

Binder fiber applications are being developed in a number of different markets, including needlepunched fabrics for home furnishings and civil engineering end uses (Harris, F., 1982; Purdy, 1983). Improved product properties have been obtained, including higher modulus, higher grab strength, lower elongation, and improved recovery after strain. Binder fibers with reduced thermal shrinkage and lower temperature requirements for bonding have been successfully used in the production of lightweight nonwovens on an experimental basis (Harris, F., II, 1982).

Binder powders are crystalline polymers in powder form (Barton, 1983). They are most often used in areas where a light and open structure with a soft hand is required. Thermoplastic powder is distributed through the web during cross-lapping and melted to achieve bonding. Binder powders are also used when a reinforced, molded product is desired. A phenolic thermosetting powder is uniformly scattered into the fibers to produce a board-like structure when

TABLE II

PROPERTIES OF FORTREL TYPE 450 BINDER FIBER

Property	Level
Denier	3.0
Staple length, in	1.5
Tenacity, gpd	1.5
Modulus, gpd	15
Elongation, %	450
Melting temperature, °F	500
Sticking temperature, °F	203
Shrinkage at 400°F, %	45

bonded. Powder application masses/unit area are normally 10 to 600 g/m^2 (Purdy, 1983). Binder powders have been used for some time in lightweight webs, less than 2.0 oz/yd^2, and in fusible interlinings. The crystallinity of the powder produces good stability to drycleaning and laundering (Barton, 1983).

A bicomponent or conjugate fiber is one composed of at least two fiber-forming polymeric components arranged in distinct zones across the cross section of the fiber and continuous along the length of the fiber (Gillies, 1979). One of the components has a softening temperature significantly lower than the softening temperature(s) of the other component(s). Normally the fiber with the lowest softening temperature is located on the peripheral or skin area of the fiber (Harris, F., 1982; Purdy, 1983; West, 1971). In its simplest form the conjugate fiber consists of high melting core surrounded by a sheath or skin of a low melting polymer (West, 1971). Other arrangements include the side-by-side, skin core, fibrous distribution, filaments in matrix, and multilobal (Gillies, 1979; Purdy, 1983).

Examples of high-melting/low-melting polymers used in conjugate fibers include nylon 6.6/nylon 6, polyester/nylon 6, and polypropylene/polyethylene (Harris, F., I, 1982). When a web of such polymers is heated to the appropriate temperature, the sheath polymer flows, forming heterofil bonds. Upon cooling, the sheath polymer solidifies. The resulting nonwoven structure is primarily point bonded (Tomioka, 1981; West, 1971). The bonds formed between conjugate fibers tend to be quite strong, whereas weaker bonds tend to form between conjugate and homofil fibers.

Widespread commercial use of conjugate fibers is a relatively recent trend. Problems including difficulties in obtaining fine denier (less than 6.0) desirable for disposable nonwovens have delayed commercial availability of the fiber. Undesirable excessive thermal shrinkage, high melting point, as well as detachment of fiber component elements have slowed the progress of the conjugate fiber as an acceptable binder for nonwovens.

The first conjugate fiber to overcome these problems was the ES fiber developed in 1977 by Chisso Corporation of Japan. ES fiber consists of polypropylene and polyethylene in a modified side-by-side arrangement (Purdy, 1983; Tomioka, 1981). Minimum denier is 1.5. The fiber has minimal shrinkage and does not split. The bonding temperature range is sufficiently wide to obtain uniform nonwovens. Nonwovens made with ES fiber have higher tensile strength and greater bulk density, with excellent hand and drape. The productivity of the ES nonwoven is about four times that of latex nonwovens, and energy savings are nearly 90% over latex nonwovens (36). Physical properties of the ES fiber are shown in Table III (Tomioka, 1981). Cost savings with ES fiber are about 20 to 30% overall. When blended with other fibers, ES fiber is necessary in amounts at 50% for high strength (Purdy, 1983).

When bicomponent fibers are used as binders, additional advantages in thermal bonding occur. The binder fiber continues to make a structural contribution to the nonwoven after bonding. The level of binding agent is well-distributed throughout the nonwoven and can be

TABLE III

PROPERTIES OF CHISSO ES BICOMPONENT FIBER

Property	Level
Linear density, d tex	1.67-20.0
Staple length	varies
Tenacity, gf/den	2.5-3.5
Elongation, %	40-120
Crimp, tpi	0.10-13
Moisture regain, (65% RH, 25°C) %	<1.0
Softening point, °C	110-120 & 150-160
Melting point, °C	130 & 165
Shrinkage (105°C hot air, 5 min) %	<1.0

at a low level, giving a much more efficient conversion of fiber into fabric. In addition, the chemistry can be further simplified to one basic type. The structural contribution from the bicomponent fiber becomes even more important when lofty structures (high void-volume, low fiber content) are being made (Floyd, 1984).

Nonwoven properties of strength, elongation, elasticity, temperature resistance, and dimensional stability are determined by such variables as fiber type, geometrical arrangement of fibers in the web, and, in particular, the nature of the bonding operation. Binder selection and bonding conditions of temperature, pressure, time, quench rate, binder concentration, and base fiber denier affect every aspect of the nonwoven product.

Higher bonding temperatures have been found to improve individual bond strength with potential impairment to fiber strength. Stiffer, stronger fabrics are produced with higher bonding temperatures because of increased penetration of the binder (Shimalla & Whitwell, 1976; Wyatt, 1980). Increased temperatures tend to produce thinner nonwoven structures, as more base fibers are incorporated into the bonded network due to increased fluidity of binder fiber. With increased bonding temperatures, modulus increases while extension decreases due to stronger interfiber bonds and increased orientation and crystallinity in the binder fiber (Wyatt, 1980). Above a certain temperature, thermoplastic fibers lose their fibrous structure and no longer contribute effectively to overall strength (Purdy, 1983).

Bonding pressure spreads the thermoplastic binder through the structure, more effectively utilizing the available binder. A final press before cooling is important for maintenance of interfiber contact prior to setting of the binder as it solidifies (Wyatt, 1980).

Increased bonding time is expected to increase the extent of fiber-fiber contact due to the kinetics of wetting. Longer bonding times can cause heat setting which imparts a degree of dimensional stability against shrinkage that is dependent on the heat-setting temperature. Generally, once the interfacial temperature of the web center corresponds to the minimum bonding temperature, bond formation occurs. If bonding occurs rapidly, little further change will ensue. In experimental work by Shimalla (1976) and Wyatt (1980), the processes involved in forming a bond at a potential bonding point were completed in less than two minutes. In general, quenching reduces the formation of a weak boundary layer, improving adhesion and resulting in a more flexible network. Increased cooling rates have been found to increase web extensibility and decrease initial modulus (Shimalla & Whitwell, 1976).

The introduction of thermoplastic binders in a web is a form of selective bonding which provides an opportunity to increase the number of bonds and to decrease free fiber length between bonds. Shimalla (1976) found that with increased binder concentration, thickness decreased, while strength, elongation, and initial modulus increased. Both Shimalla (1976) and Wyatt (1980) found that higher web structures tend to occur with the use of lower denier fibers, given that other conditions are similar.

Product and process advancements in technology of thermal bonding have provided an easier, faster, and less expensive method of producing nonwoven products. The energy saving features of the process and improved performance characteristics of the product are just two of the reasons for the recent growth in thermal bonding. Developments in the area of thermoplastic fibers in particular, such as finer denier fibers with less shrinkage, will continue to facilitate the increased use of thermal bonding techniques for the production of nonwoven fabrics.

III. PHOTODEGRADATION OF POLYESTER

Most natural fibers are known to be degraded by weathering, and the response has not been alleviated with the development of man-made fibers. Weathering is a term that refers to a complex system of components for which there are no specified standards. Variations are caused by seasons, geographic location, climate, altitude, orientation in relation to the sun, and the presence of atmospheric pollutants. Several elements of weathering have been identified as primary contributors to change exhibited in polymeric materials. These include sunlight, particularly of near-ultraviolet (uv) wavelength, moisture in liquid or vapor form, temperature, and oxygen.

The most important agent in weathering is generally considered to be sunlight. Sunlight would be an even greater influence in degradation if most of the short wavelengths were not screened out by the atmosphere. Absorption of near-uv light reaching the earth causes

some bond rupture, due to the fact that the energies of photons in the near-uv region equal or exceed the covalent bond energies of some chemical structures (Wall & Frank, 1971). Breakdown of the molecular structure from bond rupture results in the loss of strength, extensibility, general durability, and possibly appearance (Bell & Pezdirtz, 1983; Horsfall, 1981; Stuckey & Roberts, 1981; Wall & Frank, 1971).

The most energetic part of terrestrial sunlight lies in the ultraviolet spectrum from 3000 to 4000 Å. This portion of the spectrum is extremely important in photodegradation reactions. In many photodegradation reactions, bond dissociation energies involving carbon chains lie in the area of 70 to 90 kcal and correspond to the energies associated with these wavelengths. In the case of polyester, energy is absorbed from 2800 to 4000 Å and in particular at 3130 Å. The principal bond dissociation energies in polyester correspond to wavelengths approximately 3130 to 3400 Å (Wall & Frank, 1971).

In terms of wavelength, polyester absorbs light in the 290 to 400 nm wavelength range of terrestrial sunlight. The light is absorbed primarily by the ester carbonyl chromophore groups present in the polymer. Eventually the molecular weight is lowered and deterioration of physical properties occurs (Day & Wiles, I, 1972).

A number of radiation sources have been used for the purpose of inducing photodegradation in polymers, including filtered and unfiltered sunlight (Harris, F., II, 1982; Horsfall, 1981; Horsfall, 1982; Wall & Frank, 1971), photochemical reactors (Merrill & Roberts, 1977; Stuckey & Roberts, 1981), cobalt-60 γ radiation (Bell & Pezdirtz,

1983), xenon-arc lamp (Blais, Day, & Wiles, 1973; Day & Wiles, 1972; Harris, F., II, 1982; Wall & Frank, 1972), superpressure mercury lamp (Day & Wiles, III, 1972), high pressure mercury arc lamp (Day & Wiles, II, 1972), and the carbon-arc lamp (Day & Wiles, I, 1972). The most commonly used artificial light sources are the carbon-arc and the xenon-arc lamps for which standard test methods exist. The xenon-arc lamp has been found to compare more closely to sunlight than the carbon-arc (Wall & Frank, 1971). Day and Wiles (I, 1972) found that the Atlas Xenon-arc Weatherometer gave an accelerated rate of degradation in polyester in comparison to that obtained with the Atlas Carbon-arc Fade-ometer.

In some cases it has been found that lamp age in the Weatherometer influences degradation rates. The aging of lamps and filters reduces the xenon-arc intensity due to solarization of the filters and deposits formed on the lamp housing (Wall & Frank, 1971). In addition, the cut-off wavelength of the filter plays an important role in the rate and the nature of photodegradation of polyester (Day & Wiles, II, 1972). However, the temperatures experienced during daylight and Weatherometer exposures generally have not influenced degradation rates due to lack of sufficient energy to cause dissociation of chemical bonds. The rate of reactions initiated by other means may have increased with increasing temperature. The presence of moisture was shown to have little effect on the photodegradation of nylon and polyester (Day & Wiles, I, 1972; Wall & Frank, 1971). Radiation wavelength and intensity, radiation atmosphere, and the presence of

additives such as dyestuffs and delusterants have been found to influence the photodegradation process (Stuckey & Roberts, 1981).

The effects of xenon-arc radiation on the breaking strength, extension, and the energy-to-break for several nylon, polyester, and cotton/polyester yarns were studied by Wall and Frank (1971). These effects were compared to those caused by outdoor exposure behind window glass. Both xenon-arc and sunlight exposure resulted in similar, related rates of loss in properties for all yarns. The greatest percent losses occurred in the energy-to-break with the percent loss in elongation-to-break slightly less, and in breaking strength slightly lower. However, it was believed that these trends may have been related to the breaking properties of the yarns before exposure. The percent loss in energy-to-break was greatest most likely due to the combined losses in breaking strength and elongation.

Both bright and dull polyester were examined in the study. Bright polyester lost strength more slowly outdoors than in the Weatherometer, while dull polyester degraded much more rapidly outdoors. Yarn denier variation and the presence of an optical brightener appeared to have no detectable effect on degradation rates. Sensitization by titanium dioxide in the nylon and polyester yarns occurred during sunlight exposure, perhaps due to factors of weathering other than sunlight, but not during Weatherometer exposure (Wall & Frank, 1971).

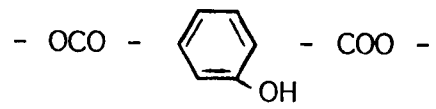
Day and Wiles (I, 1972) investigated the effects of photochemical damage on polyester. Poly(ethylene terephthalate) (PET) films were

exposed to near-uv light in the carbon-arc Fadeometer and the xenon-arc Weatherometer. Changes in tensile properties, intrinsic viscosity, infrared (IR) absorption, and fluorescence emmission spectra were measured. The rates of loss of tensile properties, decrease in molecular weight, formation of acid end groups, and production of fluorescing material all changed proportionately with exposure time. A drastic reduction from 200% to 80% elongation occurred in the less stabilized film after 300 hour exposure to the xenon-arc lamp.

Decreased number average molecular weights were derived from viscometric data, indicating degradation of the polymer chain. A faster rate of decomposition occurred with exposure to the xenon-arc than with the carbon-arc. Crosslinking reactions appeared to be insignificant in comparison with chain scission reactions.

Additional carboxyl groups were produced with exposure to both xenon-arc and carbon-arc radiation. The rate of build-up of -COOH end groups was positively related to the changes with time observed in the other measured properties. Acid end groups appeared to be photochemical products rather than hydrolysis or thermal products.

Irradiation with both light sources resulted in the formation of a blue-green fluorescent material within the polymer; however, formation occurred faster with xenon-arc radiation. The intensity of fluorescence was found to increase with increased exposure time. Prolonged irradiation of PET film was found to result in the build-up of a single fluorescent product whose excitation wavelength is 340 nm and emission wavelength is 460 nm. The product was identified as a monohydroxy compound with the following structure:



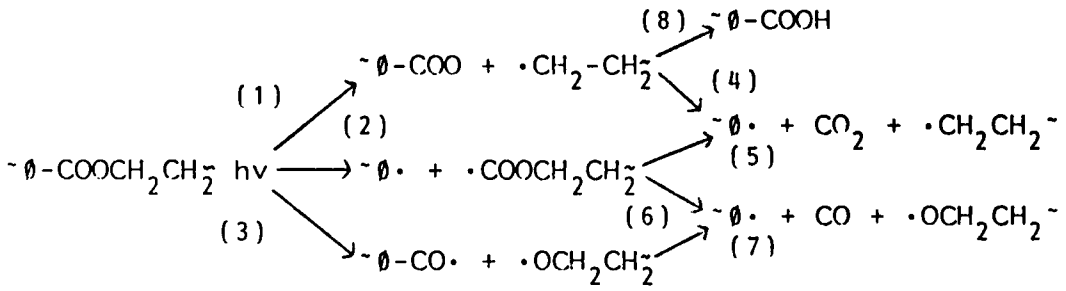
In a continuation of this study, Day and Wiles (11, 1972) investigated the effect on PET of filtered radiation in the 200 to 400 nm region in various atmospheres. It was found that wavelengths less than 315 nm were primarily responsible for causing deterioration due to strong surface absorption resulting in surface crazing and ultimate fracture under stress. The critical wavelength for the deterioration of PET corresponded to 310 nm, with irradiation at shorter wavelengths resulting in rapid deterioration in physical properties as a result of the surface (but not the bulk) undergoing major photochemical modification. Light greater that 315 nm is capable of causing deterioration in the polymer over longer (than 24 hours) irradiation times.

