UNIVERSITY OF ALBERTA

Relationship of Fiber Type, Mass and Cover to the Sun Protection Factor of Fabrics

by

SANDRA MELISSA DAVIS ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE

in

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Dear Sandra Davis,

Thank you for your letter of 11 January 1995.

I am content for you to use any material from the McKinlay and Diffey paper for your thesis.

My own Department is also carrying out research work on UVR protection from fabrics, including participation in an international intercomparison of measurements. I would very much like to receive an abstract of your thesis when it is completed.

There follows in this transmission a copy of a later erythema action paper which was published by Brian Diffey and I in the CIE Journal.

If I can be of any further help please do not hesitate to let me know.

Yours sincerely,

Dr A F McKinlay
Head, Non-ionising Radiation Department

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Robert Fedosejevs

Robert Fedosejevs, PhD

Date January 31/95

This thesis is dedicated to

my family.

Abstract

The purpose of this study was to determine the effects of fiber type, fabric structure, mass, count and cover on the Sun Protection Factor (SPF) of fabrics. Also, four fabrics were dyed to determine the effect of color on SPF.

Fabric SPF was calculated from (1) distribution and intensity of solar ultraviolet radiation (UVR) (250 to 400 nanometers) for central Alberta; (2) propensity of UVR to damage fair skin ; and (3) transmission of UVR (250 to 400 nm) through fabric samples, measured spectrophotometrically. Cover was measured using image analysis software.

Nineteen of twenty eight fabrics had SPF's less than 15, providing less protection than many sunscreens. A high correlation between mass and SPF was noted for individual fiber types. Mass had the most significant effect on SPF of all the fabric variables (fiber type, structure, count, mass and cover). Dyeing the cotton samples blue increased their SPF's by a factor of three times.

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CHAPTER I

Introduction

Clothing has been used as protection from the elements for many centuries. With changes in human activities and in the world around us, clothing has been designed as protection from such things as absorption of pesticides through skin, infliction of injury during work or recreation, and harm from gunshots. This research explores another application of protective clothing: clothing as protection from the harmful effects of exposure to ultraviolet radiation.

The incidence of skin cancer is quickly rising due in part to increased exposure to ultraviolet radiation (UVR) (Band et al., 1993; Giles, 1992). Higher levels of exposure to UVR result from decreased ozone in the stratosphere, a change to outdoor lifestyles, and prevailing social and fashion trends which expose skin. Excessive exposure can lead to carcinogenesis, sunburn, cataracts and decreased immunological responses. Genetic factors causing sensitivity to the sun may contribute to the greater risk of skin cancer in some people. Children need to be protected from over exposure, since it is now believed that cumulative UVR exposure leads to skin cancer in later life (Marks, 1988; Weinstock et al., 1989).

Previous to this study, the protection from UVR that clothing provides has been examined by several researchers. These researchers have established that some UVR passes through many types of fabric. The percent transmission of UVR through fabric depends largely on the amount of open space between the yarns and fibers (Morikofer, 1931; Pailthorpe, 1993a). There is little consensus among other findings of these studies, but some researchers have shown that wet fabrics block less UVR than dry fabrics (Jevtic, 1990), and that color, mass, thickness, fiber type, additives and finishes may also influence transmission (Robson & Diffey, 1990).

Data from such studies of UVR transmission through clothing are often reported as percent transmission (%T) of UVR. However, environmental and biological factors must be considered, as well as percent transmission, when quantifying the actual degree of protection which clothing offers the skin from UVR exposure. Hence, data have also been reported as 'protection factors'. Calculations of protection factors require either human, or *in-vivo*, testing or weighting the percent transmission with appropriate solar and biological data. Appropriate solar data include intensity and range of the solar UVR present at a specific geographical region of interest. Many factors affect these values, such as altitude, latitude, season, cloud cover and ozone thickness (Marks & Selwood, 1985). The solar data for a given locale comprise the solar action spectrum.

Biological data are averages of typical skin responses to a range of UVR exposure.

The data that are typically used are only applicable to people with fair complexions; these are the individuals most at risk of contracting skin cancer. A collection of skin response data most frequently used to represent the responses of fair-skinned individuals is the erythemal action spectrum developed by McKinlay and Diffey in 1987. Erythema is "vasodilation and an increase in the volume of blood in the dermis perceived visually as a reddening of the skin" (American Council on Scientific Affairs, 1989, p. 380) and may be caused by UVR exposure. It is used as a subjective indication of how much damage occurs to the skin due to UV exposure.

The purpose of this study is to examine some of the unconfirmed correlations of fabric parameters and UVR protectiveness found in previous studies. A thorough analysis of fabric parameters, an aspect which appeared to be lacking in previous studies, will assist in identifying the relationships of fiber type, mass, cover, structure, fabric count and color to the transmission of UVR through fabrics. If high correlations exist, the protectiveness of fabrics can be predicted from fabric parameters. Spectrophotometric measurement will be used to determine if the amount of transmission is dependent on wavelength and if fabrics block in both UVA (320 to 400 nanometers) and UVB (290 to 320 nm) regions.

Problem Statement

In light of the increasing incidence of skin cancer in North America and other regions of the world and in recognition of the fact that skin cancer is related to exposure to ultraviolet radiation, the purpose of this study is to examine the effectiveness of clothing fabrics as a barrier to solar UVR and to identify fabric parameters which contribute to UVR protectiveness.

Justification

Clothing manufacturers and retailers are marketing products, such as T-shirts, garments and umbrellas, with claims about their solar protectiveness, yet standard methods of measuring UVR transmission through fabrics and of assigning a protective rating have not been established in any country. Various test methods used in research to date have produced results which are difficult to compare and interpret. While concern for protection from UVR exposure is rising, consumers are somewhat confused in choosing appropriate UVR protective clothing and in interpreting manufacturers' claims of solar protectiveness.

This research is necessary to fill in gaps left by previous research. Inadequate analyses of fabric samples have made previous results difficult to use, as the incomplete descriptions of fabrics prevent explanation of the results. Previous studies used various types of light sources and different wavelength ranges. Menzies et al. (1991) found that using only UVB produced inaccurate results of actual protection measured on skin, and that transmission in both UVA and UVB ranges should be measured. The fact that protection factors have been calculated according to different formulae has contributed to the inability to compare results of the previous work in this area.

A more thorough analysis of fabric parameters may indicate and confirm correlations between fabric characteristics and amount of UVR transmission and may lead to a better understanding of the parameters that affect transmission of UVR. Spectrophotometric analysis will include both UVA and UVB transmission through selected fabrics, as both regions are now known to be damaging to the skin. Through the manipulation of the sun protection factor (SPF) calculations, region-specific data can be compared and a standard rating scheme for clothing may be established.

The results of this study will be beneficial to public health and consumer educators, as well as manufacturers and retailers, in the promotion of clothing as UVR protection. Medical experts, especially in dermatology and pediatrics, will be better able to counsel patients with specific clothing recommendations for protection from UVR. Caucasians (and sun-sensitive individuals of other races) will be better able to safely pursue outdoor activities when they are protected from UVR exposure with appropriate clothing.

Objectives

1. To measure UVR transmission through selected fabrics, using a spectrophotometer and integrating sphere, and to determine if transmission is wavelength dependent over the UVA and UVB range.
2. To determine the solar ultraviolet radiation protectiveness provided by the fabrics.
3. To describe the selected fabrics with respect to fiber type, mass, cover, fabric count, structure and color, and to determine if these variables are highly correlated to UVR transmission through the various fabrics.
4. To recommend a solar protection rating system, or unit, for fabrics.

Definitions

The following definitions are relevant to this study.

Biological Action Spectrum (also called Erythema Action Spectrum) represents the reaction occurring in Skin Type II skin due to exposure to ultraviolet radiation. The one chosen for this study is that given as a function of wavelength by McKinlay and Diffey (1987).

Cover "signifies the actual efficiency of the yarns in closing up the [surface of the] cloth. The cover of a cloth may be judged by the appearance of the cloth held up against the light, and it depends not only on the number of threads per cm and their linear density, but also on their regularity, hairiness, fibre composition, twist and the cloth finishing processes. Any irregularity in construction, as for example in the uniformity of the spacing of the threads, tends to reduce the level of cover" (Taylor, 1981, p. 224). Cover is measured by observing visible light transmission through the cloth. Cover factor, on the other hand, is calculated from the linear density and diameter of the yarns and does not take hairiness, irregularity of yarns or the cloth finishing into account.

Cutaneous Melanoma is a type of skin cancer which has a mortality rate of about 25%. It is not as common as the less aggressive forms of skin cancer, basal cell carcinoma and squamous cell carcinoma (Kripke, 1989).

Minimal Erythemal Dose is defined as the "smallest dose of ultraviolet (UV) radiation (expressed as Joules per meter squared) that produces redness reaching the borders of the exposure site" (Food and Drug Administration, 1993, p. 28295).

Ozone (O_3) exists in a thin layer in the stratospheric layer of the atmosphere, where it blocks solar UVR in wavelengths below 300 nm from reaching the earth's surface.

Solar Action Spectrum is the distribution of ultraviolet radiation in the atmosphere of a given geographical region. It varies according to ozone thickness, altitude, latitude, cloud cover, season and time of day.

Sunburn is a severe erythemal response in the skin and may be accompanied by blistering

Sun Protection Factor is a rating given to sunscreens which tells a consumer how many times longer he or she may stay in the sun before experiencing a minimal erythemal reaction from UVB exposure due to the protection of the sunscreen.

Ultraviolet Radiation is radiation with wavelengths in the range of 200 to 400 nm.

Delimitations

There are certain delimitations placed on this study. Firstly, the selection of fabrics was meant to ensure systematic variation of the fabric variables being studied. Thus, many fabrics were not typical of summer-weight clothing, and the results for these fabrics (such as dense nylon double knits or wool gabardine) are more theoretical than practical. Secondly, in light of the absence of standard national or global solar action spectra, the distribution of UVR for Edmonton's atmospheric conditions in July was chosen as the solar action spectrum used as a weighting factor for the SPF calculations in this study. The Sun Protection Factors are applicable to atmospheric conditions similar to Edmonton in July but are expected to provide slightly less protection than the same SPF's calculated using UVR distributions which have more radiation at shorter wavelengths, such as those found in Australia.

Limitations

Time constraints limit the number of fabric variables that can be measured and compared to the UVR transmittance and SPF of the fabrics. Previous work has suggested that many variables (additives, conditioning, finishes and thickness, in addition to those included in this work) affect the SPF, but a comprehensive study of all such aspects to determine combined effects would be very intensive and time-consuming. It is hoped that this work will build on previous knowledge and be helpful for future research.

Limitations arose during the course of the testing. Spectrophotometric measurements were corrected to account for the calibration being off by one wavelength. The method used to measure cover was not fully examined and is only useful as an estimate of the percent cover of each fabric relative to the others.

Null Hypotheses

Five null hypotheses will be tested in this experiment.

H_{O1} = There will be no significant difference in UVR transmission among fabrics with different fiber types.

H_{O2} = There will be no significant difference in UVR transmission among fabrics with varying masses.

H_{O3} = There will be no significant difference in UVR transmission among fabrics with different fabric counts.

H_{O4} = There will be no significant difference in UVR transmission among fabrics with varying degrees of cover.

H_{O5} = There will be no significant difference in UVR transmission between dyed and undyed fabrics.

CHAPTER II

Literature Review[1]

In the last two decades, media and the scientific community have highlighted the depletion of the ozone layer and the resulting elevation in levels of ultraviolet radiation reaching the earth's surface (Hacker & Flowers, 1993). Caucasian populations, lacking protective pigment found in dark-skinned persons, have experienced increased incidence of skin cancers, and this has been linked to exposure to the higher levels of UVR in the earth's atmosphere. Australia has the world's highest incidence of skin cancer (Hacker & Flowers; Marks, Ponsford & Selwood, 1983). In the United States and Canada, the incidence of skin cancer is among the top three cancers reported and is growing at the fastest rate (Band et al., 1993; Elwood et al., 1984; Hurwitz, 1988).

Ultraviolet radiation from the sun or artificial sources is associated with problems such as carcinogenesis, sunburn and photoaging. Medical experts agree that human exposure to UVR should be controlled by protecting the skin or limiting its exposure to UVR (Hurwitz, 1988). Clothing is recommended by physicians and medical experts as one of the primary methods of protecting the skin (Hacker, Browder & Ramos-Caro, 1993; Hurwitz; Kripke, 1989). The objectives of this literature review are to consider the need for protection from UVR and to review research relating to the transmission of UVR through clothing fabrics.

Ultraviolet Radiation and Solar Action Spectra

The ultraviolet radiation spectrum is broken down into three categories: UVA (320 to 400 nm), UVB (290 to 320 nm) and UVC (200 to 290 nm). Of all the sunlight reaching the earth's surface, 6% is in the ultraviolet region (Reinert, 1990). The amount of stratospheric ozone and particles in the atmosphere, as well as proximity to the equator, affect the amount of UVR which passes through to the earth's surface (Luther, 1985).

Ozone very effectively blocks solar radiation with wavelengths shorter than 290 nm from reaching the earth's surface and filters out some UVR at higher wavelengths (Luther, 1985). Since the energy of a photon of light is inversely related to the wavelength, short wavelengths of radiation have higher energy per photon and greater potential to cause damage than do rays of long wavelength. Hence, ozone acts as a protective shield by blocking UVC radiation from the earth. "Each percentage point of depletion in the stratospheric ozone could result in a

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[1] A version of this chapter has been published. Capjack, L., Kerr, N., Davis, S., Fedosejevs, R., Hatch, K., & Markee, N. (1994). Protection of humans from ultraviolet radiation through the use of textiles: A review. Family and Consumer Sciences Research Journal, 23(2), 198-218.

worldwide increase of 200,000 skin cancers and 15,000 victims of melanoma each year" (Hurwitz, 1988, p. 659).

The distribution of UVR at the earth's surface varies as the thickness of the ozone layer and the solar zenith angle vary. The distribution of solar ultraviolet radiation over the range of 200 to 400 nm at any given geographical region is called the solar action spectrum. The solar action spectrum is important in studies of sun protection. Since the solar action spectrum describes the minimum wavelength of UVR which reaches the earth, sun protection materials do not need to be able to block below this wavelength. If high levels of short wavelength radiation especially in the UVC and lower UVB regions (200 - 300 nm) are present, clothing or sunscreen must be able to block particularly well in this region.

The intensity (W/m^2) of a given wavelength of radiation is an important consideration in choosing protection as it influences the cumulative exposure obtained each day. Skin cancer rates are typically higher near the equator because radiation from the sun is more intense in that region.

Biological Action Spectra

One method of determining the effect of radiation on skin is an *in-vivo*, or human, test to measure the minimal erythemal dose (MED). MED is defined as "the minimum quantity of energy required to produce the first detectable reddening of the skin [an erythemal response]" (Menzies et al., 1991, p. 158). This quantity of energy varies among individuals due to differences in skin color, thickness and sensitivity. Amblard, Beani, Gautron, Reymond & Doyon (1982) believed that measuring a patient's MED was the best method of assessing individual variations in sun sensitivity; therefore, *in-vivo* tests on a large population of individuals can provide an average skin response to UVR exposure.

In sun protection studies and calculations, a standard UVR response function is desirable to represent human skin reactions to given intensities over the UVR wavelength range. McKinlay and Diffey (1987) proposed a reference erythemal action spectrum after statistically analyzing the results of MED measurements from several studies which included over 700 subjects. In many studies, this biological, or erythemal, action spectrum has been used along with the solar action spectrum to describe the potential damage caused by solar UVR in a given region. McKinlay and Diffey's erythemal action spectrum is limited in its usefulness because it quantifies the typical responses of individuals with Skin type One or Two complexions (according to Fitzpatrick's assessment of patients, see Table 1), and does not describe reactions typical of other skin types. However, their reference action spectrum was the first proposal which included skin response in the UVA region as well as the UVB.

Table 1

Skin Type Classification

Skin Type	Description
I	Always burns easily; never tans
II	Always burns easily; tans minimally
III	Burns moderately; tans gradually
IV	Burns minimally; Always tans well
V	Rarely burns; tans profusely
VI	Never burns; deeply pigmented

Adapted from Food and Drug Administration, Federal Register, May 12, 1993, p. 28299.

Effects of Exposure to Ultraviolet Radiation

Photoaging and other Skin Changes

There is still great debate regarding the benefit of a tan. A tan results when UVR stimulates the melanocytic cells to produce more melanin. Melanin, in turn, absorbs UVR and prevents it from penetrating deeper into the skin (American Pharmaceutical Association [APA], 1993; Warrick, 1987). While a tan may provide some protection from further damage, it is now realized that besides causing tanning UVA radiation penetrates into the dermis layer of the skin and promotes photoaging, vascular damage, reduced immunological response, and carcinogenic effects of UVB radiation (APA; Browder & Beers, 1993; Doback & Liu, 1992; Kripke, 1989; Luftman, Lowe & Moy, 1991; Mallory & Watts, 1987; Truhan, 1991).

Sunburns

Ultraviolet B rays cause phototoxic reactions such as sunburns. A sunburn is a severe erythemal response. As an individual receives multiple MED's of UVB radiation, the reaction experienced becomes more severe. A smaller dose of UVB radiation would be necessary to produce erythema in sensitive skin than in a more resistant skin type. MED's are used in rating sunscreens and in determining harmful levels of radiation. UVB exposure is also associated with the promotion of skin cancer.

Skin Cancers

Skin cancer may be of a malignant form called melanoma or less threatening forms such as basal cell carcinoma or squamous cell carcinoma. Squamous and basal cell carcinomas are generally curable and rarely develop into malignant forms of cancer (Kripke, 1989). These cancers are most likely caused by repeated exposure to the sun and appear on the head, neck, face and backs of hands (Kripke; Nogita, Kamikawa & Kawashima, 1993; Urbach, 1978). These types of cancers occur most frequently among people involved in outdoor occupations (Hacker, Browder & Ramos-Caro, 1993).

Melanoma incidence has been found to be related to social class (Holman, Mulroney & Armstrong, 1980) and to occurrence on often covered parts of the body (Armstrong, 1988). It may still be argued, however, that solar UVR contributes to the development of malignant melanoma. The finding by Mulroney, Holman and Armstrong that melanoma is related to social class could be explained "if intermittent sun exposure were more likely to induce melanoma than continuous exposure" (p. 322). That is, people of higher social class were likely to have indoor professional careers rather than outdoor occupations, so their exposure to the sun would have been limited to a recreational basis including, perhaps, annual vacations to hot climates and weekend trips to the beach. Higher melanoma incidence in this group could also be justified considering that these people likely have higher education and high awareness of the benefits of early detection and self-examination (Williams, Clifford, Hopper & Giles, 1994).

Melanoma cells are more common on the lower limbs in women and the trunk in men (Armstrong, 1988; Kripke, 1989). While these areas are often covered, they are equally likely to be uncovered, as men frequently doff their shirts while outdoors in the sun, and women frequently wear T-shirts or short skirts. Ippen (1987) suggests that the development of melanoma in these areas is due to "the summation of numerous slight actinic damage" (p.137), or the intermittent exposure as suggested by Holman, Mulroney and Armstrong (1980).

As further evidence of the relationship between melanoma and sun exposure, it is noted that fair-skinned individuals and xeroderma pigmentosum patients, who can not repair UVR-induced damage to DNA, have a higher incidence of melanoma. Associations have been found between melanoma occurrence and family history, race, age and personal history of melanoma. Of these, only exposure to solar radiation is avoidable (Weinstock et al., 1989).

Factors Related to Risk of Skin Cancer

Skin Type

The degree of reaction experienced following exposure to UVR depends largely on an individual's skin thickness, color and amount of melanin, as well as the wavelength of UVR, and other external factors (Hill et al., 1992; Mallory & Watts, 1987). Amblard, Beani, Gautron, Reymond and Doyon (1982) suggest that age and sex are determinants as well. Specific skin types, namely fair skinned light haired people are at the highest risk of suffering adverse effects of UVR exposure (Elwood et al., 1984; Garland, White, Garland, Shaw & Gorman, 1990). In the Western Canada Melanoma Study, Elwood et al. found "large differences between white populations and black and oriental populations in risk of melanoma; subjects with less melanocyte based pigmentation had a higher risk of melanoma" (p. 101).

"In 1975, Fitzpatrick introduced the concept of skin typing as a clinical classification system based on a patient's historical assessment of his or her acute skin response to natural sunlight, with respect to the development of erythema and the ability to tan" (Stern & Momtaz, 1984, p. 869). There are six skin types according to this assessment, as shown previously in Table 1. Skin type One patients are the most sun sensitive, whereas Skin type Two patients are those who burn easily and rarely tan. Skin type Two subjects are usually used in *in-vivo* testing. Studies have found correlations "between melanoma and poor tanning ability, a tendency to burn easily on accustomed exposure and a history of sunburn" (Elwood et al., 1984, p. 102; MacKie & Aitchison, 1982). These characteristics describe the historical assessments of Skin type One and Two patients.

Reactions to exposure may result from allergies or phototoxic effects of certain chemicals or drugs (Groves, 1973). Risk of contracting cancer may be genetic, as well. The disease xeroderma pigmentosum is known to make people highly susceptible to damage from UVR exposure (Hacker, Browder & Ramos-Caro, 1993).

Behavior Patterns

Although the association of UVR exposure to skin cancers has been established by medical researchers, the nature of this exposure is not clear. It has been found that individuals exposed to the sun on a daily basis suffer reactions quite different from individuals with indoor occupations who might only be exposed during recreational periods (Hacker, Browder & Ramos-Caro, 1993). Outdoor workers are generally more likely to develop squamous and basal cell carcinomas on areas that are most frequently exposed, such as the face, back of neck, hands and ears (Beral & Robinson, 1981; Marks, Jolley, Lectsas & Foley, 1990). This lends strong support to the association of these cancers with UVR exposure. Some companies have stressed, or should stress, to their workers that spending as much time in the shade and wearing a hat are important protective measures which should be used on the job (Borland, Hocking, Godkin, Gibbs & Hill, 1991; Rockley, Trieff, Wagner & Tyring, 1994).

In contrast, it has been found that individuals who spend time in the sun only during weekends, or repeatedly during intense periods of sunlight, are more likely to contract melanoma. Melanoma is more common in Caucasian people than in races with darker skin, in those who vacation in regions of intense sunlight, and on areas of the body which are likely to be exposed during leisure activities. Although the link between intermittent exposure patterns and melanoma development is difficult to understand and to explain, medical experts still stress that lifetime protection from ultraviolet radiation is important to prevent melanoma.

Childhood Exposure

Childhood exposure is important as a determinant in the aetiology of melanoma

(Hurwitz, 1988; Kripke, 1989; Truhan, 1991). Brozena, Fenske and Perez (1993) found that "...increased risk of developing melanoma appears clearly related to intermittent intense Ultraviolet B exposure in childhood and adolescence" (p. 166). The hypothesized reasons for increased risk due to childhood exposure are that (1) children may react more severely to the sun since they have thinner skin than adults, (2) children receive much more exposure to the sun than adults, and (3) "melanoma is presumably a multistage time-dependent process, so passing through critical stages earlier in life may increase the chances of completing the remaining stages of carcinogenesis" (Weinstock et al., 1989, p. 203). It is believed that severe sunburns during childhood can significantly increase the risk of contracting skin cancer (Weinstock, 1989). On the other hand, it has been estimated that the use of a sunscreen during the first eighteen years of life can significantly reduce the risk of skin cancer. However, Cockburn, Hennrikus, Scott & Sanson-Fisher (1989) found that adequate use of sun-protection measures, such as sunscreens, hats or long sleeves, was indicated by only 30% of the teen-age population studied.

Adolescents are a risk group largely because of the peer pressure to have a fashionable and desirable tan (Hurwitz, 1988; Marks & Hill, 1988). They are unaware of the great harm that may result from exposure to the sun. Adolescents have said that they face many barriers to the use of sunscreens, including cost, peer pressure to tan and the discomfort of sunscreen formulations (Cockburn, Hennrikus, Scott & Sanson-Fisher, 1989).

Environmental Conditions

Regional differences in the incidence of skin cancer are obvious from statistics and may be attributed to many factors. These factors include population differences (percentage of Caucasian - or at-risk individuals- in the region, and typical sun exposure behaviors); latitude and intensity of the sun; ozone thickness over the region; and hours of sunlight per day, month and year. Comparisons of skin cancer incidence rates must be considered in light of these regional variations. Brozena, Fenske and Perez (1993) note that "within defined race and skin pigmentation groups, additional importance is given to global latitude of residence and socio-economic status" (p. 165). Hacker and Flowers (1993) estimate that "a decline of 8° to 10° in latitude doubles the incidence of squamous cell carcinomas" (p. 115; Armstrong, 1988). Studies have also noted an increase in melanoma to the north of 50° latitude and this has been theoretically explained by sun exposure patterns, geographic and climatic factors (Armstrong, 1988). Environmental conditions might also affect the manner in which people protect themselves. Extra clothing in very hot climates might be a less desirable option than the use of shading devices or sunscreens.

Protection from UVR

Avoidance

Avoiding UVR sources is the obvious way to protect oneself from the deleterious effects of exposure. This is not practical advice for most people who must go outdoors everyday, and especially for those with outdoor occupations. Many people believe that exposure to the sun is necessary for the cutaneous production of Vitamin D. Studies have shown that sufficient Vitamin D is obtained in the diet of most North American people, although the information is still rather contradictory (Hutchinson & Hall, 1984; Matsuoka et al., 1992; Weinstock, Stampfer, Lew, Willett & Sober, 1992).

UV Absorbers in Clothing and Sunscreens

For clothing and sunscreens to protect skin from hazards of over exposure to UVR, these materials must block the UVR from reaching the skin. Ultraviolet radiation is emitted by many sources, but solar UVR is of primary concern since it is always striking the earth during daylight hours. When intercepted by materials, such as natural or synthetic polymers, dyes and sunscreen agents, the UVR is reflected, absorbed or transmitted. In general, the total radiation striking a material from all directions is equivalent to the radiation which is then absorbed, reflected and transmitted by the material at a given wavelength.

These three processes depend on the material's surface conditions, the wavelength of the radiation and the composition and thickness of the material. With respect to the composition of the material, absorption of UVR typically occurs in organic materials when pi (π) electrons use the electromagnetic energy to move to higher energy levels or orbitals. The greater the number of available pi electrons, double bonds, and conjugation of double bonds, the greater the probability that UVR will be absorbed and a transition to a higher energy level will occur. Electrons very quickly return to ground state from this excited state, generally by dissipating the energy as internal (vibrational) energy. The amount of UVR which a molecule absorbs is described by the molecular absorptivity or extinction coefficient. Sometimes when an electron moves from an excited state to ground state, energy is emitted as longer wavelength (lower energy) visible light in addition to dissipated vibrational energy. This conversion of UVR to visible light is known as fluorescence or phosphorescence. As energy is given off as heat or vibration throughout the molecule, broken bonds and fiber degradation may occasionally occur. By improving a fiber's ability to absorb UVR the potential for photodegradation of the fiber may also increase.

If a material does not absorb UVR, then the radiation is reflected, scattered or transmitted. Since fibers and yarns are round and often do not have smooth surfaces, radiation may be reflected in all directions. Some radiation may be passed through the fabric as it is reflected off the sides of yarns and fibers. This radiation passes diffusely through the fabric and must be measured in addition to radiation transmitted directly through spaces.

Sunscreens

Sunscreens are topical formulations which are applied to the skin to protect it from UVR; they consist of UVR absorbers in a base (oil, cream or lotion). Depending on the class of UVR absorbers used in the compound, the sunscreen may provide protection in the UVB and/or the UVA ranges; therefore, a sunscreen with an effective UVB absorber may prevent erythemal responses in the skin while allowing UVA tanning responses. The effectiveness of a sunscreen depends on the concentration of UV-absorbing agent in the sunscreen and the thickness of the film applied to the skin; if the sunscreen is applied sparingly, a higher concentration of UV-absorber(s) is required to reduce the amount of radiation striking the skin (Groves, 1973).