Prolonged exposure to long wavelength uv radiation caused a build-up in the fluorescent material and an increase in the concentration of -COOH end groups. Larger amounts of -COOH end groups were observed for irradiations in an oxygen-rich atmosphere, indicating that they may be produced as a result of subsequent oxidation processes. In addition, a slight discoloration of the film was observed in the oxygen-containing system. A fluorescent compound absorbing at 340 nm was formed, consistent with the presence of the monohydroxy species cited above. The formation of the compound may be explained by the mechanism of photooxidation in polymeric materials:

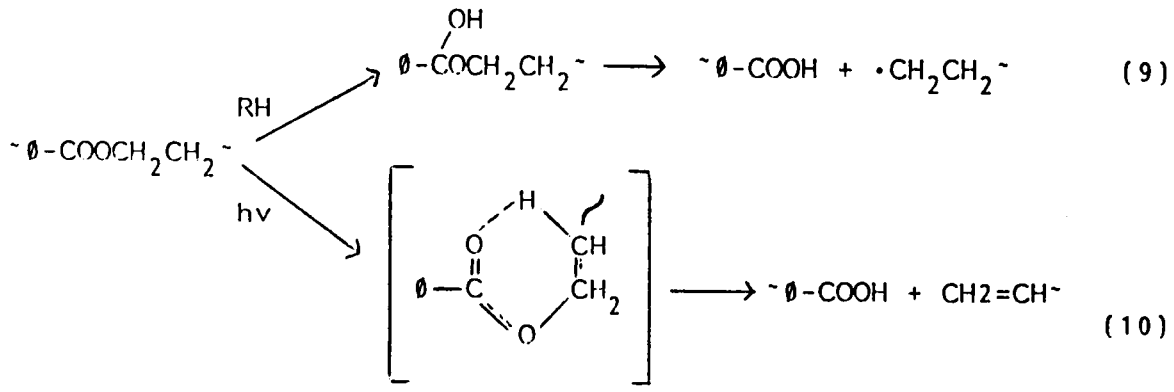
$$R\cdot + O \longrightarrow ROO\cdot \xrightarrow{R'H} ROOH \xrightarrow{h\nu} RO\cdot + \cdot OH$$

The hydroxyl radical may substitute on the phenylene ring to give the monohydroxy compound. In the absence of oxygen, such a mechanism is not possible (Day & Wiles, II, 1972).

Day and Wiles (III, 1972) further studied the vacuum photolysis and air photooxidation of PET film using light in the wavelength ranges of 225 to 420 nm and 330 to 420 nm. The predominant volatile photodegradation products were found to be CO and CO_2. The rates of formation of carboxylic acid end groups and the net weight losses of the PET film samples were determined as a function of irradiation time. From vacuum photolysis, the following reaction mechanisms were proposed for the photochemical degradation of PET:

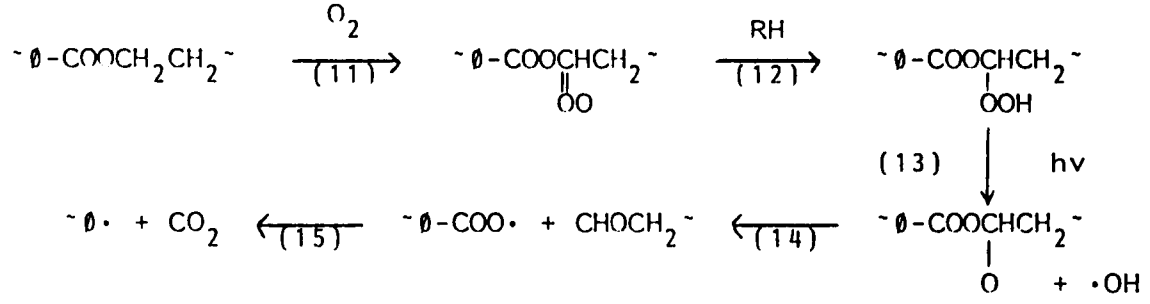


The main products of photolysis are benzoic acid and CO. Of secondary importance is CO_2. An alternative reaction sequence was suggested for the formation of O-COOH based on reaction rates and yields. Two alternative mechanisms are as follows:

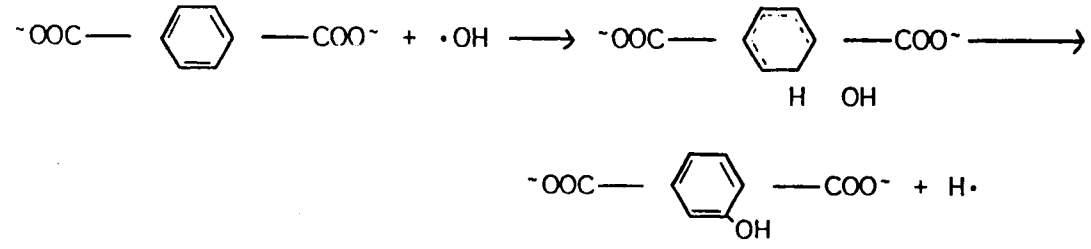


Reaction (9) involves intermolecular hydrogen abstraction from an adjacent hydrogen-containing molecule. Intramolecular hydrogen abstraction is involved in reaction (10). The Norrish type II intramolecular rearrangement in reaction (10) was found to be more feasible, based on the fact that aliphatic and aromatic esters containing a γ-hydrogen atom decompose photochemically by an intramolecular rearrangement into an olefin and the corresponding acid. Both the initial reactions leading to the production of -COOH end groups and the mechanism for the production of CO appear to be independent of environment and wavelength.

When the photooxidation study was performed under the same conditions (with the exception of the presence of air at a pressure of 1 atm), straight photolysis was still an important feature of the reaction. The composition of volatile products was similar, indicating that the same primary reactions were deemed responsible for their formation in both environments. However, the rate of production of CO_2 was much higher, indicating the participation of oxygen in the reactions carried out in air. As a result, the following photooxidative mechanism (involving hydroperoxide formation) was proposed:



The radical used as the starting point for the sequence is produced on photolysis of PET. The hydrogen abstraction (12) may result in the regeneration of the initial radical, since reactions (11) and (12) are chain propagation reactions. Reaction (13) involves the photolysis of the hydroperoxide to give a hydroxyl radical and the alkoxy radical. The monohydroxy terephthalate groups reportedly responsible for the observed fluorescence may be formed in the polymer backbone as a result of substitution of the hydroxyl radical found in reaction (13) into the phenylene ring:



It was concluded that photooxidation produces nonvolatile products within the polymer when long wavelength radiation is employed. Photochemical degradation of the oxidation products gives additional CO and CO_2 when shorter wavelength irradiation conditions are employed (Day & Wiles, III, 1972).

Blais, Day, and Wiles (1973) conducted a detailed investigation of the surface of photodegraded PET to relate the chemistry of the polymer surface to other factors that might affect the bulk mechanical properties. Changes in the surface composition of PET films were examined by attenuated total reflection infrared spectroscopy (ATIR). Electron microscopy was used to study changes in surface morphology.

UV-induced photochemical deterioration of PET films was found to lead to extensive surface degradation under moderate irradiation. Progressive deterioration of the interior was evident with prolonged exposure. Fluorescent degradation products concentrated on or near the surfaces. Mechanical properties of the deteriorated surface were grossly different from those of the interior. A drastic decrease in the molecular weight of the polymer material in the surface layers occurred as the result of chain scission induced by photochemical reactions.

When the polymer was subsequently subjected to stress, the load was distributed primarily through the degraded areas, inducing cracks in the surface layer. Tensile failure resulted from fractures initiated at the cracks and propagated through the bulk of the fiber.

Merrill and Roberts (1977) studied the effect of 1-amino-2-(2-methoxyethoxy)-4-hydroxy-9,10-anthraquinone (C.I. Disperse Red 59) on the phototendering of PET. The photophysical processes occurring in the polymer, the dye, and the dyed polymer were determined. Based on absorption and luminescence properties, the energy and nature of the dye and polymer electronic excited states were assigned. Dye-sensitized phototendering of PET was not produced by irradiation;

however, the titanium dioxide delusterant in commercial PET did function as a sensitizer in the presence of moist air. In addition, it was found that the photodegradation of PET with irradiation wavelengths less than 310 nm occurred primarily at the polymer surface. Extended exposure resulted in the formation of a thin layer of "skin" of photo-oxidized polymer. The surface was found to be capable of functioning as a radiation-absorbing barrier, thus protecting the underlying undegraded polymer.

Bell and Pezdirtz (1983) investigated the effects of several types of chemical structural changes on the response of PET-related polyesters to high-energy ionizing radiation. The effects were analyzed in terms of tensile properties, thermomechanical properties, number-average molecular weights, and viscosity.

Marked changes in response to γ-radiation occurred with changes in the aromatic portion of the PET structure. An initial rapid drop in viscosity and molecular weight with subsequent crosslinking to an insoluble network resulted from the complete removal of the benzenoid aromaticity. When the benzene portion of PET was replaced with a napthalene group, the radiation caused an immediate and steady crosslinking reaction that did not degrade the useful properties of the polymer.

The rate of crosslinking was enhanced and the rate of γ-radiation- induced chain scission was diminished when the aliphatic length of the glycolic portion of PET was expanded with poly(butylene terephthalate) and poly(decamethylene terephthalate). The substitution of electronegative chloro groups onto the benzenoid portion of PET

did not seem to affect the response to radiation. The substitution of electropositive groups onto PET appeared to lessen the chain cleavage effect of radiation in favor of crosslinking. In general, the polyesters examined underwent both chain scission and crosslinking when exposed to γ-radiation.

Phototendering studies of poly(ethylene terephthalate) homopolymer yarn and a series of poly(ethylene terephthalate-co-4,4'-sulfonyldibenzoate) copolymer yarns were conducted by Stuckey and Roberts (1981). It was found that photosensitized degradation occurred more readily in the copolymers than in the homopolymer. The inclusion of a second monomer photosensitized the degradation of the polymer. The enhanced rate of formation of the hydroxyterephthaloyl units with increasing concentrations of 4,4'-sulfonyldibenzoate indicated that the photosensitizaton proceeds by a photooxidative mechanism involving the initial dissociation of the C-S bond.

Horsfall (1981, 1982) postulated that the dyestuff, finishing operation, and exposure conditions have a pronounced influence on the photodegradation behavior of polymers. He investigated the effects of various dyestuffs and delustrants on the photodegradation of nylon 6.6, nylon 6, and polyester. The fibers were made into commercial fabrics and were exposed under glass and by direct weather (no glass) in Florida to determine the relative contribution of various factors to reduced fabric performance on exposure to light. Strength retention and abrasion resistance were used to characterize mechanical failure.

Horsfall found that extra dull PET showed excellent strength retention after dyeing with disperse dyes. Before dyeing, however, the extra dull PET exhibited much strength loss. Both the bright and extra dull PET performed well under glass, due to the fact that glass absorbs light of a wavelength of approximately 310 nm which seriously damages PET. Polyester behind glass is protected from the 310 nm wavelength. Without protective glass, the PET suffered serious strength loss. The damaging radiation is absorbed very strongly and the fabric is attacked from the surface to the center. Bright PET performed well whether dyed or not dyed when protected by glass. Extra dull PET performed less well. Performance was determined to depend upon the selection of the dyestuff, and whether or not it had received an aqueous treatment. The performance of both bright and extra dull PET decreased with exposure to direct sunlight.

Wall and Frank (1971) found that lower amounts of titanium dioxide in PET were associated with lower degradation rates when exposed to direct sunlight. The increased temperature and the presence of moisture were shown to influence the sensitization mechanism of the titanium dioxide, bringing about polymer degradation through oxidation. The uv radiation from sunlight has been related to this reaction.

Wall, Frank, and Stevens (1971) found that photosensitization of titanium dioxide was apparent in outdoor exposure but not in the xenon-arc Weatherometer exposure. The indications are that PET containing no sensitizing agents would degrade slowly when exposed to sunlight behind glass.

Wall and Frank (1971) found that fibers of decreased luster reflect less uv radiation resulting in an increased degradation rate. However, as additional studies have shown, the durability of textiles to photodegradation has been found to depend on luster, denier, cross section, and pigmentation in addition to polymer type.

CHAPTER III

EXPERIMENTAL METHODS

The purpose of this study was to determine the effects of exposure to ultraviolet light on the degradation of thermally bonded polyester nonwoven fabrics. The parameters studied include the bonding technique and the time length of exposure to ultraviolet light. The influence of exposure time has been characterized in terms of fabric (a) flexural rigidity--machine and cross directions, (b) tenacity--machine and cross directions (c) extension--machine and cross directions, (d) intrinsic viscosity, (e) gel permeation chromatography, and (f) differential scanning calorimetry, as identified in Table IV.

I. MATERIALS

Fiber Selection

Fiber selection was based on the results of a study done by Wyatt (1980) investigating the influences of fiber and processing variables on the nature of bonding and fabric performance in thermally bonded nonwovens. The same binder fiber was selected (Fortrel Type 450/Celanese) due to optimum results obtained by Wyatt. Selection of the base fiber (Trevira Type 121/Hoechst) was determined as recommended by Wyatt to use a fine denier base fiber to produce a stronger web. Properties of the base fiber are shown in Table V; properties of the binder fiber are shown in Table VI.

TABLE IV

TEST PROCEDURES: DETERMINATION OF PHYSICAL PERFORMANCE, MOLECULAR WEIGHT, AND POLYDISPERSITY OF THERMALLY BONDED POLYESTER NONWOVEN FABRICS

Test For	Instrument	Measurement
Fabric Weight	Mettler H80 Balance	weight, g/m^2
Fabric Thickness	TMI Model 540 Micrometer	thickness, 0.0001 inch
Fabric Flexural Rigidity	RLI Cantilever Bending Test	flexural rigidity, mg-cm
Tensile Strength	Instron Tensile Tester	breaking load, kN/m
Extension	Instron Tensile Tester	elongation, %
Differential Scanning Calorimetry	Perkin-Elmer DSC-2	Tm, °K; Tg, °K; H_f, cal/g; crystallinity, %
Intrinsic Viscosity	Ubbelohde Viscometer	viscosity average molecular weight, $\bar{M}v$
Gel Permeation Chromatography		number average molecular weight, $\bar{M}n$ weight average molecular weight, $\bar{M}w$ polydispersity, $\bar{M}w/\bar{M}n$

TABLE V

PROPERTIES OF TREVIRA TYPE 121 BASE FIBER

Property	Level
Denier	1.5
Staple length, in	1.5
Diameter, m	13.05
Tenacity, g/den	48.6-57.6

TABLE VI

PROPERTIES OF FORTREL TYPE 450 BINDER FIBER

Property	Level
Denier	3.0
Length, in	1.5
Diameter, m	13.05
Tenacity, g/den	13.5
Sticking T°	203°F, (95°C)
Melting T°	500°F, (260°C)
Recommended Bonding T°	356-392°F (180-200°C)

II. WEB FORMATION

Opening and carding equipment was utilized to make the webs at Starlab, Inc., Knoxville, TN. An end product was desired in which the nonwoven fabric weighed about 59.31 g/m^2 (1.75 oz/yd^2), representative of nonwovens in textile and apparel products.

Opening

All fiber samples were opened in two different operations. Base and binder fibers were initially opened in separate quantities prior to blending. Then, specific quantities were weighed to obtain a binder fiber content of 30%. The mixture was hand blended and opened again to obtain a blended lap. Sample sizes of 50 grams each were weighed out for carding.

Carding

A Saco Lowell 40 inch standard cotton card with CMC prefeed and even feed was used to card all webs in the study. After opening and blending, the lap was carded once. The carded lap was carded a second time to produce increased uniformity of fiber distribution across the web. Two webs were produced from each 50 gram lap. To achieve this the card was stopped after 12 revolutions on the collector drum. The first carded lap was quickly removed, and the card was then allowed to run for 12 more revolutions, creating a second web.

Each web was weighed after removal from the collector drum. The average weight of the web produced was 16.0 grams. One hundred webs were made with 30% binder fiber concentration. The

average size of all webs was 54" x 7.75". Each web was cut into four 12" lengths for further processing. The excess web was discarded.

III. BONDING PROCEDURE

All bonding was completed using the Wabash Hydraulic Press Model #12-12-2TMB with a West 400 Model temperature sensor. Upper and lower platen dimensions were 12" square. The bonding temperature selected was 375°F (190°C), based on manufacturer's recommendations and preliminary experimentation. Based on a 203°F (95°C) sticking temperature and a 500°F (260°C) melting temperature, the recommended bonding temperature for the Fortrel 450 binder fiber fell in range between 356-392°F (180-200°C).