Sunscreens may be chemical or physical barriers to UVR. Physical barriers, such as zinc oxide and titanium dioxide creams, reflect and scatter sunlight thus preventing it from contacting the skin (Luftman, Lowe & Moy, 1991). These formulations are opaque and sometimes aesthetically unacceptable. Chemical sunscreens filter the UVR. Chemicals which are often used are benzophenones and para-aminobenzoic acid (PABA) (Stiller, Davis, & Shupack, 1992). UVB and UVA are absorbed by different chemical structures, so a formulation which protects from both regions of radiation often has two or more chemicals in it. There are many chemicals which are suitable for use in sunscreens, and some chemicals, although having appropriate extinction coefficients and peak wavelength absorbancies, are not used in sunscreens due to dermal irritation, carcinogenic potential or insolubility in a suitable base.

The fashionability of suntans and the availability of sunscreens allowing UVA tanning have led to the popular use of suntanning products and the use of sunscreens to promote a tan, more so than to prevent UVB erythema. Johnson and Lookingbill (1984) found in their survey of 489 patients that there were many misconceptions about the role of sunscreen products, their proper usage and their effectiveness at preventing sunburns.

There are some disadvantages to the use of sunscreens as protection from ultraviolet radiation. These include the facts that some only block UVB rays; they must be applied frequently; and they are messy, unattractive and uncomfortable (Truhan, 1991). Sunscreens should not be used on infants less than six months of age, as there is some concern about elements of the formulation being absorbed through the thin skin of infants. The cost of sunscreens is a deterrent for some people. External conditions such as wind, humidity, temperature, thickness of application and adherence potential of the base alter a sunscreen's efficiency.

Some of the molecules used in sunscreens to absorb or reflect UVR are also used in fibers and finishes, such as titanium dioxide as a fiber delusterant. There are many molecules which act as UVR-absorbers and each has its own properties.

Clothing

Some fibers also have molecular structures which will absorb UVR, such as polyesters and aramids. Dyes and additives such as titanium dioxide also exhibit UV absorption. A fabric barrier is protective if it absorbs or reflects forward UVR, thus preventing it from contacting the skin. Robson and Diffey (1990) found that some fibers absorb better in some parts of the UVR spectrum than other parts. In theory, it is possible to impart UV absorbing properties to a fabric by choosing appropriate fibers, modifying fibers or adding fiber additives, dyes, coatings and/or finishes.

Medical experts frequently recommend that clothing for protection from UVR should cover as much of the body as possible. With this suggestion, it is assumed that the fabrics used in such garments will provide protection from UVR. Berne and Fischer (1980) "suggest that, for the light sensitive and the psoralen-sensitized patient, careful counselling concerning clothes is at least as important as the prescription of proper sunscreens" (p. 460). Bech-Thomsen, Wulf and Ullman (1991) found that their sun-sensitive patient experienced harmful effects of UVR exposure through lightweight clothing. They determined that there were a higher number of lesions found in uncovered areas and lightly covered areas than on skin surface which was usually covered by layers or heavier fabric.

There is some indication that people do not use clothing as protection from UVR exposure. Bolognia, Berwick, Fine, Simpson and Jasmin (1991) found that sun umbrellas and sun bonnets were not used more frequently even if the items were supplied free to the mothers of newborns in the study. Only between 2% and 7% of the subjects used "loose-fitting" clothing as protection for their infants when they were outdoors in the sun; the authors do not explain their rationale for defining protective clothing as loose-fitting. A more detailed behavioral study was performed by Lee, Marlenga and Meich (1991) to assess farmers' perceptions about various hat styles with respect to cost, comfort, practicality and aesthetics. They found that no hat provided both adequate sun protection and acceptability to farmers. A survey of Alberta adults showed that less than half of men and women indicated that they used hats, clothing, sunscreen or avoidance of the sun as protective measures (Campbell & Birdsell, 1994).

UVR Transmission Through Fabrics

Several studies have been conducted to examine the use of clothing as protection from ultraviolet radiation and will be reviewed in this section. There are three methods which are most often used to measure how much UVR passes through fabric; these include *in-vivo*, radiometric and spectrophotometric techniques. These techniques will be described and limitations to previous work will be outlined.

In-vivo Measurements

In-vivo tests are used to evaluate sunscreens according to the tentative final monograph from the U.S. Food and Drug Administration (Food and Drug Administration [FDA], 1993). Similar methods have been used with clothing in solar-protective clothing studies. Tests for sunscreens and clothing will be discussed in this section.

Measuring Effectiveness of Sunscreens

Sun Protection Factors (SPF's) are calculated from *in-vivo* tests of minimal erythemal doses with and without sunscreen in place on a human subject's skin. This number represents the increased safe exposure time before erythema results, due to the protection of the sunscreen. The SPF is defined as "the ratio of the dose of UV radiation ... required to produce minimal pinkness, assessed [up to] 24 hours after exposure in skin covered by a sunscreen, to the dose of UVR required to produce similar pinkness in unprotected skin" (Stern, Weinstein & Baker, 1986, p. 537). For example, if a person suffers an erythemal reaction after 10 minutes of exposure to midday sun, an SPF 15 product allows the individual to stay in the sun 15 times longer (or 2.5 hours) before erythema results. People who sunburn more easily require higher SPF sunscreens than people who are not very sun-sensitive.

There are many limitations to the laboratory assessment of sunscreens (Groves, 1973; Stiller, Davis & Shupack, 1992). Artificial sources of UVR do not necessarily adequately represent the solar spectrum. The *in-vivo* test is time consuming as subjects are examined for an erythemal response after as long as 24 hours after being irradiated (Groves). Erythemal response varies with anatomical positions and is determined by subjective examination. Sun Protection Factors are determined under controlled laboratory conditions which do not represent conditions during actual use, such as the effects of wind, temperature, perspiration and actual thickness of application (Truhan, 1991). In order for a sunscreen to provide the protection suggested by the SPF value, a thin film must be maintained on the surface of the skin (Warrick, 1987). Reapplying sunscreen is necessary for effectiveness; however, reapplying the sunscreen will not extend protection beyond the duration of exposure specified by the SPF value. Studies have shown that people often use less sunscreen than is required to maintain protection (Johnson & Lookingbill, 1984; APA, 1993).

In-vivo Testing of Clothing Fabric

In studies using the *in-vivo* method to measure UVR transmission through fabric, small samples of the fabric are applied to untanned skin. The area is irradiated with a UV light source and the minimal erythemal dose is measured. Sunlight or an artificial light source can be used. Subjects are usually Skin type Two patients, as these individuals are representative of those most at risk of suffering adverse reactions to UVR exposure and need protection. As with sunscreens, the ratio of MED's with and without the fabric barrier in place is used to calculate a protection factor:

$$SPF = \frac{MEDcovered}{MEDuncovered} \tag{1}$$

Menzies et al. (1991) found that *in-vivo* testing produced different results depending on the fabric's proximity to the skin. Placing samples directly on the skin reduced the fabric protection factor (FPF) considerably as opposed to having a 2 mm separation between the fabric and the skin. A small separation between skin and fabric is more realistic for clothing during wear. In Jevtic's (1990) study, placing samples directly on the skin may have been representative of the beachwear styles being tested.

Radiometry

Radiometry measures the total transmission of UVR through fabric using sunlight or a simulated solar spectrum. A solar spectrum is simulated by using a broad band ultraviolet light source filtered to a region of the UVB or of combined UVA and UVB spectral ranges. The radiometer measures total UVR transmission through the test sample when it is irradiated with the broad band UVR source. Output readings signify the total radiant energy passing through the fabric and falling on the detector surface.

Bech-Thomsen, Wulf and Ullman (1991) conducted radiometric tests of 34 fabric samples with a UVR solar simulator filtered to a range of 298 to 329 nm. They chose to use radiometry based on preliminary spectroradiometric measurements of UVR transmission through three samples of different fiber types (cotton, a blend of cotton/synthetic, and silk). From these tests they concluded that the transmission "was almost independent of the wavelength in a range from 250 to 450 nm" (p. 367). Therefore, they judged that UVR transmission through fabrics could be measured by using either a UVB or UVA light source. They found that many of the fabrics had a UVB percent transmission greater than 7%.

Hutchinson and Hall (1984) used a similar method in their assessment of UVR transmission through various clothing fabrics. The broadband UVR source they used was direct sunlight. UV-sensitive polysulphone films were exposed to sunlight with or without a fabric barrier. After exposure for a 2 hour period the change in absorbance of the polysulphone film was measured. Values for UVR transmission through various samples of women's tights and clothing varied from 5 % to 64 %. The authors do not try to draw a relationship between the amount of radiation passing through the fabric and the subsequent skin response, or the degree of protection the fabric provides.

Gies, Roy, Elliott and Zongli (1994) used a spectroradiometer with an integrating sphere to measure direct and diffusely transmitted UVR through fabrics over the wavelength range of 280 to 400 nm. They compared these results to spectrophotometric (not using an integrating sphere) and broadband radiometric (using UVA and/or UVB ranges) methods. They found that the light source used must accurately represent the distribution of solar UVR and that the detectors must respond similarly to human skin to get accurate results. Ultraviolet protection factors were slightly higher when determined radiometrically as opposed to spectrophotometrically.

Radiometric measurements are simpler than *in-vivo* assessments. They are based on the assumption that transmission is independent of wavelength. Other researchers have found, however, that there is some dependence of transmission on wavelength (Gies, Roy, Elliott & Zongli, 1994; Robson & Diffey, 1990; Pailthorpe, 1993a & b).

<u>Spectrophotometry</u>

Spectrophotometry is a measure of UVR transmission through a sample as a function of wavelength. A spectrophotometer with UV light sources irradiates a sample and an integrating sphere accessory collects photons of light which are transmitted through the sample and detected by a photomultiplier. To establish a Sun Protection Factor, the percent transmission, as a function of wavelength, is weighted with functions for the expected distribution of solar radiation in a geographic region (solar action spectrum) and the relative erythemal response of the skin to each wavelength of radiation (biological action spectrum). Researchers typically choose a solar action spectrum representative of the region where the research is being conducted. The International Commission on Illumination (CIE) spectrum developed by McKinlay and Diffey (1987) is often used as the biological action spectrum. Some researchers have presented data in formats other than the Sun Protection Factor.

Berne and Fischer (1980) tested various clothing fabrics, including women's tights, patients' shirts, and denim. The methods were similar to spectrophotometry in that they measured the transmission of three different wavelengths of light: 313 nm (UVB range), 365 nm (UVA range), and 436 nm (visible light). "In fourteen of the [twenty] materials the transmission varied by a maximum of 10% at the three wave length bands examined.... These differences are small and imply that it is possible to use the absorption of visible light as a measure of the UV-protective effect of textiles" (p. 459). Absorption of visible light could be estimated, Berne and Fischer suggested, by holding the material in front of a light bulb and observing how much light passes through.

Sliney, Benton, Cole, Epstein and Morin (1987) examined the transmission of UVR (220, 260, 280, 310, 340 nm) through industrial weight fabrics using spectrophotometric techniques. There was little variation of transmission at the five wavelengths.

Welsh and Diffey (1981) assessed the protection afforded by a number of fabrics by using spectrophotometry. The test involved irradiating the samples with bandwidths of 2 nm in 5 nm steps from 290 to 320 nm. Transmission over the UVB range was weighted with a solar action spectrum representing midday summer sun in the United Kingdom (60° latitude, 0.32 cm ozone thickness, and sea level) and a biological action spectrum proposed by Mackenzie and Frain-Bell (1973), who estimated erythema in human skin due to UVB exposure. Welsh and Diffey found that transmission in the UVB range was relatively constant, i.e., the transmission spectra over the range were flat, and reduced their equation so that a Protection Factor could be calculated by the following equation:

$$PF=\frac{1}{T} \qquad (2)$$

where, T= transmitted radiation at any one wavelength in the range 290 - 320 nm. While many fabrics may transmit radiation uniformly throughout the UVB range, the rate of tranmission in the UVA range may differ.

Robson and Diffey (1990) found that the transmission, and hence the protection factor, varied over the range 290 to 400 nm for a variety of fabrics. They calculated sun protection factors according to the following equation:

$$SPF=\frac{\sum E(\lambda)\varepsilon(\lambda)}{\sum E(\lambda)\varepsilon(\lambda)/PF(\lambda)} \qquad (3)$$

"where, $E(\lambda)$ is the spectral irradiance of terrestrial sunlight under defined conditions, and $\varepsilon(\lambda)$ is the relative effectiveness of UV at wavelength λ nm in producing delayed erythema in human skin (erythema action spectrum)" (p. 33). The protection factor (PF) at each wavelength was the ratio of unfiltered radiation to that radiation transmitted through the fabric.

Pailthorpe and Auer (1991) examined the use of shade cloths as barriers to ultraviolet light. Shade cloths are used indoors and outdoors to shade visible light, control light and glare, and to preserve fabrics, art or vegetation which are sensitive to UV (Grasso & Hunn, 1992). UVR transmission was tested with a Cary 3 UV-Vis spectrophotometer and an SPF was calculated from the following equations:

$$\text{SPF} = 100 \,/\, \%\ \text{UV transmission} \qquad (4)$$

or

$$\text{SPF} = 100 \,/\, (100 - \%\ \text{UV shade}) \qquad (5)$$

Pailthorpe and Auer substituted the manufacturers' claimed % (visible) shade for the calculated % UV shade (where % shade = 100 - % transmission) and determined that visible percent shade was a reasonable prediction of percent of UVR shade. The highest SPF of shadecloths in Pailthorpe and Auer's study was 4.3.

Unisearch, University of New South Wales, Australia offers spectrophotometric testing for a fee to manufacturers who wish to have protection factor ratings for clothing (Pailthorpe, 1993a). Since the SPF of fabrics depends on fiber type, additives, color, fabric structure and condition (wet, dry or worn), Pailthorpe concedes that UVR transmission must be measured for each fabric and SPF calculated by weighting the data with solar and biological action spectra. Twelve of the twenty-two fabrics in Pailthorpe's study have SPF's of 15 or less. All but two of these fabrics were white. Pailthorpe does not reveal details of the spectrophotometric procedure nor of the data used as weighting factors in the SPF calculations.