Preliminary experimental investigation was conducted using bonding temperatures of 260°F (127°C), 300°F (149°C), 350°F (176°C), 375°F (190°C), and 400°F (204°C) at 30 second, 1 minute, and 1.5 minute dwell times. Results of each temperature/time combination were compared with market samples on the basis of hand, stiffness, and tensile strength. The temperature/time combination that produced samples nearest those market samples was the 375°F (190°C)/30 second combination. The time past 30 seconds did not appear to greatly increase bonding as there were no significant changes in stiffness and strength, although some undesirable glazing did occur at the 1 minute bonding interval.

The bonding temperature of 375°F (190°C) is significantly greater than 25°F above the Tg of the binder fiber as recommended by Wyatt

(1980). However, it is within the manufacturer's recommendations and was used in combination with a shorter dwell time than that used by Wyatt. The bonding pressure used was 111.11 psi (765.55 kPa) as a result of limited pressure setting capabilities.

Webs were bonded between ferrotype triple-plated chrome plates. The plate/web assembly was placed between the heated platens, and the pressure was applied to the assembly for 30 seconds. The process was repeated for all bonded webs. The average weight for bonded samples was 1.90 oz/yd^2.

IV. NONWOVEN FABRIC TESTING

Physical characteristics of fabric weight, thickness, flexural rigidity, tenacity, and breaking elongation were measured using the American Society for Testing and Materials (ASTM) standard test procedures (ASTM, 1980). Prior to testing, all samples were conditioned at 70 ± 2°F (21°C) and 65 ± 2% relative humidity according to ASTM standard D1776-79. A web consisted of four sections from which random sample selection was made for testing purposes. Samples were cut from the interior portion of the bonded web; fabric edges were not included in the sample.

Fabric weight was determined by ASTM standard D1910-64. A Mettler H80 balance was used to determine the weights of five randomly selected 2" x 2" (5.08 cm x 5.08 cm) samples from each bonded web. The mean weight was converted to oz/yd^2 by the following formula:

$$\text{Weight, oz/yd}^2 = \frac{\text{weight of specimen, g X 45.72}}{\text{length of specimen, in X width of specimen, in}}$$

Ounces per square yard were converted to g/m^2 by the following formula:

$$g/m^2 = oz/yd^2 \times 33.906$$

Fabric thickness was measured according to ASTM standard D1777-64 using the TMI Model 540 Micrometer. Measurements were recorded to the nearest 0.0001 inch. The mean thickness was recorded from ten randomly selected specimens for each bonded web. Thickness values were converted to mm.

Fabric flexural rigidity was determined according to ASTM standard 1388-64, Option A. The RLI Electric Cantilever Bending Apparatus by Testing Machines, Inc., was used in the test procedure. A 1" x 6" (25 mm x 150 mm) specimen in the machine direction and the cross direction were cut from each sample. Four readings were taken on each specimen, with each side up, first on one end and then the other. The four readings (in cm) were averaged to get a mean length of overhang. From this value, the bending length c, in cm, and the flexural rigidity G, in mg-cm, were calculated using the following equations:

$$\text{Bending length, } c = 0/2$$

where 0 = the length of overhang, cm;

$$\text{Flexural rigidity, } G = W \times (0/2)^3 = W \times c^3$$

where W = weight per unit area, mg/cm^2.

Fiber tensile strength and elongation were measured according to ASTM standard D1682-64. Specimen size was modified from the recommended 1" x 7" (25 mm x 178 mm), as specified in ASTM standard D1117-80, to 1" x 6" (25 mm x 150 mm). Two specimens in both the machine direction and cross direction per sample were broken on the Instron Tensile Tester. The B load cell was used with a 5 inch/minute chart speed and a 2 inch/minute cross head speed. A 2 inch gauge was used with full scale load at 20 lbs. The average breaking load was reported in kN/m, and the apparent elongation was reported in percent.

Chemical analysis of the thermally bonded nonwoven fabric was determined through differential scanning calorimetry, intrinsic viscosity, and gel permeation chromatography.

Differential scanning calorimetry was performed using the Perkin-Elmer DSC-2. The glass transition (Tg) and melting transition (Tm) temperatures were determined along with the heat of fusion (ΔHf) and the degree of crystallinity of the fibers. The Tg and Tm of the samples were taken directly from the DSC charts. The heat of fusion (ΔHF, cal/g) is equal to the area under the thermal peak, measured with a planimeter. The determination of percent crystallinity is based upon the ΔHf measurement and the assumption that ΔHF is proportional to the percent crystallinity. If the heat of fusion ΔH*f of a 100%

crystalline polymer is known (33.45 cal/g for polyester), the percent crystallinity can be calculated from

$$\% \text{ crystallinity} = \Delta Hf/\Delta H^{*}f \times 100\%$$

According to the DSC instruction manual, the ΔHf is calculated from

$$Hsam = H\ tin \times W\ tin/Wsam \times Asam/Atim \times Rsam/Rtin$$

where

Htin = heat of transition of tin (14.45 cal/gm);

Wtin and Wsam = sample weight in mg;

Asam and Atin = peak area in in^2;

Rsam and Rtin = range sensitivity in mcal/sec-in.

One sample for each exposure time length, each weighing about 5 mg, was tested according to the following parameters;

DSC heating rate: 20 deg/min

DSC cooling rate: 320 deg/min

DSC range: 10 mcal/sec

Temperature range: 253-600 K

Reference Calibration Standard: Tin

Instrinsic viscosity and thus the weight average molecular weight were determined according to procedure described by Morton (1975). A Ubbelohde viscometer No. 1 C A710 was used in a 25°C constant temperature water bath. The polyester nonwoven sample was ground using a Wiley Mill with a size 20 screen. The sample was then

dissolved in a 40/60 by weight phenol/tetrachlorethane solvent solution. Five concentrations were run per sample. The weight average molecular weight was calculated according to the following formula:

$$\text{relative viscosity} = \eta_{rel} = \frac{\text{polymer solution flow time (seconds)}}{\text{solvent flow time (seconds)}}$$

$$\text{specific viscosity} = \eta_{sp} = \eta_{rel} - 1$$

$$\text{inherent viscosity} = \eta_{ihn} = \eta_{sp}/c = \ln \eta_{rel}/c = \ln (\eta_{rel}-1)/c$$

Concentration (expressed as grams of polymer/100 ml of solvent) was plotted against $\ln \eta_{sp}$ for five points with the straight line extrapolated to zero on the Y axis. The intrinsic viscosity was the Y intercept at c = 0, according to the following equation:

$$[\eta] = (\eta_{sp}/c) = (\ln \eta_{rel}/c)$$
$$c \longrightarrow 0 \qquad c \longrightarrow 0$$

The intrinsic viscosity was used to determine the weight average molecular weight ($\bar{M}w$) according to the Mark-Houwink equation:

$$[\eta] = KM^a$$

where M = weight average molecular weight.

K = constant.

a = constant.

Gel permeation chromatography was performed by Springborn Laboratories, Inc., (Enfield, Connecticut) on one unexposed and six different exposure level samples. Number average molecular weight, weight average molecular weight, and polydispersity values were obtained.

Number average molecular weight ($\bar{M}n$) is defined as the total weight (w) of all the molecules in a polymer sample divided by the total number of moles present:

$$Mn = \frac{\sum iN_iM_i}{\Sigma N_i}$$

where N_i = number of molecules of species of i.

M_i = molecular weight of species of i.

The weight average molecular weight ($\bar{M}w$) is defined as

$$Mw = \frac{\sum ig_iM_i}{\Sigma g_i}$$

where g_i = weight.

M_i = molecular weight of each fraction (Siggia & Mark, 1971).

The polydispersity value is the ratio of the two average molecular weights, $\bar{M}w/\bar{M}n$, which depends on the breadth of the distribution of the average molecular weights. The polydispersity value would be unity ($\bar{M}n = \bar{M}w$) for a perfectly monodisperse polymer. If the polymer is polydisperse, then $\bar{M}n < \bar{M}w$. The ratio is greater than unity for all

actual polymers and increases with increasing polydispersity (Odian, 1981). The most probable distribution is the term used for the molecular weight distribution in a step-growth polymerization reaction in which all functional groups have an equal probability of reacting. In such cases, $\bar{M}w/\bar{M}n = 2$. This type of distribution also occurs in the random scission of an infinite molecular weight polymer chain (Lenz, 1967).

Gel permeation chromatography was completed according to the following parameters. Calibration was by polystyrene standards and is reported in terms of polystyrene molecular weight.

solvent:	m-cresol
	1/8% Benzoic Acid
	0.1% DLDTP
temperature:	100°C
flow rate:	1 cc/min
Gel Columns, A:	10^6 T21178
	3×10^5 T9221
	10^4 T12111
	250 T10900
concentration:	0.5%
sensitivity:	8X
injection time:	120 sec

V. EXPOSURE TO ULTRAVIOLET LIGHT

Photodegradation of the thermally bonded polyester nonwoven fabric was induced by exposure to ultraviolet light in the Atlas Xenon-arc

Weatherometer Model 25W located in the USDA Textiles and Clothing Laboratory, Knoxville, TN. Four machine direction and four cross direction samples were randomly selected for each of six different time lengths of exposure. Sample size was 9.75" x 6.50". The following conditions were used:

lamp:	calibrated 2500 watt lamp
outer filter:	borosilicate
inner filter:	borosilicate
nominal irradiance:	0.97 $w/m^2/nm$ @ 420 nm
chamber temperature:	121°F (49°C)
relative humidity:	58%

A total of eight samples were exposed to continuous light from the xenon arc for periods of 100, 200, 250, 300, 350, and 400 hours. Two replications were run for the 100 hour, 200 hour and 300 hour exposures. Lamp and filter aging and wattage levels were controlled according to the manufacturer's specifications (Instruction Manual, Atlas Model 25W Weatherometer).

VI. DATA ANALYSIS

A paired t-test was used to evaluate the differences in physical and chemical properties of the nonwoven product before and after exposure to ultraviolet light for each time period. A one-way analysis of variance was completed to determine differences in physical and chemical properties based on increasing length of exposure time. Regression analysis was completed for all independent variables.

Statistical analysis was completed on the Digital Equipment Corporation--VAX/VMS Version V4.2.

CHAPTER IV

RESULTS AND DISCUSSION

The purpose of this study was to determine the effects of exposure to ultraviolet light on the physical performance behavior of the thermally bonded polyester nonwoven fabric. Additional objectives were to determine the effects of exposure to ultraviolet light on the molecular weight and polydispersity of the polyester fiber and to predict the exposure time length at which physical performance behavior is adversely affected due to degradation upon exposure to ultraviolet light at 121°C and 58% relative humidity over varying lengths of time. Initial studies were completed to determine the optimal bonding conditions of time and temperature.

I. BONDING CONDITIONS

Wyatt (1980) reported that increasing the bonding temperature and the concentration of binder fiber in the web produced nonwoven fabrics with increased flexural rigidity, increased tenacity, and decreased elongation. These results were attributed to the adhesion mechanism. Increasing temperatures enhanced the flow characteristics of the binder fiber, resulting in an adhesion contact area where joints with base fibers had formerly existed. Thus, restrictions were placed on fiber movement within the nonwoven system.

To produce fabrics with compatible stiffness and strength, Wyatt (1980) recommended a bonding temperature approximately 25°F above

the glass transition temperature (Tg) of the binder fiber. The manufacturer's report on the Fortrel Type 450 binder fiber indicated a recommended bonding temperature of 356-392°F (180-200°C). Initial bonding trials were completed at three different temperatures and two time periods in the following design (Table VII).

TABLE VII

BONDING TRIAL CONDITIONS

	Time	
Temperature	30 sec.	60 sec.
350°F (176°C)	x	x
375°F (190°C)	x	x
400°F (204°C)	x	x

Flexural rigidity, tensile strength, and extension were measured for webs bonded at each temperature/time combination. Results are illustrated in Figures I, II, and III. Flexural rigidity appeared to increase with increased bonding temperature and to decrease with increased bonding time. The bonding time of 60 seconds did not seem to greatly increase bonding over that apparent at the 30 second bonding time. Tensile strength was measured in terms of breaking load and percent elongation.

Breaking load generally increased with increasing bonding temperatures and decreased with increasing bonding time. Elongation decreased with increasing breaking load. Increased bonding

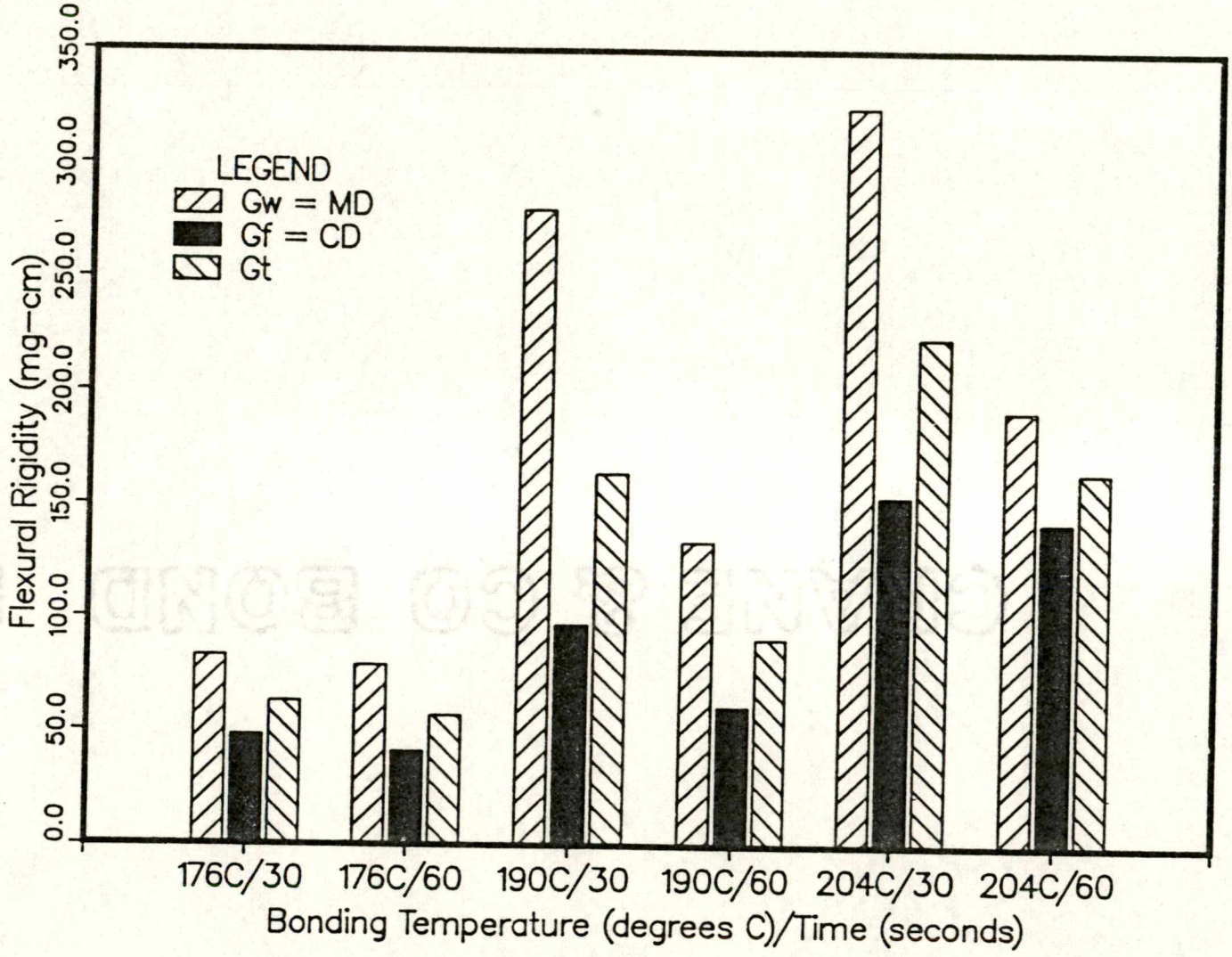


Figure 1. Initial Bonding Trials: Flexural Rigidity

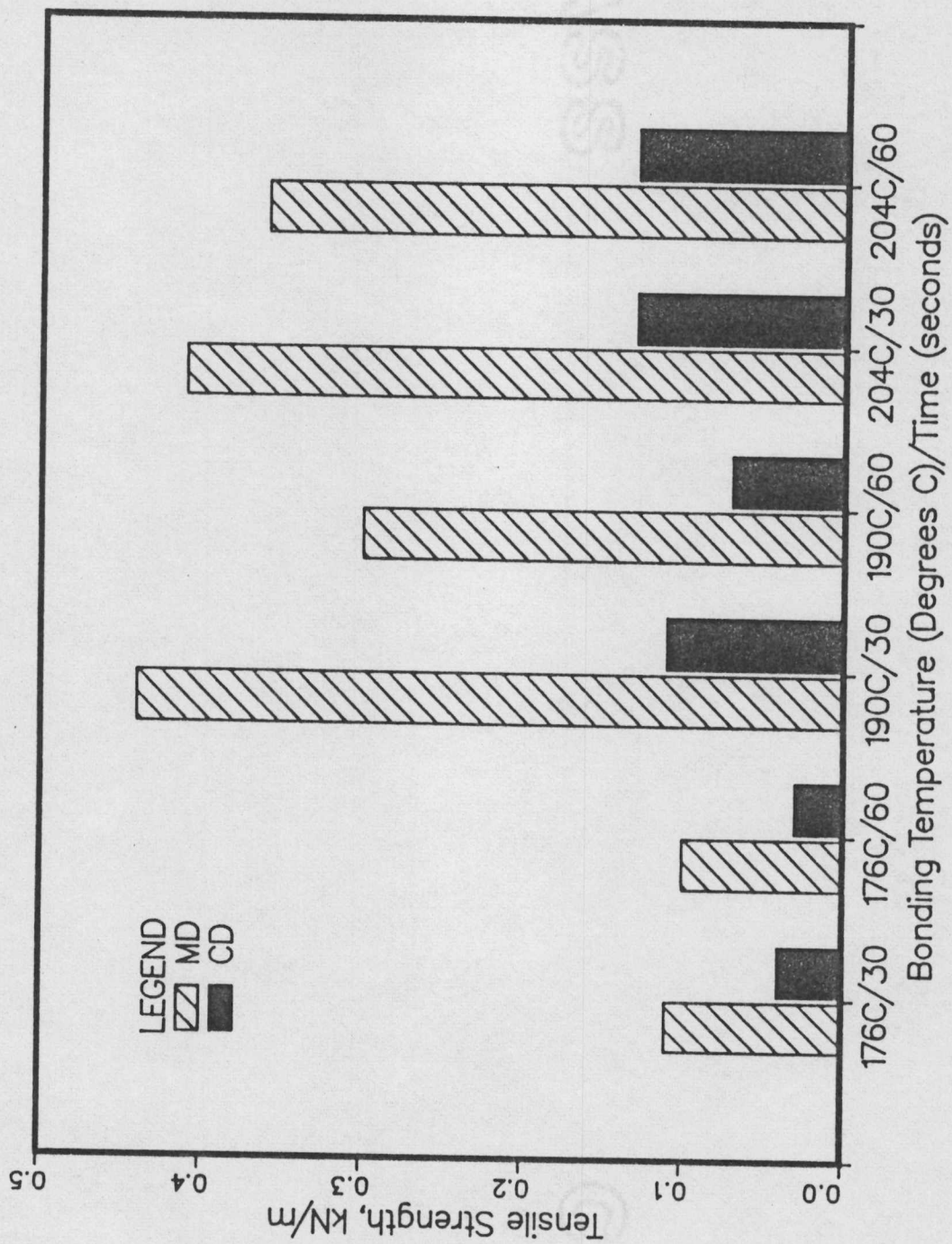


Figure 11. Initial Bonding Trials: Tensile Strength

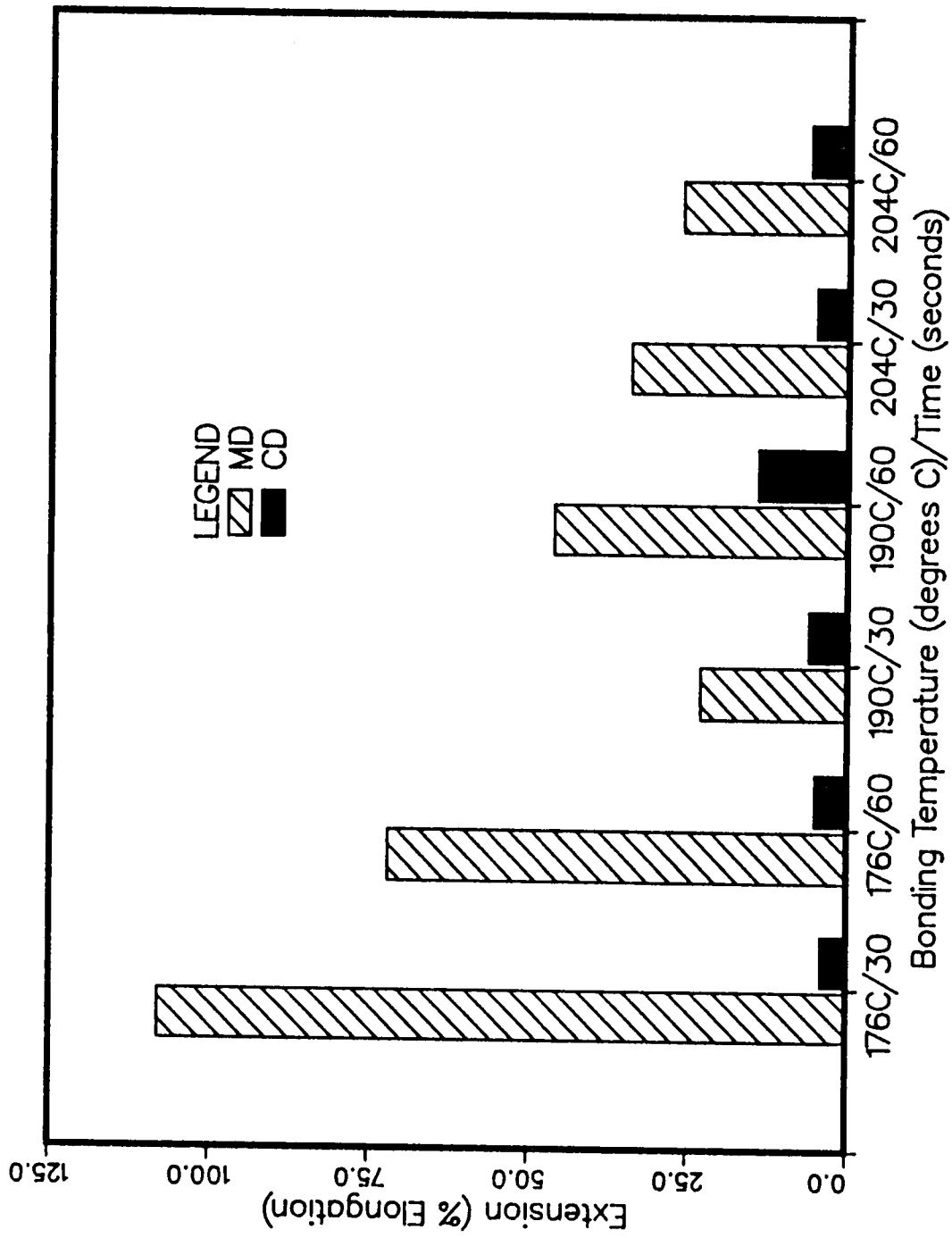


Figure III. Initial Bonding Trials: Extension

temperatures have been found to produce stiffer, stronger fabrics caused by increased binder penetration. Individual bond strength is generally improved; however, fiber strength may be decreased (Shimalla & Whitwell, 1976; Winchester & Whitwell, 1970). This effect is apparent in the increased flexural rigidity with increased bonding temperature. In addition, breaking strength increased with increased bonding temperatures.

The effect of temperature on flexural rigidity, strength, and elongation may be compounded by the response of the binder fiber to increased temperature. Wyatt (1980) reported that, with increased temperature, the orientation and crystallinity of the Fortrel Type 450 binder fiber increased, resulting in a stronger fiber with a higher modulus. Clearly the properties of the nonwoven product containing this binder fiber would be affected.

Bonding time has been found to have little effect on the properties of the nonwoven product (Wyatt, 1980; Shimalla & Whitwell, 1976). Fiber-fiber contact may increase as a result of the kinetics of wetting; however, the nonwoven produced for this study appeared to exhibit very little improvement with increased bonding time. In fact, flexural rigidity, breaking strength, and elongation decreased with the 60 second bonding time. In addition, an undesirable hand resulted from glazing of the product surface at the 60 second bonding time. Surface glazing did not occur with the 30 second bonding time.

Flexural rigidity and tensile strength measurements of the experimental bonded products were compared to the same measurements of

five commercially prepared carded dry laid parallel nonwoven fabrics obtained from Staflex. These products included two polyester/rayon blends (% content unknown) and three 100% polyester samples. Those measurements are shown in Table VIII.

TABLE VIII

AVERAGE FLEXURAL RIGIDITY AND TENSILE STRENGTH OF COMMERCIALLY PREPARED NONWOVEN FABRICS

	Flexural Rigidity (mg-cm)			Breaking Load (kN/m)		Elongation (%)	
	Gw	Gf	Gt	MD	CD	MD	CD
mean	458.71	73.33	182.69	1.85	0.45	70.6	135.8
low	84.72	25.18	46.12	0.84	0.19	53.6	97.3
high	903.61	125.59	336.87	2.77	0.61	115.3	178.0

Although the values for tensile strength were different, the machine and cross direction ratios (4:1) for breaking load of the 375°F/30 second bonded samples compared most favorably to those of the commercially prepared samples. In addition, total flexural rigidity of the 375°F/30 second bonded samples most closely approximated the total flexural rigidity of the commercial samples. On that basis, the bonding temperature was determined to be 375°F (190°C) with a bonding time of 30 seconds.

II. MOLECULAR WEIGHT AND POLYDISPERSITY

The length of the polymer backbone ultimately determines the useful mechanical properties of a fiber, which directly influence the

mechanical properties of the nonwoven product. In the nonwoven product, fiber properties are especially crucial, as the yarn structure is nonexistent.

Typically, photodegradation has a pronounced effect on the molecular weight and polydispersity of the fiber structure and that effect varies with fiber content. For instance, photodegradation affects polypropylene and nylon rather drastically but has been found to have lesser effects on polyester. Molecular weight of the polyester fiber in the thermally bonded product was measured by (a) viscosity and (b) gel permeation chromatography. Polydispersity was additionally calculated from gel permeation chromatography data. Differential scanning calorimetry was used to determine the degree of crystallinity of the fiber with increased exposure time.

Viscosity

Solution viscosity is essentially a measure of the size of polymer molecules and it is empirically related to molecular weight for linear polymers. Measurements are made by comparing the efflux time for a specified volume of polymer solution to flow through a capillary tube with the corresponding efflux time for the solvent. Solution concentration is expressed in g/100 ml (g/dl). Intrinsic viscosity, from which molecular weight is derived, is independent of concentration but is a function of the solvent used. For many polymers, the viscosity average molecular weight ($\bar{M}v$) is 10 to 20% below $\bar{M}w$, and is nearer to $\bar{M}w$ than to $\bar{M}n$ (Billmeyer, 1971).

Values for relative viscosity (η_{rel}) and specific viscosity (η_{sp}) are shown in Tables IX and X respectively. Values for intrinsic viscosity and $\bar{M}v$ are given in Table XI. Viscosity average molecular weight was derived from the Mark-Houwink equation:

$$[\eta] = KM^a$$

where $K = 2.1 \times 10^{-4}$

$a = 0.82$

for the tetrachlorethane/phenol (1:1) solvent (Polymer Handbook, 1975). Plots of intrinsic viscosity versus concentration for the unexposed control, 100 hour, and 300 hour exposure levels are shown in Figures IV through VI.

As shown in Figure VII, with increased exposure time, $\bar{M}v$ decreased steadily through 250 hours of exposure. However, between 250 and 300 hours, $\bar{M}v$ rose to a value slightly above that at the 200 hour level, then slowly decreased from 300 to 350 hours of exposure. It appeared to level off after 350 hours of exposure.

Day and Wiles (1972), Blais, Day and Wiles (1973) and Carlsson and Wiles (1976) have reported decreased molecular weight in polyester after exposure to UV light. Day and Wiles (1972) observed decreased number average molecular weights ($\bar{M}n$) from viscometric data. Chain scission reactions appeared to predominate over crosslinking reactions, with additional -COOH end groups produced. Blais, Day and Wiles (1973) also reported a decrease in the molecular weight of polyester, largely occurring as a result of chain scission in the surface layers of

TABLE IX

RELATIVE VISCOSITY, η_{rel}

Exposure Time (Hours)	Concentration (g/dl)				
	8.00	0.53	0.40	0.32	0.26
	Relative Viscosity, η_{rel}				
0	1.6488	1.4098	1.3028	1.2582	1.1953
100	1.6408	1.4058	1.2770	1.2345	1.1896
200	1.5839	1.3645	1.2876	1.2306	1.1823
250	1.5652	1.3554	1.2623	1.2169	1.1686
300	1.6118	1.3843	1.2810	1.2240	1.1842
350	1.5991	1.3781	1.2809	1.2185	1.1798
400	1.5499	1.3470	1.2673	1.2120	1.1797

TABLE X

SPECIFIC VISCOSITY, η_{sp}

Exposure Time (Hours)	Concentration (g/dl)				
	8.00	0.53	0.40	0.32	0.26
	Specific Viscosity, η_{sp}				
0	0.6488	0.4098	0.3028	0.2582	0.1953
100	0.6408	0.4058	0.2770	0.2345	0.1896
200	0.5839	0.3645	0.2876	0.2306	0.1823
250	0.5652	0.3554	0.2623	0.2169	0.1686
300	0.6118	0.3843	0.2810	0.2240	0.1842
350	0.5991	0.3781	0.2809	0.2185	0.1798
400	0.5499	0.3470	0.2673	0.2120	0.1797

TABLE XI

INTRINSIC VISCOSITY AND VISCOSITY AVERAGE MOLECULAR WEIGHT

Exposure Time (Hours)	$[\eta]^a$	$\bar{M}_v{}^b$
0	0.720	20,467
100	0.715	20,294
200	0.665	18,577
250	0.617	16,955
300	0.670	18,747
350	0.650	18,067
400	0.660	18,047

[a] $[\eta]$ = Intrinsic viscosity = $(\eta_{sp}/c)_{c\ o} = (\ln \eta_{rel}/c)_{c\ o}$

[b] $\bar{M}_v$ = Viscosity average molecular weight, $[\eta] = KM^a$, where $K = 2.1 \times 10^{-4}$; $a = 0.82$.