Menzies et al. (1991) compared spectrophotometric and *in-vivo* testing of fabrics to evaluate the use of spectrophotometric tests in predicting protectiveness of the fabrics. When *in-vivo* tests were conducted with a 2 mm space between fabric and skin, the fabrics' protection factors were in agreement with the spectrophotometric UV-transmission data. Menzies et al. note that "calculations using our data show that restriction of the wavelength range to UVB (280 - 320 nm) leads to unreliable estimates" (p. 160) of the Fabric Protection Factor (FPF). The FPF is calculated as the ratio of MED with fabric protection to MED without protection in *in-vivo* tests and as a summation of the fraction of transmitted radiation weighted with functions for solar and biological action spectra for the spectrophotometric technique.

When radiation transmitted through fabric is independent of wavelength, radiometric testing could be used in place of the spectrophotometric method. Menzies et al. (1991) determined that spectrophotometry was an appropriate predictor of actual protection compared to *in-vivo* tests. Accurate transmission measurements using spectrophotometry require filtering of fluoresce and phosphorescence.

Protection Ratings

There is some debate as to how results of testing should be reported. The different calculations used previously make results difficult to compare. The results of testing by Berne and Fischer (1980) were reported as average percent transmission for three wavelengths, and as a Protection Factor, or the inverse of the transmittance. Women's tights (31 g/m^2) showed 75% average transmission and had a protection factor of 1.3, whereas dark blue denim (319 g/m^2) had 0.06% average transmission and protection factor equal to 1,700. An intermediate sample was a white cotton shirt (154 g/m^2) which resulted in 14% transmission and a protection factor of 7.

Sliney, Benton, Cole, Epstein and Morin (1987) found that industrial protective garments for welders differed from typical summer-weight clothing fabrics in that they were denser and heavier. These dense fabrics had transmission values as low as 0.0005%. Results, therefore, were reported in a more convenient logarithmic expression called Optical Density (OD) which is defined mathematically by the following equation:

$$OD = -\log(\tau) = 2 - \log(T\%) \qquad (6)$$

In this equation, τ represents transmittance and T is the percent transmission.

Measurement of UVR transmission and calculation of protection factors vary throughout the literature. In Pailthorpe's (1993a, b) work, protection factors were calculated from UV transmission data, solar irradiance data and erythemal action spectra. Specific formulae are not published in his papers. Other authors have used the terms Relative Protection Factor (RPF) (Jevtic, 1990), Fabric Protection Factor (FPF) (Menzies et al., 1991), Sun Protection Factor (SPF) (Pailthorpe, 1993; Robson and Diffey, 1991), and Ultraviolet Protection Factor (UPF) (Gies & Roy, 1993 & 1994; Gies, Roy, Elliott & Zongli, 1994).

In-vivo (FDA, 1993) and *in-vitro* measurements of SPF are considered equivalent since both are corrected for solar UVR distribution (Menzies et al., 1991) and since the biological action spectrum (McKinlay & Diffey, 1987) is used in *in-vitro* methods to represent actual skin responses. This equivalence holds when the *in-vivo* SPF is calculated according to equation 1, as directed by the Food and Drug Administration and the *in-vitro* SPF is defined according to the following equation used by Menzies et al. (1991) and Robson and Diffey (1990):

$$SPF = \frac{\int S(\lambda)E(\lambda)d\lambda}{\int S(\lambda)E(\lambda)T(\lambda)d\lambda} \quad (7)$$

where S = solar action spectrum, E = erythemal action spectrum and T = transmission as a functin of wavelength. However, since the calculation and use of Sun Protection Factor ratings is not standardized for clothing, other methods of calculation have been used.

Pailthorpe (1993b) suggested that SPF could be calculated from the cover factor of fabrics. This method would be valid if yarns were opaque to UVR, since it is based on the assumption that the only transmitted radiation is that which passes through spaces between yarns. Indeed, it has been shown that most fibre types transmit some amount of UVR and total transmission is the sum of direct transmission through spaces as well as diffusely transmitted radiation (Robson & Diffey, 1990). The degree of UVR transmission through yarns depends on fiber type, fiber additives, and presence of fluorescent whitening agents and finishes.

Jevtic (1990) rated fabrics with a Relative Protection Factor which was the inverse of transmittance. Welsh and Diffey (1981) also reduced their Protection Factor to this form. This rating is not equivalent to *in-vivo* calculated SPF's since no allowance is made for skin's reaction to the amount of UVR transmitted and there is no correction to make the light source relative to the solar distribution of UVR. The same limitations result from reporting simply percent of UVR transmission rather than a Sun Protection Factor. The Optical Density ratings used by Sliney, Benton, Cole, Epstein and Morin (1987) are a form of transmittance and also are not equivalent to the Sun Protection Factor rating scheme used for sunscreens.

The use of Sun Protection Factor has been most prominent as it is often felt that consumers are familiar with its meaning, since it is used on sunscreens; however, Johnson and Lookingbill (1984) showed that there are many misconceptions about sunscreen rating systems. In their study, 1% of respondents believed that higher SPF's provide less protection and 51% did not know what SPF meant.

The Sun Protection Factor rating for sunscreens applies to protection from UVB radiation only since it is a measure of UVB radiation exposure (APA, 1993; Stiller, Davis & Shupack, 1992). UVA radiation is much less likely than UVB to cause erythema in the skin; however, the effects of UVA exposure are damaging and should be avoided. If sunscreens which only block UVB radiation are used during prolonged exposure to the sun, the risk of suffering adverse effects of UVA exposure may heighten (Doback & Liu, 1992). New ratings have been proposed to quantify UVA ratings, but none have been formally adopted. More sunscreens including both UVA and UVB absorbers are being produced today.

Clothing fabrics do not form an even `film' over the skin, so UVR exposure through clothing is not necessarily equivalent to exposure, or protection, experienced with sunscreens. Since the SPF, as calculated for clothing fabric, is dependent on geographic variations in the local solar spectrum, it might not be easily implemented as a standard. SPF's in one country would not be exactly equivalent to those of countries at different latitudes since the solar action spectra would vary. Thus, a standard solar spectrum needs to be determined for calculation of standard SPF values.

Alternatives to the SPF rating system are suggested so that clothing can be assigned values higher than those allowed in sunscreen rating legislation. Many fabrics do not provide protection in excess of sunscreens. For those fabrics which do provide a great degree of protection, it must be recognized that at very high SPF's (or UPF's) "values greater than 40 or more correspond to only small decrements in UVR transmission" (Gies, Roy, Elliott & Zongli, 1994, p. 133.) Thus an upper limit similar to that placed on sunscreens may be appropriate for clothing fabrics as well.

Fabric Characteristics related to UVR Transmission

A great limitation to previous work in this field is that fabric samples have not been adequately described, making it difficult to understand the influences of fabric parameters on UVR transmission. There is little published research to verify correlations between amount of transmission and fabric characteristics. Such work would be valuable since an understanding of the fabric parameters would allow fabric, and clothing, to be constructed in a manner which is more protective. In 1993, Pailthorpe published a newsletter which summarizes the findings of previous work in the field. Briefly, he noted that UVR transmission through fabrics is influenced by the method of construction (i.e., the spaces between the yarns), mass, fiber type, color, and the presence of additives. Wet samples resulted in lower protection factors than dry fabrics. His later work (1993b) elaborates on relationships of UVR transmission to fabric structure, color, and use of additives. "Unisearch", the laboratory with which Pailthorpe is associated, currently has two patent applications pending approval. The patents relate to finishes used on textiles to increase sun protection.

While some relationships seem evident from previous literature, no one factor has been indicated as the single predictor of UVR transmission through fabric. It seems that several fabric parameters together account for the fabric's permeability.

<u>Construction</u>

It makes sense that construction should be an important variable in the transmission of UVR through textiles. Electromagnetic radiation passes readily through the spaces between yarns in a fabric. A fabric made of the most UV-absorbing fiber will not be valuable if it is made into a very open-weave textile. In previous studies, structure has been described as either woven or knitted. Openness has been described as the 'hole effect' (Morikofer, 1931). Menzies et al. (1991) elaborate on the 'hole effect'. If the spaces between the yarns are relatively large, then assessment of minimal erythemal doses on skin will be evaluations of direct transmission through the spaces. With greater distance between fabric and skin, more scattering of the transmitted radiation occurs and a higher MED will be detected since radiation will be spread over a greater area rather than localized. Pailthorpe (1993b) argues that, assuming the yarns are opaque and transmission occurs through spaces between yarns, the greater the number and size of openings in the fabric, the greater the amount of UVR transmission. That is, with more yarns covering a surface (a higher cover factor), greater protection will be provided by the fabric. If yarns were opaque to UVR, a direct relationship between SPF and cover factor could be described by SPF = 100 / (100 - cover factor). Pailthorpe (1993) does not present any values for the cover factor of samples used in his studies, but states that a minimum cover factor of 93% is necessary to achieve an SPF of 15 or more.

Taylor (1981) explains the difference between the two similar fabric characteristics `cover factor' and `cover'.

> `Cover' ... signifies the actual efficiency of the yarns in closing up the cloth. The cover of a cloth may be judged by the appearance of the cloth when held up against the light, and it depends not only on the number of threads per cm and their linear density, but also on their regularity, hairiness, fibre composition, twist and the cloth finishing processes. Any irregularity in construction, as for example in the uniformity of the spacing of the threads, tends to reduce the level of cover. `Cover factor' is calculated from only two of these quantities [threads per cm and linear density] and, therefore, cannot provide a complete indication of cover (Taylor, p. 224).

The cover of a fabric could change by shrinkage or application of certain finishes. No method of measuring cover has been described in the literature other than subjectively comparing fabrics for visible light transmission.

The earliest study on transmission of radiation through fabrics is a detailed article in German by Mörikofer (1931). Although the methodology used is not clearly interpreted, it appears that direct and diffuse transmission were measured separately. Mörikofer made some noteworthy conclusions. He found that the spaces between the yarns were the most important criteria in the fabric for affecting transmission, and that the proportion of direct and diffuse transmission through the fabrics varied with fabric structure. In terms of fabric analysis, Mörikofer separated light from heavy fabrics, used four different fiber types, and recorded thickness and `hole effect'.

Pailthorpe and Auer (1991) concluded that transmission resulted from radiation passing through spaces in the fabric, and was not likely to indicate transmission through fibers or yarns. Thus, the construction, which determines the proportion of space, is an important determinant of the protection provided by the fabric. Pailthorpe (1993b) found that the Lacoste (tuck stitch) knit structure provided the least protection of knitted fabrics included in his study. For fabrics with the same number of picks and ends per centimeter and the same mass, the plain weave structure provided the highest SPF over other woven structures.

Color

Most fabrics are colored by dyes or prints. Some researchers have examined the relationship between color and UV transmission; however, an in-depth study of UVR absorption by specific dye molecules could explain many observations in this area. Some dye molecules have the ability to absorb ultraviolet radiation as well as visible radiation (400 nm to 750 nm).

Genkov and Atmazov (1968) found that samples of a single cotton fabric showed a reduction in permeability from 6.7% to 1.3% when a dark green version was used rather than a white/colored dotted print. Hutchinson and Hall (1984) examined the transmission of sunlight through clothing fabrics in a six part experiment. They used different types of hosiery, clothing systems (or layers), and various colors of identical fabrics. Color and, secondly, structure were found to influence results, lighter colors allowing greater transmission of UVR than darker colors. Berne & Fischer (1980) also found that dark shades of the same fabric were more protective.

Fiber type

Genkov and Atmažov (1968) compared UV and infrared permeability of cotton, synthetic and blended textiles. While the study included groups for each of these fiber types, the samples within the groups had various knitting stitches, thicknesses and colors. They found that synthetic fibers were more permeable than cottons or blends. Genkov and Atmažov concluded that fiber type was the primary determinant of UVR and infrared radiation permeability, with structure and color following in importance.

Robson and Diffey (1990) examined 60 samples of fabric, representing six different fiber types: cotton, wool, silk, polyester, viscose and acrylic. The samples varied in design and construction. "The results showed that protection offered by fabrics against UV is influenced by a number of factors, including the nature of the textile, structure of the fabric and type of weave" (p. 33-34). Transmission varied with wavelength for most of the samples. Large variations in SPF were noted with samples of each fiber type. Polyester samples ranged from SPF of 2 to SPF of 828. Robson and Diffey note that "other factors that may affect the transmission of UV that were not examined in this study include the addition of delustering agents...,the addition of fluorescent brighteners..., and the coating of fibers with crease-resistant finishes" (p. 34).

In Hutchinson and Hall's (1984) study, "the percentage transmission of UV (%T) ranged from 64 percent through 10 denier tights to 5 per cent through black cotton. The finish (fabric reflectivity) rather than denier (fabric density) appeared to have a greater influence on the transmission of UV through tights" (p. 299).

Synthetic fibers may contain molecular groups or additives which absorb UVR radiation. Fibers which are good absorbers of UVR are more likely to produce UVR absorbing fabric if a construction method is chosen to reduce spaces between the fibers and yarns, or if a finish is applied which reduces transmission through spaces. Finishes may also contribute to the UVR absorbing properties of a fabric if fibers do not have the propensity to block UVR. Any finishes which are applied to consumer products are not identified on labels and chemical compositions are difficult to identify. Natural fibers may contain certain components which improve protection. Pailthorpe (1993) found that bleached cotton provided less protection than unbleached cotton because bleaching removed any lignin that may have been present and able to absorb UV radiation.

<u>Mass & thickness</u>

Mass and thickness may contribute to the protective nature of fabrics. Increasing mass while maintaining other fabric characteristics (e.g. fiber type, fabric count, construction method) can be achieved by using denser yarns. With more material present in the fabric with high mass, than in the original fabric, there is increased potential for UV-absorption by fibres and additives. Thus UVR transmission is reduced.