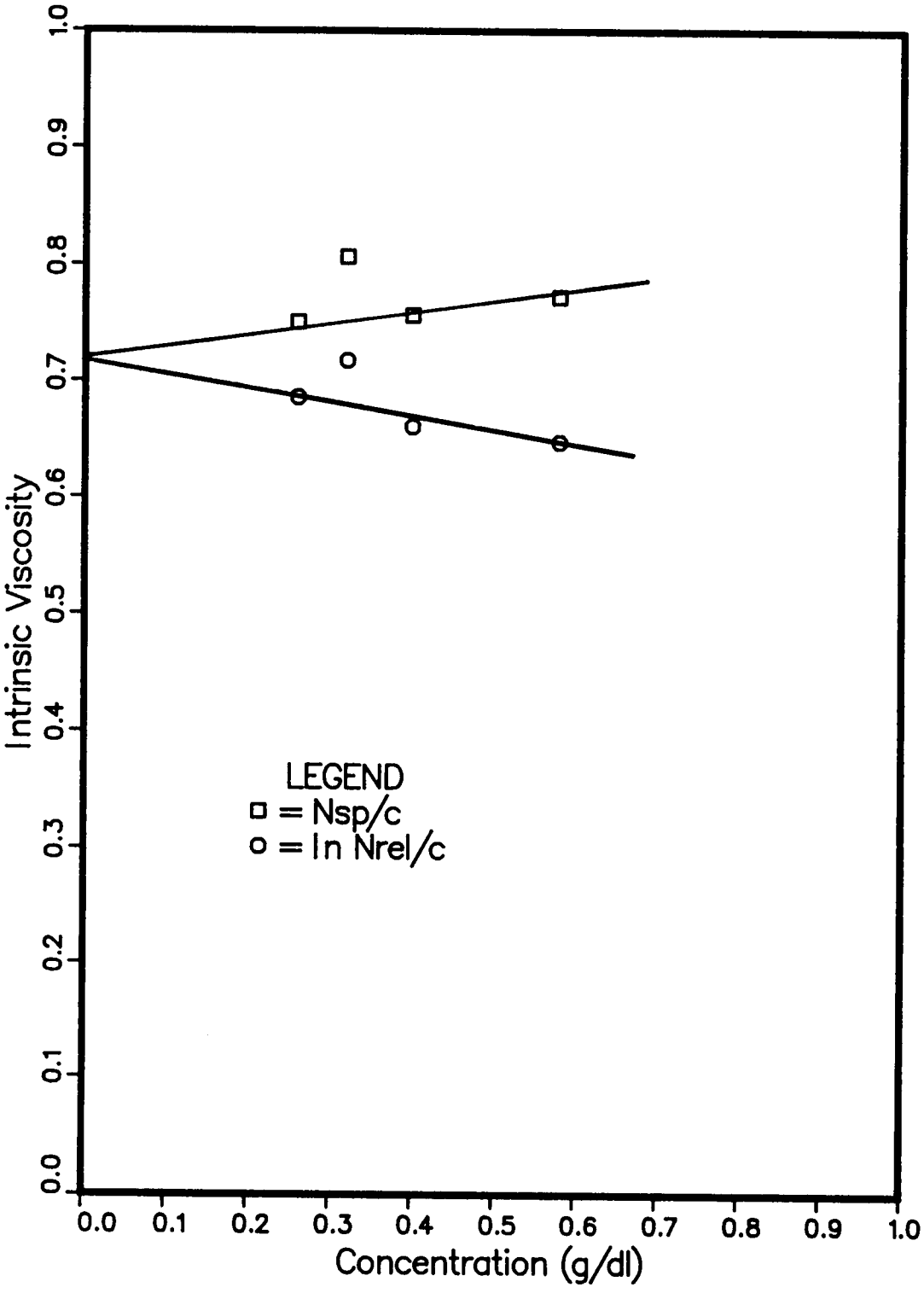


Figure IV. Intrinsic Viscosity: Unexposed Control

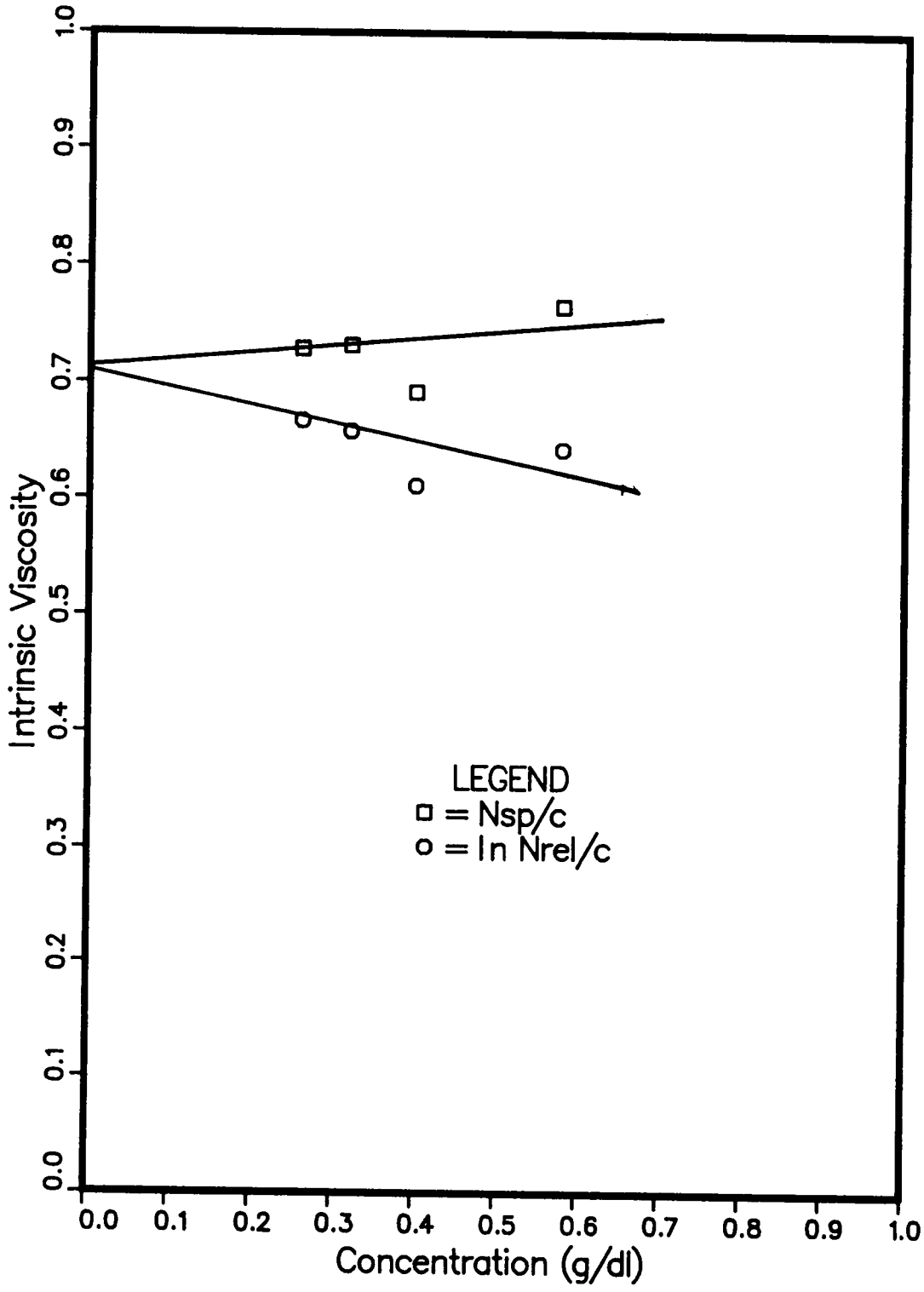


Figure V. Intrinsic Viscosity: 100 Hour Exposure

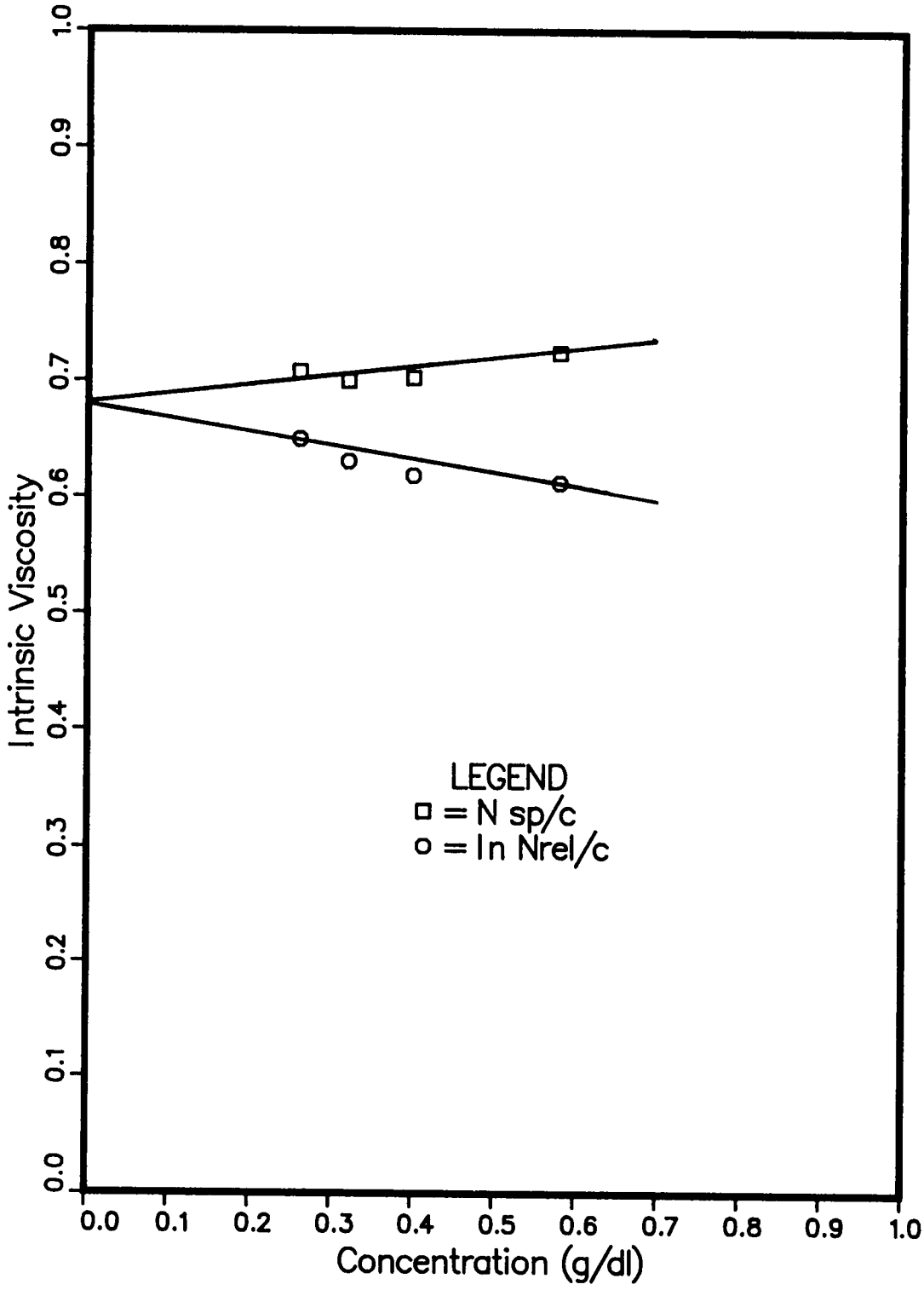


Figure VI. Intrinsic Viscosity: 300 Hour Exposure

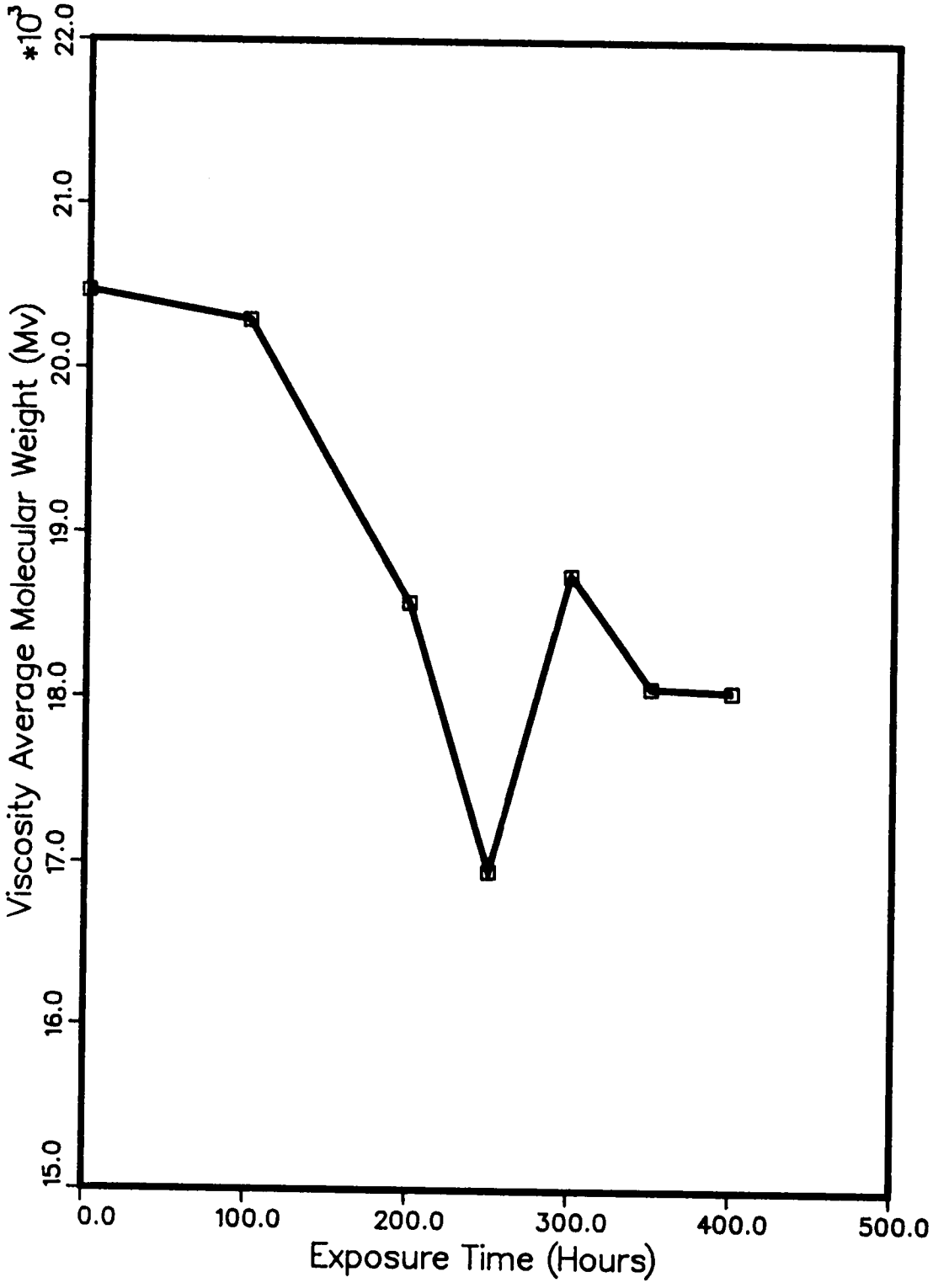


Figure VII. Viscosity Average Molecular Weight

the polymer. Carlsson and Wiles (1976) additionally confirmed lower molecular weight in the surface layers of the polyester fiber, and in particular in the surface directly facing the uv light source.

The research cited above supports this experimental work that appears to indicate decreased molecular weight with increased time of exposure to uv light. It would appear that the greatest degradation occurred with 250 hours of exposure to uv light, indicating perhaps that more uniformly short molecules were produced. Although there is no known literature to support this viewpoint, it is conceivable that the apparent minimum in $\bar{M}v$ at the 250 hour exposure level could be attributed to the possibility that shorter molecule fragments incorporated with less degraded, longer molecules at this exposure time might serve to increase the fluidity of the molecular solution. The apparent increase in $\bar{M}v$ from 250 to 300 hours of exposure to uv light may be due to more uniform molecular lengths as a result of increased degradation.

Although the increase in $\bar{M}v$ from 250 to 300 hours of exposure to a value slightly higher than that obtained at 200 hours of exposure was unexpected, crosslinking effects also may have been responsible for that increase. Atmospheric conditions within the Weatherometer chamber were controlled only through air circulation, temperature, and relative humidity. Reactions may have occurred with ozone, nitrogen oxide, and/or other reactive species that might have induced crosslinking and thus an increase in molecular weight during that time period (V. R. Allen, personal communication, July 29, 1986; M. H. Lietzke, personal communication, August 5, 1986).

The molecular weight and polydispersity values obtained from gel permeation chromatography (GPC) performed by Springborn Laboratories, Inc. lends some support to the increased viscosity observed in the work between 250 and 300 hours of exposure to uv light. One unexposed sample and 100, 200, 250, 300, 350 and 400 hour exposure level samples were analyzed for number average molecular weight ($\bar{M}n$), weight average molecular weight ($\bar{M}w$), and polydispersity. All average molecular weights ($\bar{M}n$, $\bar{M}w$, $\bar{M}v$) are compared in Figure VIII. Values for polydispersity are shown in Figure IX.

Both $\bar{M}w$ and $\bar{M}n$ decreased steadily through 200 hours of exposure to uv light. However, upon exposure to 300 hours of uv light, $\bar{M}n$ increased slightly while $\bar{M}w$ continued to decrease by a relatively small amount. Polydispersity increased as expected from molecular weight data, then decreased by a small amount with 300 hours of exposure. All of these trends indicated potential chain scission reactions up to 300 hours of exposure, with a possibility of crosslinking indicated with increased average molecular weight averages at the 300 hour exposure level.