A thick fabric acts as a barrier since radiation has a greater distance to travel through the thicker fabric than through a thinner one. This greater thickness increases the probability that fibers, additives and impurities will scatter radiation. With each additional layer of fabric, the percent of UVR transmission is reduced greatly. Layers of clothing or pile weaves may increase protection. It is important to consider that a thick, heavy fabric could also be very open in construction, which would allow direct exposure of the skin to UV radiation.

Berne and Fischer (1980) found that the transmission of radiation through the fabric samples was related to weight, with heavier fabrics absorbing or blocking more than light weight samples; layers also increased protection. Pailthorpe (1993b) explains that the added yarn which will also increase the mass of a fabric will also increase the percent cover of that fabric. Thus, an increase in SPF is expected for increases in both mass and SPF.

<u>Condition</u>

The condition of a fabric is an important consideration. Clothing fabrics may provide less protection as the fabric gets worn. Thus, a protection factor assigned to a fabric would be valid for a certain number of wearings or washings. Also, it is conceivable that a protection factor could be increased after washing if shrinkage occurred and reduced the size of spaces between yarns. In one study, laundered fabrics (prepared according to AATCC 124-1978, Procedure IIIB) were found to have increased protective value since some shrinkage/compression of the fabrics occurred, thereby reducing the proportion of open space (Sliney, Benton, Cole, Epstein, & Morin, 1987).

Wet fabrics have been shown to provide less protection than dry samples (Jevtic, 1990). Jevtic compared two items of clothing in an *in-vivo* test to measure sun protection. Ten subjects with Skin Types One or Two were used. Jevtic found that the lycra/polyester surf shirt had relative sun protection factors of 36 (green) and 35 (orange), where the relative protection factor is the reciprocal of transmission. A T-shirt had a relative protection factor (RPF) of 16. The RPF's for both pieces of clothing were reduced by a third when they were wet. Jevtic suggested that "water itself ... is a relatively poor barrier to light, and it is thought that decreased reflectivity and increased scattered radiation allows greater penetration of light through wet materials" (p. 7). Jevtic concluded that the tightness of the weave, color and thickness all significantly affect a fabric's relative opacity to light.

Welsh and Diffey (1981) did not find a direct relationship between the protection factor and a sample's thickness, color or fiber type. While Welsh and Diffey recorded the thickness and structure (woven or knitted) of the samples, they did not characterize the openness of the structures (cover), which they concluded was a primary variable in determination of the protectiveness of the fabric.

CHAPTER III

Methodology

The purpose of this study was to examine the effectiveness of clothing as protection from ultraviolet radiation. More specifically, fabric characteristics were examined for their relationship to UVR transmission to determine if certain fabric characteristics, such as cover or mass, could be used to predict the solar-protective performance of materials. The main independent variables were fiber type, fabric count, structure, mass, and cover. Color was an independent variable in a separate qualitative study. The dependent variable, UVR transmission, was measured with a spectrophotometer fitted with an integrating sphere.

Independent Variables: Fabric Descriptors

There were six independent variables in this study: fiber type, fabric structure, fabric count, fabric mass, cover and color. Fabric count (yarns/cm), cover and fabric mass together described the compactness of fabric structure. Cover described the degree of open space in a fabric. Color was examined separately in a small qualitative experiment.

Various fabrics ordered from Test Fabrics Incorporated (P.O. Box 420, Middlesex, New Jersey, USA, 08846) were chosen to represent a wide variety of fiber types, weights and structures (see Appendix A). All fabrics were white, bleached or unbleached. Information about the fabric parameters (fiber type, mass, fabric count, structure and cover) was recorded. This information is presented in the Results Chapter.

The fiber types which were tested were cotton, wool, polyester, nylon, flax, acetate, acrylic, rayon and two blends: polyester/wool and polyester/cotton. Confirmation of the fiber types was done through microscopic analysis and chemical solubility tests, AATCC method #20-1990, if necessary. Structure refers to the construction method of a fabric. In this study, structure was described as "woven " or "knitted". Fabric count helped to describe the tightness of a weave or knit. This was done according to "CAN/CGSB-4.2 No. 7-M88 - Knitted Fabric Count" and "ISO 7211/2 - 1984(E) - Determination of number of threads per unit length". Including the tightness of weave or knit as a variable was important for testing the transmission of radiation through the fibers or yarns. If a tightly woven fabric was found to readily transmit UVR, then transmission through the yarns or fibers would be suspected to contribute to total transmitted radiation. Fabric count and structure did not provide all the necessary information regarding tightness of a weave, since the size of the yarns (linear density) must be considered as well.

Mass was measured according to test method "CAN/CGSB-4.2 No. 5.1-M90 - Unit mass of fabrics". Five specimens were cut so as to have different warp and weft yarns for each specimen, were conditioned at 65% relative humidity and 21° C for at least 4 hours, and were weighed on an analytical balance. The mass per unit area (grams per meter squared) was calculated.

Cover

The fifth independent variable, cover, describes the proportion of the space in a given area of fabric occupied by warp and filling yarns relative to the empty space. It is a more complex descriptor than the other variables, and there is no universally accepted standard method of measuring cover. This is an important aspect of solar protective fabrics, as UVR transmission through open spaces accounts for the majority of transmission through many fabrics.

Grosberg (1969) and Booth (1969) suggest, that to measure the cover factor of textiles, detailed calculations are necessary to account for the geometry of yarns as they bend and cross over each other in the woven structure. Linear density and yarn diameter must be measured in order to calculate cover factor. Taylor (1981) differentiates between 'cover' and 'cover factor' and suggests that 'cover' provides a better description of the fabric's ability to cover a surface since it takes into account the proportion of stray fibers protruding into spaces between yarns rather than simply the number of threads per centimeter and their linear density. Taylor recommends assessing visible light transmission through a fabric to describe a fabric's cover. Schweger and Kerr (1987) suggest a method for measuring the percentage area covered by yarns in a woven fabric. This involves measuring (under a microscope with a calibrated eyepiece micrometer) the width of at least 20 yarns and at least 20 spaces between yarns in the warp and weft direction of the fabric sample. Then the percentage area of covered space for one repeat of the fabric is calculated based on the average widths of spaces and yarns in the fabric. This method is accurate if the spaces are square or rectangular and fairly regular in shape; it lacks accuracy if a fabric contains hairy spun yarns, because yarn diameters and spacing must be estimated. Numerous measurements must be made and averaged. This method can not be used to determine the cover of knitted fabrics or fabrics with spaces that are irregular in shape rather than rectangular. Morton (1962) developed a direct-reading photometer for measuring the transmission of visible light through fabrics as a measure of cover. This involved using darkly dyed fabric samples and a light source.

For this study, three methods were examined as possible ways to measure cover. The three methods included the measurement of yarn spacing using a calibrated eyepiece micrometer on a light microscope (Schweger & Kerr, 1987), a variation of the direct reading photometer method developed by Morton (1962), and a method developed by the researcher using image analysis software. The method involving image analysis was considered the most precise and accurate, was simple and rapid, and could be used for knits as well as woven fabrics. Image analysis software was employed to capture and analyze a video image of each fabric sample magnified 30x with an optical light microscope. Four areas were chosen in each fabric, and an average percent cover was calculated for these areas. The image included from one to approximately fifty repeats in the fabric design, depending on the yarn sizes and tightness of knit or weave. The video terminal consisted of 256 x 256 pixels, each of which had a value from 0 to 255 representing the grayness of that pixel. When moving the cursor around on the video screen, the different values and their location on the grid appeared on the computer monitor. For each of the four images, a distinction (based on the numerical value on the black to white scale of 0 to 255) was made by the operator between covered and uncovered space. The computer redrew the images in two colors, red and green, with one color representing covered space and the other uncovered. The number of pixels on the video terminal which fell into each of the two color categories was calculated by the computer program, and the percentage of covered pixels out of the total number of pixels was taken as the percent cover.

Limitations to this method were mainly in the microscopy part of the set-up. The center of the image was more brightly illuminated than the edges of the image. Focusing and adjusting the light intensity dramatically changed the image on the screen, and thick samples were difficult to bring into focus due to their depth. Also, very fine and transparent yarns appeared invisible when illuminated by intense light from the microscope. Determining a cut-off value between open space and space covered by these transparent yarns proved difficult and was dependent on the on the judgement of the operator. Because of these limitations the final measured values of cover reported here were estimated to be accurate to ~5 to 10%. It is expected that with further refinement the accuracy of this technique could be improved. The benefit of this method was that stray yarns were included in the calculation of covered area and irregular shapes posed no difficulty in the measurement.

Color

In order to examine the effects of color on UVR transmission, specimens from each of the four cotton fabrics were dyed blue using Procion M Midnight Blue reactive dye (3% shade owf, 4.6 g fabric mass, 50:1 liquor ratio) and were tested for UVR transmission. The dye recipe included 138 mL dye, 13.8 g NaCl, 23 g Na_2CO_3, and 285.2 g distilled water. Four specimens were also treated to the same recipe, excluding the dye, to account for any differences caused by shrinkage or other distortion. The difference in SPF of dyed and undyed specimens was reported.

Measuring the Dependent Variable - UVR Transmission

Spectrophotometry is commonly used as a means of measuring how much light is reflected or transmitted by any material over a certain set of wavelengths. This method has been used in previous studies of solar-protective clothing (Menzies et al., 1991; Robson & Diffey, 1990). Menzies et al. outlined three requirements for accurate spectrophotometric assessments.

> Firstly, all forward-scattered and transmitted light must be collected and either spatially averaged using an integrating sphere or its spatial variation monitored explicitly using a position-sensitive detector. ... Secondly, spectral measurements must span a range that includes all erythemally active wavelengths, including the UVA region (320-400 nm). ... Finally, the fluorescence must be adequately accounted for (Menzies et al., p. 160).

These conditions have all been met by this study. An integrating sphere was used to collect all forward-scattered and directly transmitted light, the wavelength range included 250 - 400 nanometers, and fluorescence was eliminated by the use of a 3 mm UG-5 fluorescence filter adapted for the spectrophotometer. Spectrophotometry was chosen because the equipment was readily available, because it measures transmission as a function of wavelength, and because it was used successfully by other researchers (Menzies et al., 1991; Pailthorpe, 1993a&b; Robson & Diffey, 1990).

Equipment

Transmission of ultraviolet radiation through the fabric samples was measured with a Varian Cary 2415 UV-Vis-NIR spectrophotometer, to which an integrating sphere had been added for measuring directly and diffusely transmitted light. Light was filtered to desired bandwidth and was split into two beams. One beam passed through the sample and the other acted as a reference beam, striking a completely white ($BaSO_4$ coated) reference surface. All measurements were made with respect to this reference beam. The spectrophotometer was controlled through the accompanying Varian DS 15 Data Station. On the Data Station the parameters of the scan were indicated, including spectral band width, range, and operating modes.

The monochromator filtered the incident radiation to a 2 nm bandwidth. The sample was located flush to the opening of the integrating sphere so that a greater portion of the scattered radiation transmitted was collected by the sphere. The integrating sphere, which is coated on the inside with white $BaSO_4$ paint, collected all the UV light which passed through the sample, and the intensity of light was detected by a photomultiplier on the top of the sphere.

If radiation absorbed in the fabric sample was re-emitted as fluoresced visible light, this light would be detected by the photomultiplier, indicating a higher percentage transmission of radiation than actually occurred in the UVR region. In order to block such radiation, a 3 mm UG-5 fluorescence blocking filter was curved to fit snugly in front of the photomultiplier detector.

Procedure

Five specimens of each fabric were mounted on 5 cm washers with a 2 cm opening. The five specimens of each test fabric were selected so that no specimen had the same warp and weft yarns.

Spectrophotometric tests were conducted as follows:

1. After turning on the spectrophotometer and selecting the appropriate parameters, a baseline scan was run without a sample in place. This baseline was used as a correction factor for the scans. (The parameters which had to be specified included the wavelength range (250 - 400 nm), the spectral bandwidth (2 nm), pen and chart functions were off, the beam interface was reversed, and the slit opening was set at one third.)
2. Specimens, glued to washers, were placed on a holder situated at the front of the integrating sphere, allowing the fabric to fit against the sphere's opening.
3. Each specimen (five per sample) was scanned once. Data was saved on the Data Station and transferred to a personal computer. Noisy scans were identified from the output received on the data station as the scan was being run. These scans were repeated and noisy scans were omitted from analysis, since they were caused by the electronics in the instruments and were not due to the nature of the fabric.
4. Transmission data were converted to Sun Protection Factors and an average SPF was calculated for the five specimens of each test fabric. The Sun Protection Factor calculations weighted the percent transmission with McKinlay and Diffey's (1987) biological action spectrum (Appendix B) and a solar action spectrum representing Edmonton's atmospheric conditions in late June and early July (Appendix B). The following formula is the mathematical equation used, where S is the solar action spectrum, E is the biological action spectrum and T is the percent of UVR transmission through fabric specimens. Each of these is a function of wavelength (λ) over the range 250 nm to 400 nm.

$$SPF = \frac{\sum S(\lambda)E(\lambda)}{\sum S(\lambda)E(\lambda)T(\lambda)} \tag{7}$$

Pre-test

A pre-test was conducted with fourteen swatches of fabric. Independent fabric variables (mass, cover, count, and structure) were examined to determine if they created a significant difference in UVR transmission. Fiber types were not varied systematically in the randomly chosen fabrics but included cotton, polyester/cotton, polyester, nylon and wool blends. The samples were a variety of colors and prints. Fabric analysis and UVR transmission testing were carried out for each of these samples when sufficient fabric was available for the analysis. Differences seemed to be evident among fiber types, structures, colors and masses.

As a test of variability within one fiber type group, the UVR transmission of fifteen specimens cut from a sample of bleached cotton fabric was measured and SPFs were calculated. The mean (3.52), standard deviation (0.33) and coefficient of variation (9.32%) were calculated to determine the typical sample repeatability of the SPF test method, according to CAN/CGSB-no. 1-M87. One specimen was tested ten times and the variability using a single sample was determined by calculating mean (3.23), standard deviation (0.35) and coefficient of variation (10.81%). The SPF test method and specimen repeatability were determined to be precise with reasonable coefficients of variation (9% to 11%). Results of the Pre-test, including repeatability and precision tests are included in Appendix C.