Differential Scanning Calorimetry

Differential scanning calorimetry measurements were limited to the unexposed control and exposure times of 100, 200, 250, and 300 hours of exposure. The data obtained at these exposure levels do provide support for the observed change in physical performance behavior. Values for the glass transition temperature (Tg), melting transition

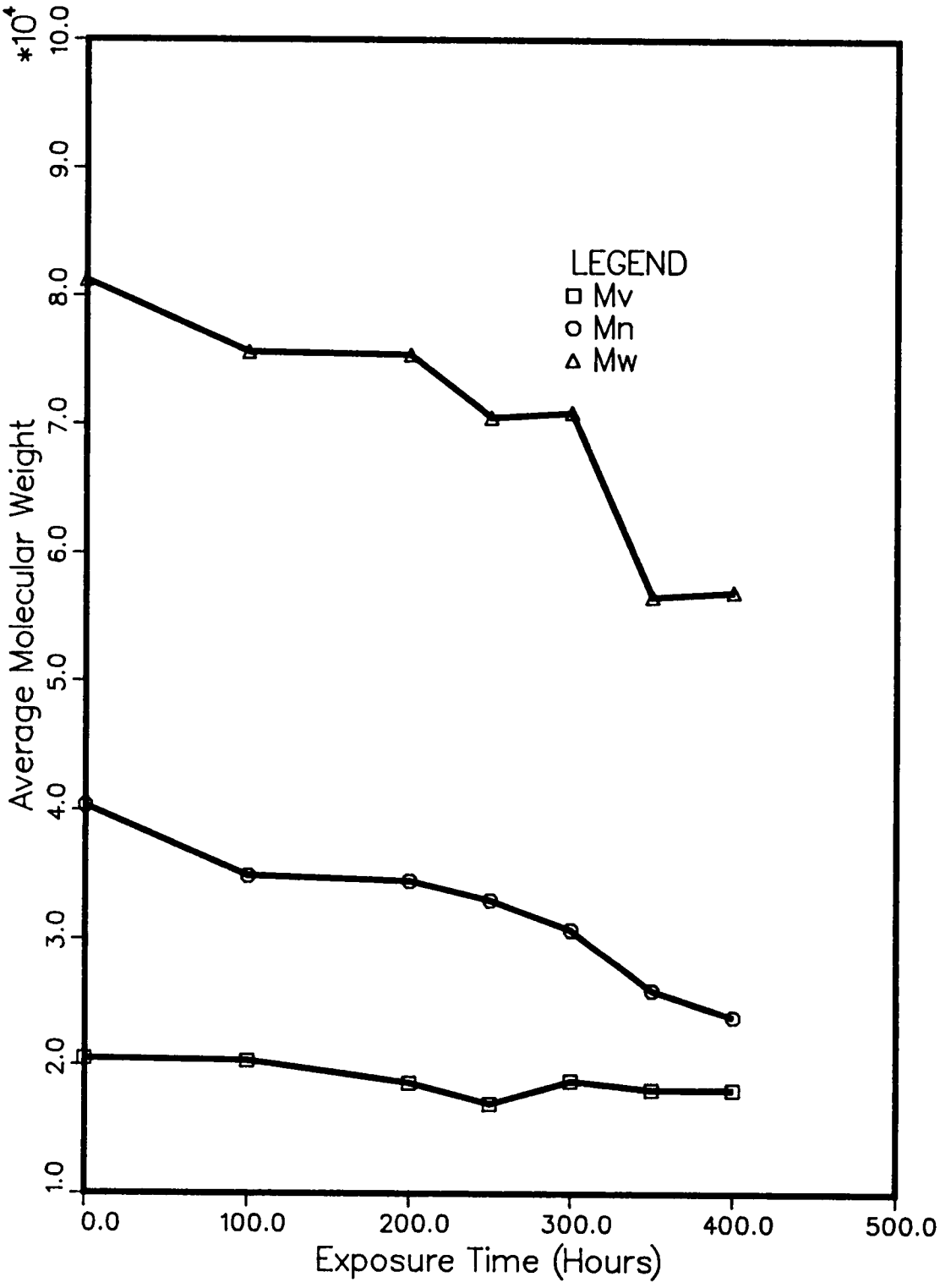


Figure VIII. Relationship Between $\bar{M}w$, $\bar{M}n$, $\bar{M}v$

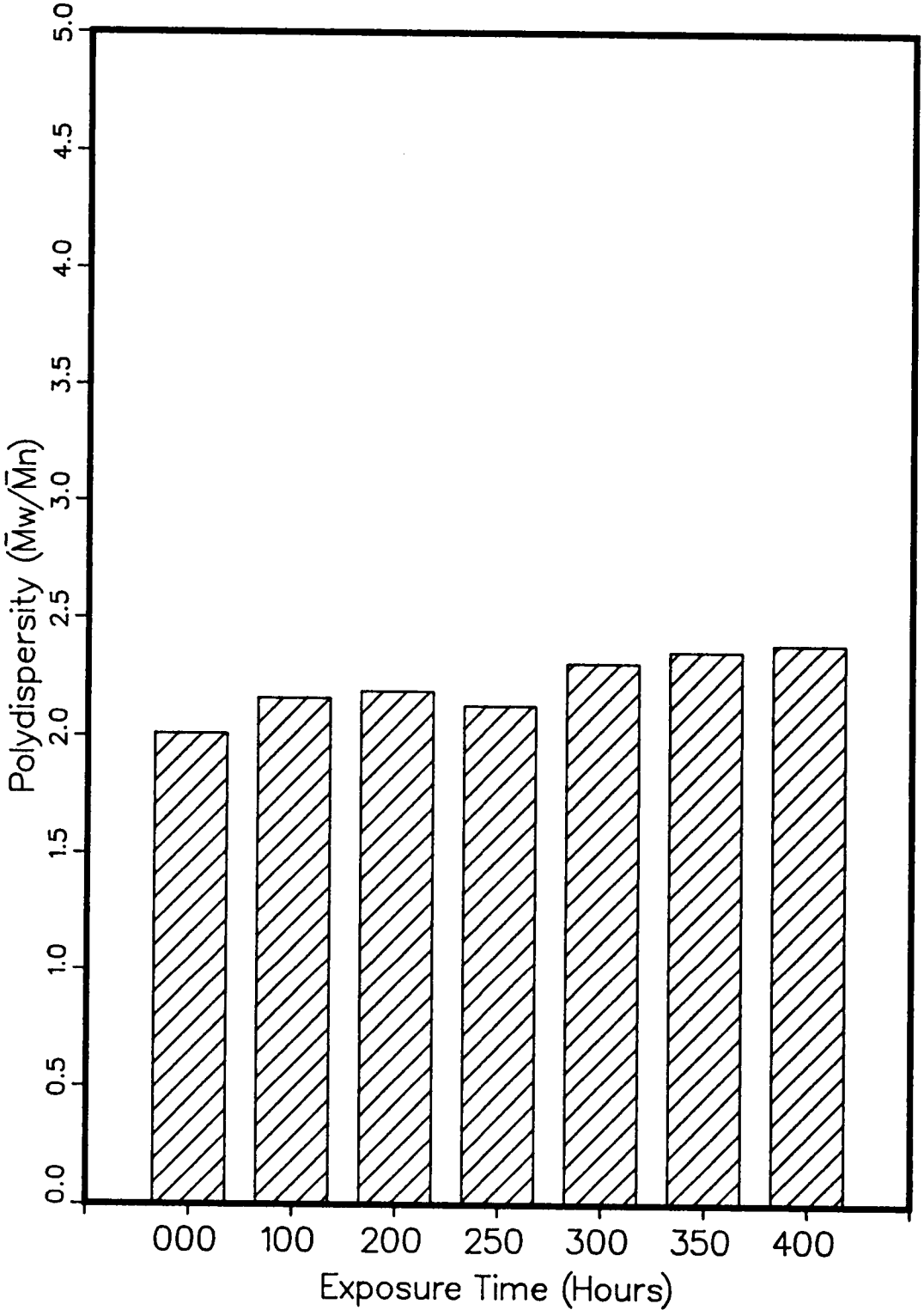


Figure IX. Polydispersity: 0-400 Hours

temperature (Tm), heat of fusion (ΔHf), and degree of crystallinity (%C) are shown in Table XII.

Melting transition temperature and glass transition temperature from 0 to 300 hours of exposure are illustrated in Figure X. Tm is the melting point of the most perfectly crystalline regions. No change in Tm is apparent with increased exposure time. This is to be expected, as Tm is usually considered to be independent of molecular weight in the polymer ranges (Billmeyer, 1970). Chain ends are usually associated with defects in the crystalline regions of polymers, and are therefore unlikely to change Tm.

The Tg is the temperature range in which the thermal motion of the molecules slows to the point that they are unable to respond within a reasonable time to the action of applied force. Thus the polymer changes from a soft to a hard substance as the temperature is lowered through this temperature range (Bueche, 1962).

Tg and Tm are related for many polymers in that Tg is approximately one-half to two-thirds the value of Tm. This appears to be the case for the polyester nonwovens used in this study (Table XII). Lower ratios of Tm to Tg are associated with increased crystallization (Billmeyer, 1970). From Figure X, it can be seen that the difference between Tm and Tg appeared to be the least at 200 hours of exposure to uv light.

The degree of crystallinity as determined from the DSC analysis is illustrated in Figure XI. In support of Billmeyer's theory, the degree of crystallinity is the greatest at 200 hours of exposure, which corresponds to the lowest ratio of Tm to Tg.

TABLE XII

DIFFERENTIAL SCANNING CALORIMETRY

Exposure Time (Hours)	T_g[a] (°K)	T_m[b] (°K)	ΔH_f[c] (cal/g)	%C[d]
0	343.41	529.27	6.30	18.86
100	368.15	529.32	6.01	17.99
200	387.68	528.68	7.50	22.42
250	344.49	528.62	4.71	14.09
300	319.96	520.03	4.40	13.16

[a] T_g = Glass transition temperature

[b] T_m = Melting transition temperature

[c] ΔH_f = Heat of fusion

[d] %C = Percent crystallinity

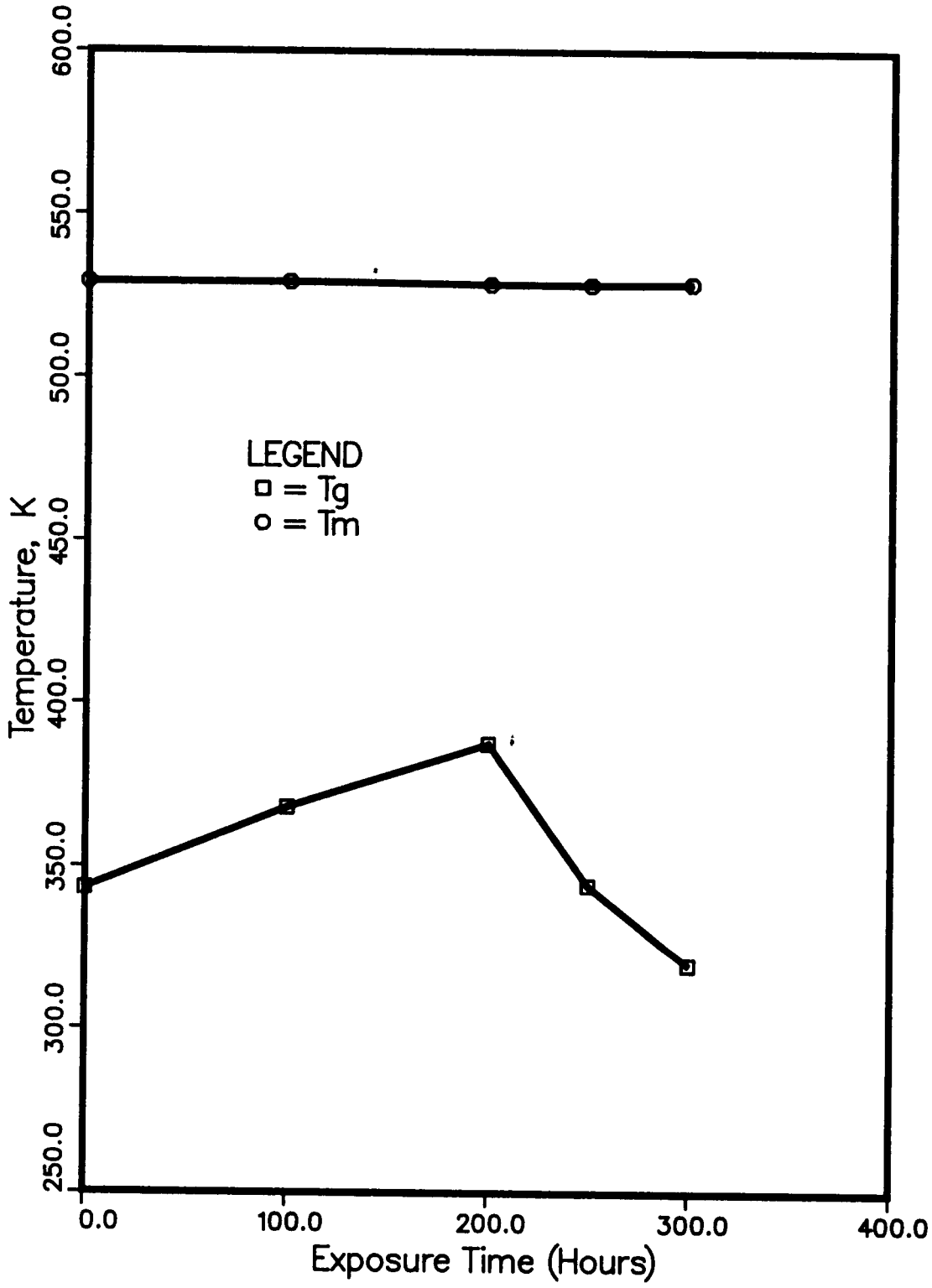


Figure X. Tm and Tg: 0-300 Hours

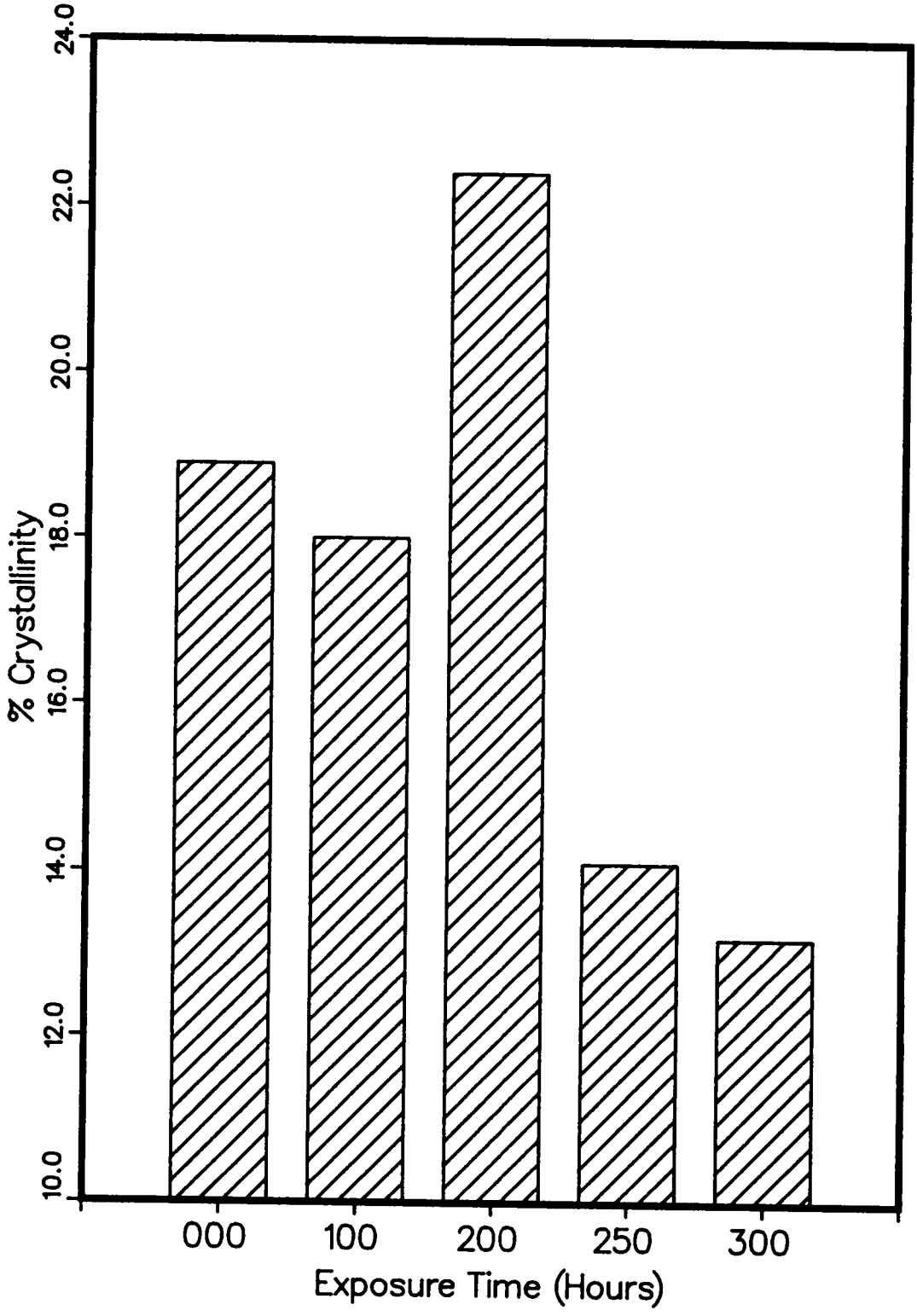


Figure XI. Degree of Crystallinity: 0-300 Hours

Tg is affected by chain branching and crosslinking. A higher concentration of chain ends in a branched polymer lowers the Tg. Crosslinking effectively raises Tg (Billmeyer, 1970). The Tg trend exhibited in Figure X indicates an increase in Tg with exposure times increasing to 200 hours, which may indicate crosslinking. Thereafter, Tg decreases notably with increased exposure time, perhaps indicating a higher concentration of chain ends as a result of chain scission from exposure to uv light, thereby overriding the crosslinking effect.

Heat of fusion (ΔHf) refers to the evolution of heat when molecules originally in a liquid come together to form a crystal. Whenever strong intermolecular bonding is possible, ΔHf will be larger due to the tighter association bonds between the molecules in a crystal over those in a liquid. Positive changes in ΔHf favor formation of crystalline structure (Billmeyer, 1970). The effect of increased exposure time on ΔHf is illustrated in Figure XII. Decreases in ΔHf are apparent at all exposure levels with the exception of the 200 hour exposure. The observed increase in ΔHf with 200 hours of exposure indicates increased crystallinity, again perhaps attributed to chamber atmosphere-induced crosslinking reactions within the polyester fiber.

III. PHYSICAL PERFORMANCE BEHAVIOR

The mechanical properties of large molecules that determine physical performance behavior ultimately depend on the extended length of the polymer backbone. Extensive entanglement and folding facilitates the formation of crystallites interconnected by amorphous zones. Since

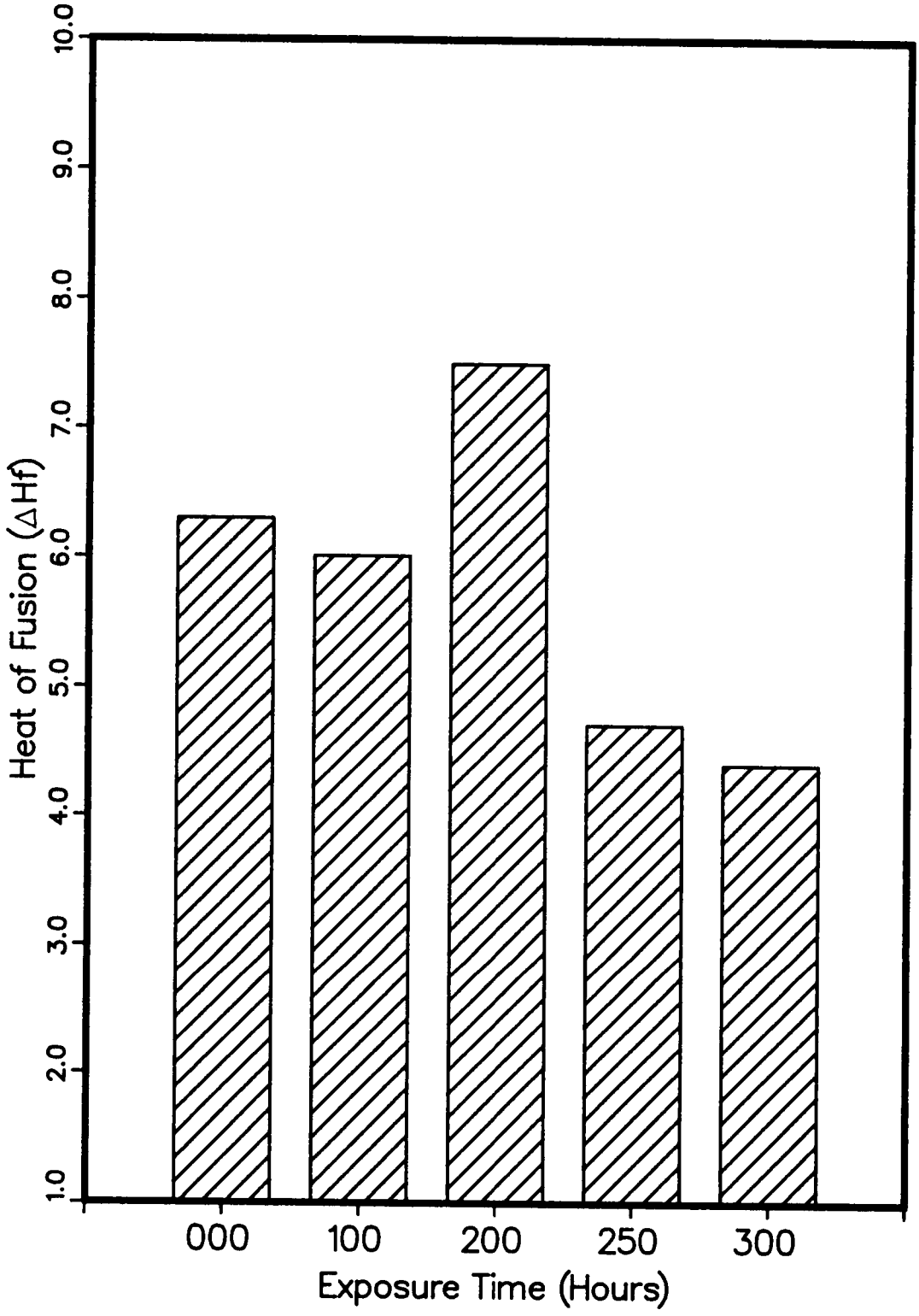


Figure XII. Heat of Fusion: 0-300 Hours

scission reactions occur primarily within the amorphous zones which connect the crystallites, any backbone cleavage typically results in a weakening of the polymer structure (Carlsson & Wiles, 1976).

In this study, physical performance behavior was characterized in terms of (a) flexural rigidity--machine and cross directions, (b) tenacity--machine and cross directions, and (c) extension--machine and cross directions. The effects of fabric weight and thickness are first discussed in relation to physical performance behavior.

Fabric Weight and Thickness

Efforts were made during web processing to control for uniformity of weight, thickness, and distribution of the binder fiber in order to decrease the effects of these variables on physical performance behavior. The average weight of the nonwoven product was 62.35 g/m^2, with little variability between bonded samples. Average fabric thickness was 0.005 inch (1.27×10^{-4} mm), with a standard deviation of 0.0008 inch (2.2×10^{-5} mm). Variations in thickness may have been the result of potentially uneven distribution of the binder fiber throughout the web. Scanning electron microscopy (SEM) photomicrographs were obtained at 150X magnification to determine the binder fiber distribution. On the average, the binder fiber was uniformly distributed throughout the web. The binder fibers did not appear to melt completely and did retain a structure that appeared to contribute to product properties.

Flexural Rigidity

There was no clear trend apparent in flexural rigidity (Figure XIII), with increased exposure up to 400 hours. With increased exposure time, flexural rigidity increased, then decreased consistently, until flexural rigidity values at 350 and 400 hours of exposure began to level out. Analysis of variance procedure indicated a significant difference at the 0.05 level between time length of exposure and flexural rigidity of the nonwoven. Using Tukey's Studentized Range Test for flexural rigidity, a comparison significant at the .05 level was identified between 100 to 200 hour exposures. Beyond 200 hours of exposure, comparisons were not significant in that values for flexural rigidity became increasingly similar with increased exposure times.

If all three curves are examined in Figure XIII, no clear trend for flexural rigidity emerges. Values for the cross direction (CD) are approximately one half the values for the machine direction (MD). Such behavior is typical in parallel laid nonwovens. MD values include the bending effect of base fibers and the binder fiber penetration. Because of the small degree of orientation in the CD, mechanical properties of the CD are almost entirely dependent on the degree of bonding and therefore may not be a reliable predictive measure of the flexural rigidity behavior of the nonwoven. In the same manner, the total flexural rigidity (Gt) is a function of the CD flexural rigidity (Gf) and again may not be an effective predictive assessment. Upon examination of the MD flexural rigidity (Gw), there appears to be a slight overall decrease in flexural rigidity with increased exposure

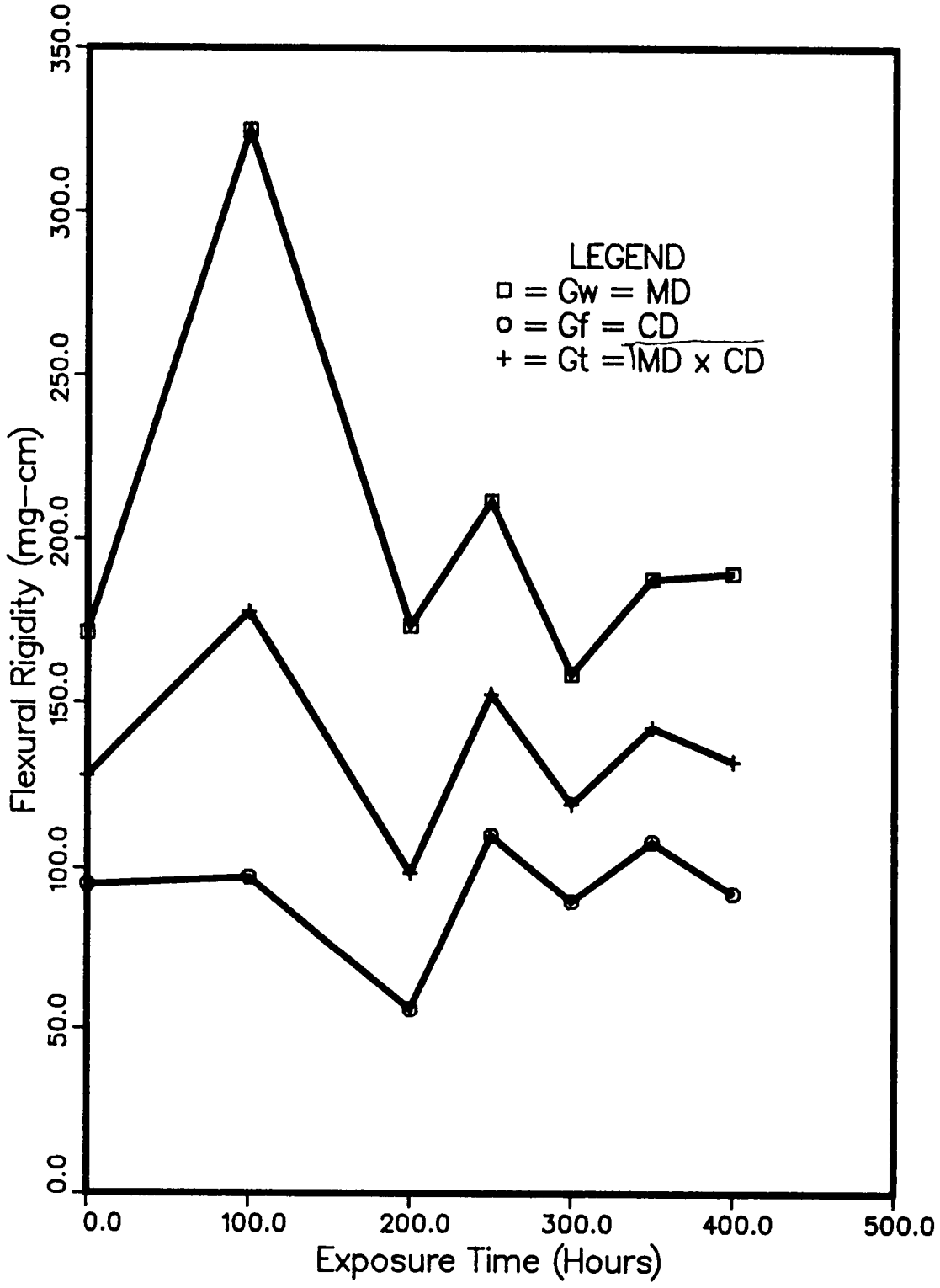


Figure XIII. Flexural Rigidity--Gw, Gf, Gt

time. As shown in Figure XIII, there is an initial increase in MD flexural rigidity with 100 hours of exposure to uv light. Initially, crosslinking appears to take place with subsequent loss of chain length evidenced by molecular weight decreases. It is expected that the reduced chain length would increase softness and make the nonwoven more flexible. However, crosslinking appears to offset the molecular weight decrease and helps to overcome the increased softness by making the nonwoven more rigid.

In the absence of oxygen, polyester has been found to undergo crosslinking, probably as a result of radical addition to phenyl rings in adjacent chains (Carlsson & Wiles, 1976). Crosslinking reactions are reduced, but still may occur, in the presence of oxygen due to oxygen interception of radical intermediates. Thus additional backbone cleavage reactions become important, promoting decreased molecular weight and less rigid fibers. Exposure to uv light in this study was performed in the presence of oxygen in the Weatherometer exposure chamber; thus both crosslinking and chain scission may have occurred to produce the trends observed in the MD in Figure XIII.

Tensile Strength (MD and CD)

The average values for MD are generally 2.5 to 3.5 times higher than those of the CD, again due to the inherent strength of the MD oriented fibers in parallel laid webs. Analysis of variance procedure indicated a significant different at the .05 level between time length of exposure and tensile strength. Using Tukey's Studentized Range Test for tenacity, comparisons significantly different at the .05 level

appeared between the control and all exposures at 250 hours and beyond, the 100 hour exposure and all exposures at 250 hours and beyond, and the 200 hour exposure and all exposures at 250 hours and beyond. With the exception of the 200 to 300 hour exposure time, tensile strength steadily decreased in both the MD and CD. However, a sharp increase in tensile strength occurred between 200 and 300 hours of exposure, a finding in contrast to most reported studies (Figure XIV).

The observed values for tensile strength are supported by the changes occurring in the molecular weight of the polyester fiber. Increases in molecular weight may be due to crosslinking. For all average molecular weight determinations, ($\bar{M}v$, $\bar{M}n$, $\bar{M}w$), decreases in molecular weight were directly related to decreases in tensile strength up to 200 hours of exposure and in most cases after 300 hours of exposure. The lowest molecular weight averages were observed at 250 hours of exposure. These averages increased at 300 hours of exposure, indicating some crosslinking which would of course increase the effective molecular weight. Then molecular weight appeared to decrease and level at 350 and 400 hour exposures. Tensile strength patterns followed the same trend, with the exception of the 250 hour exposure. Molecular weight was at its lowest, yet tensile strength increased markedly.