To check the absolute accuracy of the instrument, two calibrated neutral density filters with transmissions of 10% and 1% were purchased and tested in the standard textile measurement mode. The transmission as a function of wavelength was compared to the factory calibration curve and found to agree within 2& (relative error) for the 10% transmission filter and within 4% (relative) for the 1% transmission filter. Further inaccuracies could arise from nonuniformity of the response function for the integrating sphere in measuring scattered light which is estimated to be on the order of a few percent. Overall the accuracy of the transmission measurements is estimated to be better than 5% (relative error) for fabrics with transmissions greater than 1%.

As a further check on instrument accuracy, 30 specimens were tested by Optical Data Associates (ODA), Tuscon, Arizona. Equipment and procedures were essentially the same except that ODA had newer models of the Cary Spectrophotometer and integrating sphere. Small variations of up to 2% in the absolute value of the transmission were evident between results from the two laboratories, neither lab consistently having the higher or lower results. Differences were likely due to variations in the calibrations of the two instruments and some detection of fluorescence, particularly by Optical Data Associates who used a thinner UG5 filter, 2 mm rather than 3 mm, to block fluorescence.

Experimental Design

The operational definitions of the four initial independent variables (fiber type, structure, mass, fabric count) created a 9 x 2 x 2 x 2 factorial experiment when the variables were divided into appropriate levels: nine levels for fiber type, two for structure (knitted, woven), and two for mass and count (high, low). Because it was not possible to obtain fabrics with high and low mass and high and low count in each fiber type and structure, the design was reduced to a 9 x 2 x 2 factorial experiment, where the third level pertained to count or mass, whichever was determined to be more meaningful, that is, where variation existed. For each of the 36 cells a representative sample was needed. However, the sample fabrics did not meet each requirement for all of the cells, so a decision was made that the samples available met the needs of the study and the test proceeded with missing cells. Twenty-eight samples (140 specimens) were tested for UVR transmission.

Empty cells in the experimental design were noted and are identified in the factorial design in Appendix D. Many of the missing cells for fabrics were not typical of summer-weight clothing fabrics or not typical combinations of variables; for example, no fabric was available for the cell requiring a heavy acetate knit. It was justifiable to proceed with the fabrics available. The 9 x 2 x 2 factorial design was modified slightly for the statistical analysis of results (see below).

Statistical Analysis

Differences in Sun Protection Factors of the twenty-eight samples were described with respect to fiber type, structure, mass, count and cover. To confirm significant effects of fiber type, structure, mass and cover on SPF, an analysis of variance was conducted. The anlaysis used fiber type (six levels), structure (two levels) and mass (three levels) as independent variables. Fiber type was reduced to six levels since cellulosics performed similarly and it was deemed appropriate to group them together. The fiber type groups, then, were poyester, nylon, wool, cellulosics (linen, cotton, rayon and acetate), acrylic and blends. Mass was labelled as low (less than 120 g/m^2), medium (120 to 190 g/m^2) and high (greater than 190 g/m^2). Structure was divided into knit and woven as originally planned. Cover was directly related to mass and structure and, thus, was not considered an independent variable in the ANOVA.

The factorial design tested by the ANOVA was a 6 x 3 x 2 design which tested for individual and combined effects of fiber type, structure and mass on SPF. Sun Protection Factors were used rather than percent UVR transmission as the dependent variable in the statistical analysis.

Scatter plots of mass versus SPF for each fiber type were used to examine the fiber types individually. A least squares quadratic regression curve was proposed to fit the data, and regression coefficients were reported.

CHAPTER IV

Results and Discussion

The purpose of this study was to examine the effectiveness of clothing fabrics in blocking UVR and to identify fabric parameters which contribute to UVR protectiveness. Twenty-eight fabrics were selected with various fiber types, masses, fabric counts and construction. Table 2 is a summary of all the information determined for each fabric, including fiber type, structure, count, mass, percent cover and SPF. The information will be discussed in detail, focusing on relationships among these variables. The proportion of covered space to open space was calculated with image analysis software and is described as the percent cover.

Spectrophotometric Measurements

The average SPF (based on measurements of UVR transmission through 5 specimens for each fabric) is reported in Table 2. Spectrophotometric measurements indicated that the amount of transmitted radiation varied with wavelength for most fabrics. Specific patterns of transmission were observed for different fiber types and will be discussed in this section. A representative graph of transmission versus wavelength for each of the twenty-eight samples may be found in Appendix E.

There were six polyester fabrics in the experiment. Transmission through these fabrics was characterized by a steep increase between 310 nm and 320 nm. Another sharp rise was evident between 355 nm and 375 nm. Figure 1 shows a representative distribution of transmitted radiation versus wavelength for the spun polyester plain weave (2) which had an SPF of 12. The polyester fabrics blocked most of the erythemally active UVC and UVB radiation with the majority of transmitted radiation being in the UVA range. SPF's ranged from 7 to 77 for these fabrics. Genkov and Atmažov (1968) tested six polyester fabrics of different colors. Transmission of UVR was between 3.3% and 5.4% for all six colored samples.

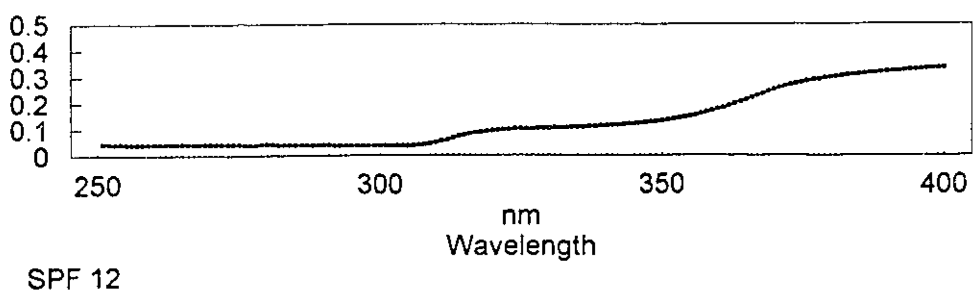

Figure 1. Transmission of UVR through spun polyester sample (2).

Table 2
Description of fabrics by fiber type[a]

#	Fiber Type	Structure	Count[b] warp x weft - woven wales x courses - knit	Count[b] total	Mass g/m²	Cover[b] %	SPF[b]
1	polyester	plain woven	38 x 25	63	68.1	87	7
2	polyester	plain woven	25 x 23	48	132.8	83	12
3	polyester	plain woven	41 x 24	65	149.2	98	34
4	polyester	rib knit	15 x 13	28	105.9	81	17
5	polyester	double knit	11 x 14	25	198.1	87	32
6	polyester	double knit	13 x 8	21	256.9	93	77
7	nylon	plain woven	36 x 42	78	61.4	96	5
8	nylon	plain woven	20 x 20	40	124.9	81	5
9	nylon	tricot knit	16 x 18	34	73.0	85	4
10	nylon	double knit	12 x 18	30	235.7	99	77
11	cotton	plain woven	33 x 34	67	106.1	81	4
12	cotton	twill woven	45 x 20	65	264.8	100	13
13	cotton	jersey knit	15 x 13	28	123.9	83	4
14	cotton	"lacoste" knit	9 x 4	13	141.1	86	3
15	wool	plain woven	20 x 21	41	117.5	82	8
16	wool	twill woven	22 x 20	42	263.4	100	139
17	wool	jersey knit	11 x 15	26	194.1	95	22
18	rayon	plain woven	29 x 23	52	139.6	86	5
19	linen	plain woven	21 x 19	40	107.1	79	5
20	linen	plain woven	15 x 15	30	237.3	92	9
21	acrylic	plain woven	40 x 40	80	131.1	84	7
22	acrylic	plain woven	20 x 15	35	143.1	86	10
23	acrylic	jersey knit	24 x 29	54	128.3	75	6
24	acrylic	jersey knit	26 x 34	60	343.6	95	104
25	acetate	plain woven	20 x 13	33	192.6	85	5
26	acetate	tricot knit	12 x 19	31	76.8	79	4
27	poly/wool	plain woven	24 x 22	46	166.6	89	17
28	poly/cotton	plain woven	57 x 29	86	129.8	83	11

[a] all fabrics were white (wool samples were naturally slightly yellowish; cottons were bleached)
[b] reported count is average of five measurements, SPF is average of five, percent cover is average of four

Three nylon samples (7, 8, 9) exhibited very similar transmission over the range being tested. Transmission through the nylon taffeta (7), spun nylon plain weave (8) and nylon tricot knit (9) was 16 - 22% at 250 nm (depending on the specific fabric), sharply increasing between 340 nm and 370 nm and gradually increasing to approximately 39 - 46% at 400 nm. Thus, while transmission was relatively constant through the UVC and UVB wavelengths, it was greater in the UVA region. One region of sharp increase in transmission was noted for nylon, whereas two were observed for polyester. Each of these nylon fabrics was rated SPF 4 or 5. Figure 2 shows percent transmission versus wavelength for the nylon tricot (9). The fourth nylon fabric, a double knit (10), had an SPF of 77. Very little transmission occurred below 350 nm, but an increase was noted beyond this wavelength. Since the mass was much higher than for the other nylon samples and this sample was also thicker, it is conceivable that the reduction is an additive effect of increased thickness which filters the radiation.

Other researchers measured the amount of UVR transmission through nylon fabrics. Genkov and Atmažov (1968) reported 11.8% transmission through a white nylon sample. No further description of the sample was provided. Hutchinson and Hall (1984) found a range of 14% to 64% transmission of UVR through various pairs of nylon hosiery. These values are comparable to the transmission values described earlier for the samples in this study.

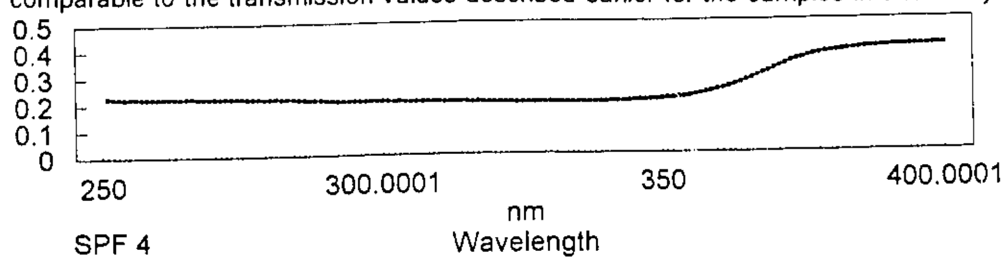

Figure 2. Transmission through nylon tricot sample (9).

A smooth increase in transmission from 250 nm to 400 nm was noted for all cotton samples. Figure 3 shows the transmission of UVR through bleached cotton print cloth (11). All four of the fabrics had SPF's less than 15, transmitting some radiation in each of the UVC, UVB and UVA ranges. Greiter, Siladji and Bilek (1985) found that there was 10.6% transmission of UVB and 20.4% of UVA through cotton. The bleached cotton print cloth (11) exhibits a similar increase from 22% transmission in UVB to 32% in UVA wavelengths. This large difference suggests that use of only UVA or UVB would be misleading as an estimate of protection. Hutchinson and Hall (1984) found a white cotton fabric exhibited 18% transmission of UVR. Mörikofer (1931) measured 18% transmission through cotton stockings, 40% through cotton voile, and 50% through white muslin.

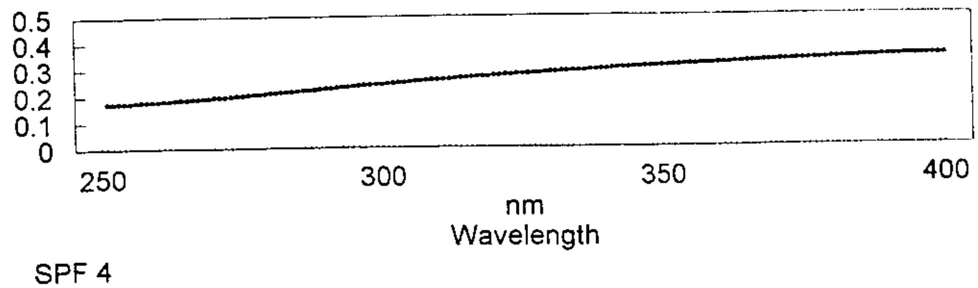

Figure 3. Transmission through bleached cotton print cloth (11).

The greatest variations in patterns of transmission for the same fiber type were noted for the wool samples. The wool challis (15) had an SPF of 8. It transmitted up to 6% of UVC radiation and showed a linear increase in transmission through the UVB and UVA wavelengths up to approximately 33% transmission at 380 nm. The wool jersey knit (17) with an SPF 22 transmitted 2-3% of UVC wavelengths, showed a slight increase between 290 and 325 nm to 6-8%, then decreased after 345 nm to ~4% at 400 nm. This fabric transmitted UVR much more consistently over the whole range than did the wool challis, which transmitted considerably more UVA and UVB than UVC radiation. Wool gabardine (16) had an SPF of 139. This fabric blocked virtually all UVC and most UVB radiation. Transmission through wool gabardine increased from a negligible amount at 315 nm to 12% at 400 nm.

Handkerchief linen (19) had an SPF of 5 and transmitted from 16 to 18% over the whole range from 250 to 400 nm with 20% transmission at 400 nm. A smooth increase in transmission from 6% at 250 nm to 22% at 400 nm was noted for the linen suiting (20) which had an SPF of 9. This pattern was very similar to the cotton samples and was not unexpected since both cotton and linen are cellulosic fibers. The two linen samples varied with respect to characteristic transmission patterns. The viscose rayon challis (18), also a cellulosic, was comparable to cotton. Transmission through this sample was approximately 12-14% for UVC, increasing gradually to 32% at 400 nm. This fabric had an SPF of 5.