Loss of tensile properties in polyester following exposure to ultraviolet light has been observed by Wall and Frank (1971), Day and Wiles (1972) and Carlsson and Wiles (1976). Generally, loss in tensile

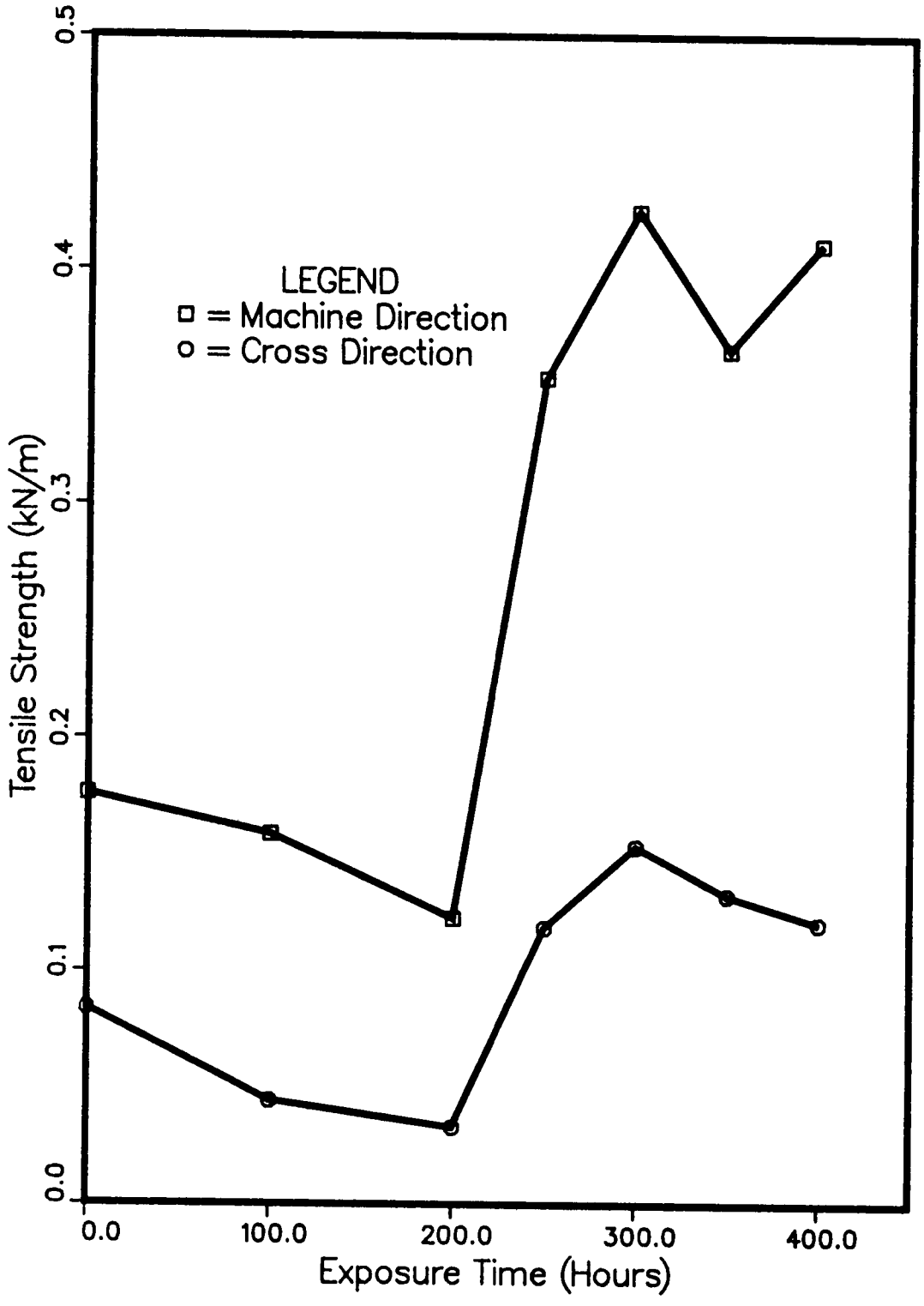


Figure XIV. Tensile Strenth--Machine and Cross Directions

properties has been accompanied by decreased molecular weight and the increased formation of carboxylic acid end groups.

In particular, Carlsson and Wiles (1976) attribute decreased tenacity in the polyester fiber to backbone scission and the resulting surface cracks under low stress. All of the damaging shortwave uv is absorbed by the surface of the polyester fiber at a depth of a few microns. The surface then serves as a shield to the remainder of the fiber. However, no surface changes even after extensive exposure (600-1200 hours) have been observed. Polyester in the unstressed state is not expected to crack during exposure because the inter- and intramolecular forces in the fiber structure will resist surface contraction. However, extensive backbone scission occurs on the surface skin. Thus, even a small extension causes cracking at right angles to the applied stress in the photooxidized layer, effectively decreasing tenacity.

Extension

Analysis of variance procedures indicated a significant difference between time length of exposure and extension. Using Tukey's Studentized Range Test, extension behavior in both the MD and CD with 300 hours of exposure was significantly different from all other exposure time lengths. Both the MD and CD exhibited a similar pattern in extension behavior, with CD values always less than MD values as expected with the parallel laid nonwoven.

As shown in Figure XV, with increased exposure time length, extension decreased as expected upon exposure to uv light up to

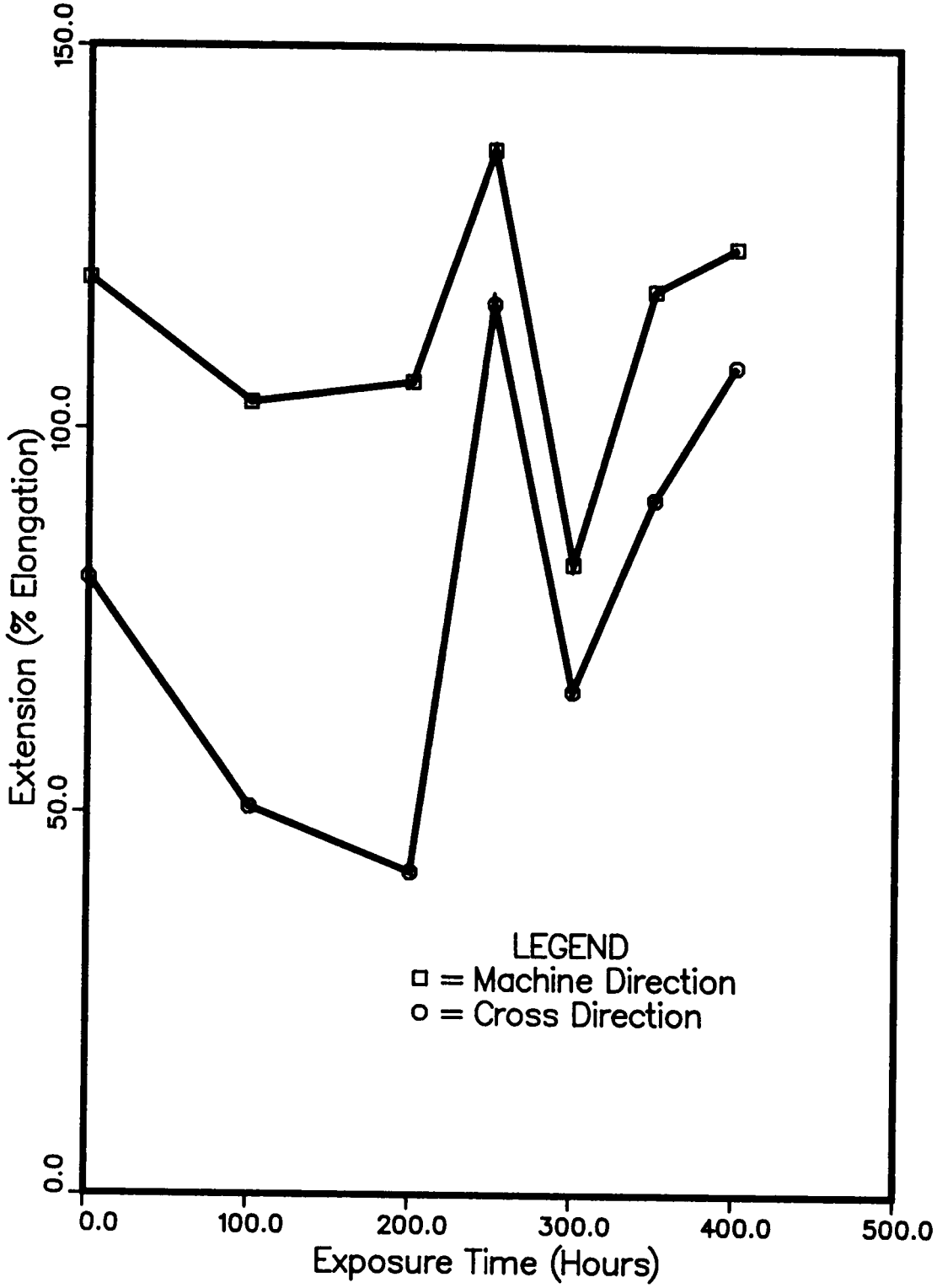


Figure XV. Extension--Machine and Cross Directions

200 hours. Similar loss in extension has been observed by Wall and Frank (1971), Day and Wiles (I, 1972), and Blais, Day and Wiles (1973). The great increase in extension between 200 and 250 hours of exposure is supported by a simultaneous decrease in the degree of crystallinity during the same time period (Figure XI, p. 82). Typically, the less crystalline fiber would exhibit greater capabilities for extension than the more crystalline fiber.

The subsequent decrease in extension at 300 hours and increase thereafter is somewhat difficult to interpret. It would be expected that extension would decrease based on the work of Wall and Frank (1971). However, the increase in extension from 300 to 400 hours of exposure is compatible with the observed decreases in all average molecular weights.

CHAPTER V

SUMMARY AND CONCLUSIONS

The objectives of this study were to determine the effects of exposure to uv light at 121°F (49°C) and 58% relative humidity on the physical performance behavior of thermally bonded polyester nonwoven fabrics, and to determine the length of exposure time at which the mechanical properties of the nonwoven fabric are adversely affected due to degradation by uv light. In addition, the effects of exposure to uv light on the polyester fiber were evaluated in terms of molecular weight and polydispersity.

The thermally bonded polyester nonwovens used were produced specifically for this study. Base and binder fibers, as well as the 30% binder content, were taken from recommendations made by Wyatt (1980). Blending of binder and base fibers occurred during the opening process. The laps were carded twice to facilitate better uniformity and distribution of the binder fibers throughout the parallel-laid webs.

All webs were bonded using a hydraulic press with a pressure of 111.11 psi (765.55 kPa). Bonding temperature and bonding time were determined by experimentation based upon manufacturer's recommendations and Wyatt's (1980) recommendations. Preliminary bonding trials were performed at 260°F (127°C), 300°F (149°C), 350°F (176°C), 375°F (190°C), and 400°F (204°C) at 30 second, 60 second and 90 second intervals. After comparison of experimental fabrics with representative commercially prepared market samples for visual uniformity and hand,

additional bonding trials were completed at 350°F (176°C), 375°F (190°C), and 400°F (204°C) at 30 second and 60 second intervals. Results of those temperature/time trials were compared with market samples on the basis of hand, flexural rigidity, and tensile strength. The samples bonded at 375°F (190°C) for 30 seconds compared most favorably to market samples; thus, the 375°F (190°C)/30 second conditions were used for all further bonding trials.

Physical and mechanical properties of the nonwoven fabric were evaluated prior to exposure to uv light. Properties measured included weight, thickness, flexural rigidity--machine and cross directions, tenacity--machine and cross directions, and elongation--machine and cross directions.

Samples were exposed to ultraviolet light in the Atlas Xenon-arc Weatherometer for periods of 100, 200, 250, 300, 350, and 400 hours. Following exposure, physical and mechanical properties were measured, as well as changes in molecular weight and polydispersity ($\bar{M}w/\bar{M}n$) of the polyester fiber. Changes in molecular weight were determined through viscosity and gel permeation chromatography. Changes in polydispersity were calculated from the gel permeation chromatography results. Differential scanning calorimetry was used to determine changes in the degree of crystallinity. Scanning electron microscope photomicrographs were evaluated to assess the degree of fiber surface damage. Results from the data collected were analyzed according to the hypotheses.

I. MOLECULAR WEIGHT AND POLYDISPERSITY

Hypothesis II: There will be a significant difference in the molecular weight and polydispersity of the polyester fiber in the thermally bonded nonwoven product before and after exposure to ultraviolet light.

In support of Hypothesis II, differences were observed in the molecular weight and polydispersity of the polyester fiber before and after exposure to ultraviolet light. Although large differences were identified between lengths of exposure time, there were not a sufficient number of replications to determine the statistical significance of those differences. The number of replications was limited due to cost and processing time.

With increased exposure time, viscosity average molecular weight appeared to decrease with up to 250 hours of exposure, probably as a result of uv-induced chain scission. An apparent increase in $\bar{M}v$ between 250 and 300 hours of exposure may be the result of crosslinking effects due to atmospheric conditions. The decrease in $\bar{M}v$ following 300 hours of exposure to uv light is most likely attributed to a predominance of chain scission reactions. Decreased $\bar{M}w$ and $\bar{M}n$ and increased polydispersity through 300 hours of exposure to uv light was supported by gel permeation chromatography (GPC) data.

From differential scanning calorimetry (DSC) analysis, it appeared that the greatest degree of crystallinity occurred with 200 hours of exposure to uv light, with decreased degree of crystallinity occurring thereafter. The crystallinity behavior corresponded to Tm/Tg ratios

as cited in the literature in that the lower Tg/Tm ratios, the greater the crystallization within the fiber structure.

The trend in the Tg behavior of the polyester fiber indicated a possibility of crosslinking due to increased chain length with exposure times increasing to 200 hours. Thereafter, Tg decreased notably, perhaps indicating a higher concentration of chain ends as a result of chain scission from exposure to uv light.

II. PHYSICAL PERFORMANCE BEHAVIOR

Hypothesis I: There will be a significant difference in the physical performance behavior of thermally bonded polyester nonwoven fabrics before and after exposure to ultraviolet light.

In support of Hypothesis I, significant differences at the 0.05 level were observed for measurements of all mechanical properties under study. SEM photomicrographs indicated a uniform distribution of binder fiber throughout the web as was expected, with both binder fiber and base fiber oriented in the machine direction. Little variation occurred in fabric weight and thickness.

Because of the observed machine direction orientation of the fibers, flexural rigidity assessment was primarily focused upon the machine direction. With increased exposure time, a slight overall decrease in flexural rigidity was observed. The initial increase in flexural rigidity with 100 hours of exposure to uv light may be attributed to crosslinking. Subsequent decreases in molecular weight indicate loss of chain length due to chain scission reactions.

Tensile strength patterns appeared to parallel molecular weight trends up to 200 hours of exposure and in most cases after 300 hours of exposure. The lowest molecular weight averages were observed at 250 hours of exposure and increased at 300 hours of exposure, again indicating some possible crosslinking behavior. Molecular weight appeared to decrease and level off at 350 and 400 hours of exposure. Tensile strength patterns followed the same trend, with the exception of the 250 hour exposure. Tensile strength increased markedly while molecular weight at its lowest.

III. CONCLUSIONS

While only a relatively few investigations have been performed on the effects of uv light on polyester, most of these seem to suggest that various degrees of degradation do occur (Day & Wiles, 1972; Blais, Day & Wiles, 1978; Carlsson & Wiles, 1976). In agreement with these investigations, the results obtained in this study indicated that thermally bonded polyester nonwoven fabrics are adversely affected by exposure to uv light in the Xenon-arc Weatherometer. However, the effects of photodegradation observed, as was predicted, appeared to be less for polyester than for fibers such as nylon and polypropylene.

Decreases in both tenacity and flexural rigidity appeared to occur with time up to 200 hours of exposure and after 300 hours of exposure to uv light. Trends in molecular weight and polydispersity support the observed mechanical behavior. Although there was an unexpected occurrence of increased strength and flexural rigidity between 200 and

300 hours of exposure to uv light, crosslinking may be an effect that caused the increase in those mechanical properties. The apparent decreases in those properties thereafter are believed to be attributed to continued chain scission reactions.

IV. RECOMMENDATIONS

Since the thermally bonded polyester nonwoven fabric used in this study is most appropriate for end use as interlining or interfacing, it is recommended that further investigation be performed using layered systems such as draperies, upholstered configurations, and outerwear more representative of actual end use. The fabrics used in layered systems may well serve to filter some of the damaging uv wavelengths, therefore diminishing the photodegradation of the thermally bonded polyester nonwoven product. In addition, exposure to uv light for time periods more extensive than those investigated in this study is recommended to more adequately assess photodegradation behavior.

In the thermally bonded nonwoven using a binder fiber as the bonding agent, the system is essentially composed of three components. Mechanical failure could occur as a result of failure in the base fiber, binder fiber, and/or adhesion mechanism between the two. Further investigation is necessary to determine the contribution of base fiber, binder fiber, and bond mechanism to failure due to photodegradation.

Atmospheric control within the exposure chamber seems to be necessary to more accurately assess the chemical mechanisms occurring

in response to exposure to uv light. However, further investigation of photodegradation due to sunlight exposure appears to be both warranted and realistic.

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VITA

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