Transmission in the UVC and UVB ranges for acetate suiting (25) (a cellulose ester) compared well to that for the handkerchief linen (19) and the three nylon samples (7-9); all of these fabrics had mean SPF's of 4 or 5. There was 17 - 20% transmission in the UVC and UVB wavelengths through the acetate suiting, and a gradual increase up to ~26% at 400 nm. Transmission of UVA wavelengths was highest through nylon samples, followed by acetate, with the least amount of UVA transmission being through linen. Lignin content in linen may contribute to the added protectiveness in the UVA region. Acetate tricot (26) had a similarly low SPF of 4 and a transmission pattern resembling nylon as shown in Figure 4. A slight decrease in transmission from 26% at 250 nm to 24% at 330 nm was followed by a gradual increase to

38% at 400 nm.

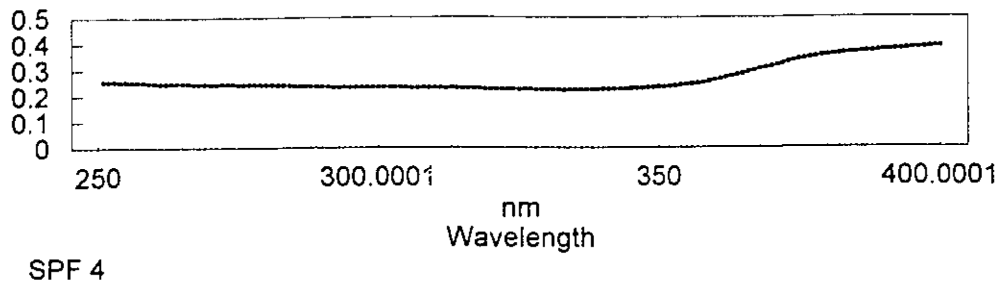

Figure 4. Transmission of UVR through acetate tricot sample (26).

Transmission through the three acrylic samples (21-23), with SPF's of 6, 7 and 10, was relatively constant through the UVC and UVB wavelengths with a steep rise in transmission occurring between 355 nm and 375 nm. This sharp increase resembles the second step observed in polyester samples. The fourth acrylic sample (24) had a high SPF of 104 and was similar to the wool gabardine (16) in that it transmitted a negligible amount of UVC and UVB. Transmission increased from 2% at 360 nm to 8% at 400 nm.

Two blends were tested as part of this study. The blends were polyester with wool and polyester with cotton. The poly/wool fabric (27) had an SPF of 17. Transmission through this fabric was similar to 100% polyester fabrics with sharp increases between 310 and 320 nm and again after 355 nm. For the poly/cotton (28) fabric, the first rise was evident between 310 and 320 nm, but a small dip in transmission occurred at 380 nm. Transmission varied from ~5 % at 250 nm to ~18% at 400 nm. Figure 5 shows the transmission through the polyester/cotton sample.

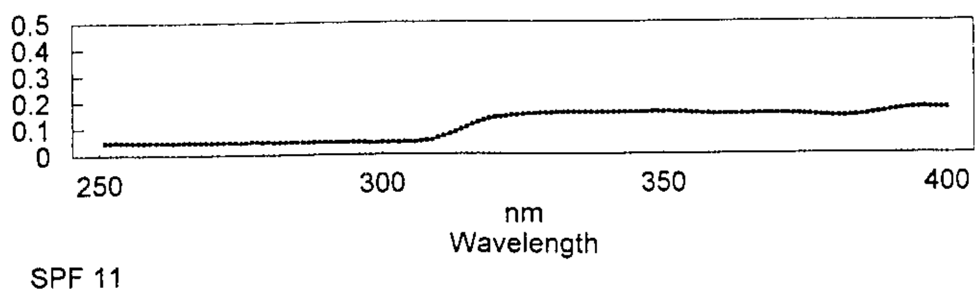

Figure 5. Transmission through polyester/cotton fabric (28).

Fluorescence

Slight increases in transmittance at the low end of the wavelength range suggest that fluorescence was influencing readings from the photomultiplier. A stronger fluorescence filter, such as a UG-11 rather than a UG-5, would eliminate most of the effects of fluorescence, but the wavelength range used would have to be decreased since the photomultiplier would detect nothing above approximately 380 nm. Menzies et al. (1991) used a UG-11 filter to block fluorescence.

Fabric Analysis

A limitation to this study was the small sample size used, twenty-eight fabrics. However, the observations and results are helpful as they contribute to the existing body of knowledge by emphasizing fabric variables and as a basis for the design of future studies examining the relationships between SPF and fabric variables.

Spectrophotometry was used to measure UVR tranmission, from which SPF's were calculated based on a solar action spectrum S(λ) for atmospheric conditions in Edmonton, Alberta. It is important to recall that a great limitation in this field is the lack of a standardized test method for measuring UVR transmission and subsequently determining SPF. There is no consistency in the weighting functions, S (λ) and E (λ), that are used in calculations or in reporting procedures. The results of this study will be compared to previous literature, keeping in mind that Sun Protection Factors can be calulated using different functions for the solar action spectrum S(λ) and erythemal action spectrum E(λ), and that some researchers have assumed that Protection Factors are equivalent to the inverse of transmittance. Such discrepancies will be pointed out where possible and necessary.

Fiber Type

The nine fiber types represented were polyester, nylon, cotton, wool, rayon, linen, acrylic, acetate and blends (polyester/wool and polyester/cotton). The nylon samples were interesting since varied constructions had little effect on the SPF for three of the four fabrics. Three nylon fabrics had an SPF of approximately 5. They included a taffeta (7) with a high count and a low mass, spun nylon plain weave (8) with a mid-range count and mass, and a tricot knit (9) with low count and mass, as shown in Table 3. The low SPF for the tightly woven nylon taffeta indicates that transmission is occurring through the yarns and fibers since spaces are too small to account for a great amount of direct transmission.

The fourth nylon sample was a double knit (10) with high mass and high percent cover and had an SPF of 77. This fabric was substantially thicker as well as heavier than the other three. Added thickness of fabric will reduce transmission considerably. This likely explains the higher SPF for the fourth nylon sample seen here. Nylon polymers often have delusterant and fluorescent whitening agents incorporated into the polymer. These additives can often increase the amount of absorbed radiation in the ultraviolet spectral region.

Table 3

Nylon samples

Description	SPF[b]	Mass (g/m^2)	Cover[b] (%)	Count[a]
nylon taffeta (7)	5	61.4	96	78
spun nylon plain weave (8)	5	124.9	91	40
tricot knit (9)	4	73.0	85	34
nylon double knit (10)	77	235.7	99	30

[a] yarns/cm (warp) plus yarns/cm (weft) for wovens; courses/cm plus wales/cm for knits; average of 5 counts.
[b] reported SPF is average of five specimens; Cover is average of four measurements

Pailthorpe's (1993a) results for nylon coincide with this study's finding. He rated a white nylon warp knit as SPF 5+, wet or dry. Menzies et al. (1991) arrived at slightly higher, but comparable, values of SPF 8, for on-skin measurements, or SPF 10, for 2 mm off-skin measurements, when testing a white nylon warp knit (161 g/m^2). Both of these researchers used spectrophotometric methods.

The polyester samples exhibited a distinctive pattern of UVR transmission in which increases occurred at ~310 nm and at 350 to 370 nm. Robson and Diffey's (1990) paper includes a graph of SPF versus wavelength for a polyester fabric which is comparable to the patterns observed in this study. This pattern is important to note since less protection is offered from UVA than from UVB radiation. It is conceivable that UVA tanning responses could occur through these polyester fabrics, while less damage from the UVB radiation would occur. Using only UVB light sources in testing would result in a higher SPF for a given fabric. However, the value obtained would depend on the spectral distribution of the light source in the region above and below 310 nm.

As opposed to the nylon samples, a range of SPF's resulted with the variations in fabric construction. The lowest SPF of 7 was for the polyester batiste (1) which had a relatively high count (63) but mid-range cover and low mass. The taffeta (3) had an SPF of 34, approximately 5 times higher than the batiste (1). It had a similar count (65) and a high cover (98%); its mass was twice as high as the batiste fabric. The SPF's for polyester were higher than initially expected based on the semi-transparency of the taffeta and thinness of the batiste and taffeta.

Conjugated double bonds in the molecular structure of polyester polymers, which favor absorption of UVR, could explain the high SPF's obtained.

Table 4

Polyester samples

Description	*SPF*[b]	*Cover*[b] *(%)*	*Mass (g/m²)*	*Count*[a]
polyester knit (6)	77	93	256.9	21
polyester taffeta (3)	34	98	149.2	65
polyester knit (5)	32	87	198.1	25
polyester knit (4)	17	81	105.9	28
polyester weave (2)	12	83	132.8	48
polyester plain weave (1)	7	87	68.1	63

[a] yarns/cm (warp) plus yarns/cm (weft) for wovens; courses/cm plus wales/cm for knits; average of 5 counts.
[b] reported SPF is average of five specimens; Cover is average of four measurements

Pailthorpe's (1993a) results include one polyester plain weave fabric which had an SPF of 10+, wet or dry. Robson and Diffey (1990) reported results for twenty nine polyester fabrics also tested spectrophotometrically. Two white polyester fabrics were an open satin blouse fabric with an SPF of 73 and a satin weave blouse fabric with an SPF of 578. For all of the fabrics, the SPF's ranged from 2 to 828. Only the color and item of clothing were reported to describe the samples; cover and fabric mass were not reported. The SPF's for the two white fabrics, at 73 and 578, were much higher than those reported in this study or by Pailthorpe. The reason for this difference is not clear but it may be related to fabric mass. Welsh and Diffey (1981) found SPF's ranging from 6 to 68 for 13 polyester samples. The structure and thickness were reported in this paper, but thickness was not considered to be related to the protection factor of the fabrics. Structure was relevant as it determined the size of spaces in the fabric and, thus, the proportion of direct transmission through the fabric.

Cotton is an important fiber for sun-protection due to its comfort in hot weather and its popularity as a natural fiber. UVR transmission through cotton increased smoothly with wavelength. It should be noted that all of the present cotton samples were bleached. All four white cotton fabrics had SPF values less than 15. The highest rating was SPF 13 for the white twill weave (12). Since this fabric had a mass of 264.8 g/m^2 (about twice that of the other cotton samples) and maximum percent cover, some transmission through yarns must have occurred. The other three cotton fabrics had low SPF's of 3 or 4 and various constructions: loose plain weave (11), jersey knit (13), tuck stitch "lacoste" knit (14).

Gies and Roy (1993) tested 137 cotton fabrics, only 24 of which had SPF's less than 15. Fabric descriptions (including color) were not provided for this set of samples. Pailthorpe (1993b) reported results of tests on various white fabrics. Six cotton fabrics (including a single knit, plain weave and twill weave) were given SPF's of 15+ or less; one cotton fabric was rated 20+ (a single knit). Robson and Diffey (1990) tested ten cotton fabrics. The white samples (a plain weave sheeting, jersey knit T-shirt, and terry beach robe) had SPF's of 44, 32 and 871 respectively. The whole group of cotton fabrics in their study had SPF's ranging from 8 to 1571. While the colored fabrics may offer high protection, these researchers obtained much higher values for the white cotton fabrics than were found in this study. Welsh and Diffey (1981) tested four cotton fabrics all of which were colored (dyed or printed). Three of these woven cotton fabrics had SPF's >1000 and the fourth had an SPF of 36. The importance of dyes is discussed later in this chapter and likely helps to explain Welsh and Diffey's results. Berne and Fischer (1981) used a white cotton shirt in their tests and found it had a protection factor of 7. Two layers of this fabric increased the protection factor to 19.

The cotton samples in this study consistently offered less protection than similar polyester fabrics as is shown in Table 5. Although the cotton fabrics had a similar cover and count, their SPF values were 3 to 5 times lower. Polyester's natural tendency to absorb UV may account for its superior performance in this respect. Pailthorpe (1993a) suggests that removal of lignin from cotton by bleaching may reduce its SPF.

Table 5

Comparison of Polyester and Cotton Samples

Description	*Cover*[b] *(%)*	*SPF*[b]	*Mass* (g/m^2)	*Count*[a]
polyester taffeta (3)	98	34	149.2	41 x 24
cotton twill (12)	100	13	264.8	45 x 20
polyester knit (4)	81	17	106.1	15 x 13
cotton jersey knit (13)	83	4	124.1	15 x 13
polyester plain weave (2)	83	12	133.0	25 x 23
cotton print cloth (11)	81	4	106.1	33 x 34

[a] yarns/cm (warp) plus yarns/cm (weft) for wovens; courses/cm plus wales/cm for knits; average of 5 counts.
[b] reported SPF is average of five specimens; Cover is average of four measurements

Three of the four acrylic fabrics in this study had SPF's less than 15. The fourth fabric was a dense double knit (24) with high count, mass and percent cover and an SPF of 104. A positive relationship was noted between SPF and both mass and cover for the acrylic samples as is shown in Table 6.

Robson and Diffey (1990) tested five acrylic fabrics which had SPF's ranging from 17 to 84. None of these knitted fabrics were white and data such as mass and cover were not provided. Bech-Thomsen, Wulf and Ullman (1991) found that two acrylic fabrics from shirts transmitted 16% and 18% UVB. Color and construction were not reported. Hutchinson and Hall (1984) tested four acrylic knitted fabrics. They transmitted from 7% to 36% UVR.

Wool and acrylic are often constructed in similar fabrics, such as in bulky sweaters. Three wool samples were tested in this study. As with the acrylic samples, SPF increased with greater mass and cover as shown in Table 7. However, an acrylic jersey knit (23) with a mass of 128.3 g/m^2 and SPF 6 had a lower SPF than a wool plain weave (15) with mass 117.5 g/m^2 and SPF 8. Also the acrylic double knit (24) (SPF 104) with mass 343.6 g/m^2 had a lower SPF than a wool twill weave (16) with a lower mass (263.4 g/m^2, SPF 139). Thus, correlations exist within the two groups but not across the two groups. Differences may be attributed to fiber type, structure or some variable not measured in this study such as thickness or presence of fluorescent whitening agents or delusterant.

The wool gabardine (16) also had a much higher SPF of 139 than the cotton twill (12) with an SPF of 13; both fabrics had a high mass of 263 to 265 g/m^2 and 100% cover. High SPF's for the wool fabrics might be explained by wool's density, color or structure, namely the presence of benzene rings and conjugated double bonds in some of the amino acids. Scales on the surface of the wool fibers may increase scattering of the radiation off the irregular surface. Though not measured, the fabrics might have been thicker than otherwise comparable fabrics, further increasing the proportion of scattered radiation. Also, since wool has a natural yellowish color, when bleached or undyed, the structures which absorb visible radiation might also absorb UV. It has been shown in previous studies that wool is sensitive to photodegradation and many processes have been developed to improve wool's resistance to UV damage, including the incorporation of UV-absorbers in dyes and finishes.

Table 6

Acrylic samples

Description	*SPF*[b]	*Mass (g/m^2)*	*Cover*[b] *(%)*	*Count*[a]
acrylic jersey knit (24)	104	343.6	95	60
acrylic plain woven (22)	10	143.1	86	35
acrylic plain woven (21)	7	131.1	84	80
acrylic jersey knit (23)	6	128.3	75	54

[a] yarns/cm (warp) plus yarns/cm (weft) for wovens; courses/cm plus wales/cm for knits; average of 5 counts.
[b] reported SPF is average of five specimens; Cover is average of four measurements

Robson and Diffey (1990) tested three wool samples. The white sample (presumably bleached) was a plain weave blouse fabric and had an SPF of 16. A red wool crepe had an SPF of 12 and the black plain weave had an SPF of 95. Pailthorpe (1993) tested one white wool plain weave sample and found it offered an SPF of 30+ (15+ when wet). Welsh and Diffey (1981) rated a fawn-colored wool jersey knit (0.7 mm thick) as SPF 150. The sparse descriptions of the fabric samples provided by these researchers makes comparison of results difficult.

Table 7

Wool samples

Description	*SPF*[b]	*Mass (g/m²)*	*Cover*[b] *(%)*	*Count*[a]
wool twill weave (17)	139	263.4	100	42
wool jersey knit (16)	22	194.1	95	41
wool plain weave (15)	8	117.5	82	26

[a] yarns/cm (warp) plus yarns/cm (weft) for wovens; courses/cm plus wales/cm for knits; average of 5 counts.
[b] reported SPF is average of five specimens; Cover is average of four measurements

Berne and Fischer (1980) tested one white wool knit (700 g/m^2) and found it transmitted 8% of UV on average at the three wavelengths used and had an SPF of 12. As the transmission through the three wool samples (15, 16, 17) varied, it is difficult to suggest whether or not Berne and Fischer's results are typical of wool's performance. Sliney, Benton, Cole, Epstein and Morin (1987) tested four blended fabrics consisting of 90% wool and 10% other fibers. The two heavier fabrics (32 and 24 oz.) were rated as excellent protection for welders, having optical density ratings of 5.5 (substantially higher than the suggested safe value of 4.0). The other two fabrics (both 22 oz.) were rated as good protection with optical densities of 4.7. All four of these fabrics were taken from protective garments and are heavier than summer-weight fabrics used in most sun-protection studies. Denim fabric is typically 14 oz per square yard, much lighter than the wool blends tested by Sliney, Benton, Cole, Epstein and Morin.

All linen, rayon and acetate fabrics had SPF's of less than 10. The linen suiting fabric (20) had a high mass (237.3 g/m^2) and cover (92%) but still provided less protection than a sunscreen of SPF 15. As cellulosics or cellulose-derived polymers, these fibers do not have a high propensity to block UV radiation.

Menzies et al. (1991) found that a pink plain weave triacetate fabric (112 g/m^2) had a protection factor of approximately 11.5. Robson and Diffey (1990) tested ten viscose rayon fabrics. The lowest SPF was for a cream-colored crepe (SPF 10). All other viscose fabrics were dyed or printed and SPF's ranged from 19 to 183, considerably higher than the SPF of 5 for the white viscose fabric measured in this study.

Mass

Masses ranged from 61.4 g/m^2 for a nylon taffeta (7) to 343.6 g/m^2 for an acrylic knit (24). Mass was plotted against SPF for each fiber type. Within fiber type groups, mass was shown to have a significant effect on SPF. The data were fit to a least squares quadratic regression curve and high correlations were indicated by coefficient of determination values ranging from r^2 = 0.95 for the nine cellulosics fabrics to r^2 = 1.0 for the four acrylic fabrics, as shown in Appendix F. Blends were not plotted since there were only two samples. While the quadratic regression curve fit the data extremely well, a larger number of samples for each fiber type is necessary to determine if this highly correlated relationship holds in general for each fiber. Although a general increase in SPF was noted with increase in mass, this relationship was not as consistent for all twenty eight samples taken together. The best fit quadratic curve was drawn, in this case as shown in Figure 6, and the coefficient of determination was r^2 = 0.723 (Figure 6). Since the SPF's measured in this study are specific to the white fabrics used, the correlation between mass and SPF may be more or less significant for other fabrics, especially if color is added as a variable, since color might be a stronger predictor of SPF than mass. A test of significance using ANOVA indicated that mass had a significant effect on SPF ($p<0.05$). It can be seen in Figure 6 that mass does not fully account for a fabric's protectiveness as there is great variation between SPF's for a given mass, especially at high masses. Woven fabrics with low or high masses may have SPF's below 20. Knitted fabrics with high masses are more likely to have high SPF's than are woven samples in this study.

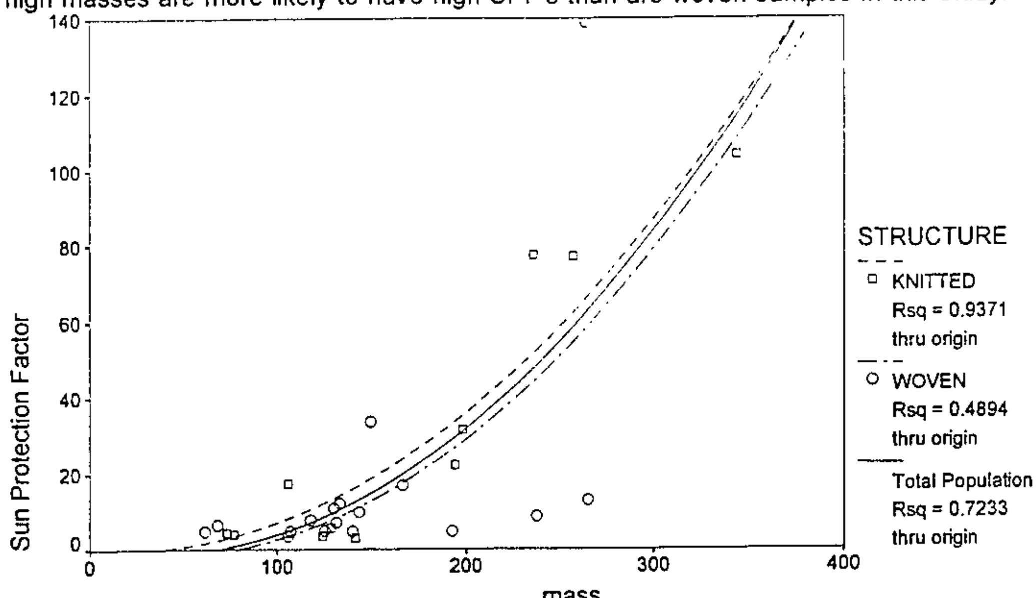

Figure 6. Mass versus SPF.

Berne and Fischer (1980) found that heavier fabrics blocked more radiation than lighter fabrics. In general, the same relationship was observed in this study. Other researchers have emphasized that several variables together account for a fabric's protectiveness (Gies, Roy, Elliott & Zongli, 1994; Pailthorpe, 1993b; Robson and Diffey, 1990).

<u>Cover</u>

The measured cover ranged from 75% for an acrylic knit (23) to ~100% for both cotton (12) and wool (16) twill weaves. In the case where yarns are opaque to UVR, it has been suggested by Pailthorpe (1993a) and Capjack et al.(1994) that there is a direct relationship between SPF and the direct transmission through the spaces between yarns: SPF = 100 / (100 - % cover). Any transmission that may occur through yarns would decrease the SPF. Figure 7 shows the relationship between cover and SPF for the samples in this study as well as plotted points representing maximum SPF for a given cover as defined by the above equation. It is obvious that the assumption of opaque yarns does not hold true since many of the recorded SPF's are lower than that suggested by this direct relationship, exhibiting more transmission than can be explained simply by direct transmission through spaces. It is interesting that SPF values greater than 15 were noted for both low (81%) and high (up to 100%) values of measured cover. This suggests that direct transmission through the spaces may be reduced somehow. Perhaps many small stray yarns protruding into spaces, which would not have been considered part of the covered space, act strongly in some fabrics to absorb UVR. This also suggests that all stray fibers for these samples should have been included in the calculation of cover. More knitted fabrics exhibited this phenomenom than woven fabrics. This may be because the yarns in a knitted structure are looped and do not form spaces which are as uniform or which have as straight boundaries as the spaces found in woven structures. Viewing the thickness created by the looping is difficult with the microscope's limited depth of field.

It must be noted that the procedures used to determine cover were developed by the researcher and no evidence of their use was found in literature. It was observed that readings made on separate days varied, mainly due to operator bias. The operator had to make a distinction between covered and uncovered space and the distinction depended on the intensity of light passing through the sample, and the subjective determination of which stray fibers were to be considered in covered or opened space. Two fabrics (wool jersey knit (17) and nylon double knit (10)) were analyzed much later than the other fabrics. Analysis of three cotton fabrics was repeated at this later date and results were higher than previously recorded: 93% cover for the cotton print cloth as opposed to 81% previously measured; 91% rather than 83% for cotton jersey knit; and 88% rather than 86% for the cotton lacoste knit. This suggests that results are only accurate within 2 to 10%. The lower values were reported in the results since they were measured with the majority of fabrics at the earlier date. The percent cover values reported for the wool jersey knit (17) and nylon double knit (10) are likely higher than that which would have been determined earlier. Such discrepancies in this methodology need to be resolved in the future. For the purposes of this study, values for cover are a useful comparison of the fabrics relative to one another with respect to covered space. However, further study is necessary to improve the accuracy of the measurement.

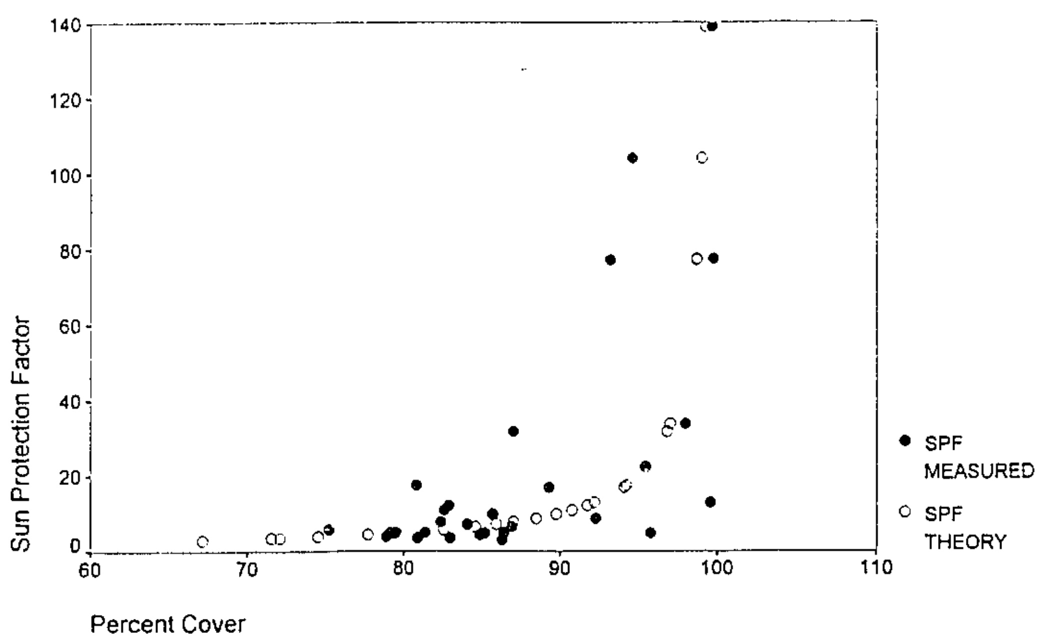

Figure 7. Cover versus SPF, theoretical and experimental.

It was observed that for fabrics with a similar percent cover, a great variation in SPF could result. For the seven fabrics with percent cover ranging from 95% to 100% in Table 8, the SPF's were 5, 13, 22, 34, 77, 104 and 139. For fabrics in the range of 75% to 85% cover, SPF's ranged from ~3 to ~12. Since all fabrics with less cover than 86% had SPF's lower than 20, it can be concluded that if the proportion of open space is high, there will be direct transmission of UVR through the open spaces. As the proportion of open spaces decreases (i.e., cover increases), the SPF varies as the proportions of directly and diffusely transmitted radiation vary. The proportion of diffusely transmitted radiation depends on the geometry of the fibers, thickness of the fabric, smoothness of the surfaces of fibers and yarns, spectral qualities of the fibers and additives, and presence of dyes.

Table 8

Comparison of Fabrics with High Percent Cover

Description	*Cover*[b] *(%)*	*SPF*[b]	*Mass* *(g/m²)*	Count[a]
bleached cotton twill (12)	100	13	264.8	45 x 20
white wool gabardine (16)	100	139	263.4	22 x 20
white nylon double knit (10)	99	77	235.7	12 x 18
white polyester taffeta (3)	98	34	149.2	41 x 24
white nylon taffeta (7)	96	5	61.5	36 x 42
acrylic jersey knit (24)	95	104	343.6	26 x 34
wool jersey knit (17)	95	22	194.1	11 x 15

[a] yarns/cm (warp) plus yarns/cm (weft) for wovens; courses/cm plus wales/cm for knits; average of 5 counts.
[b] reported SPF is average of five specimens; Cover is average of four measurements

As pointed out by Pailthorpe (1993b), assuming yarns to be opaque to UVR, a minimum of 93% cover is required to achieve an SPF of 15 or more. Yet, the cotton twill (12) has 100% cover and a low SPF of 13; nylon taffeta (7) had a 96% cover and an SPF of only 5. It is evident that the assumption of opaque yarns does not hold and that fiber composition and mass are important contributors to SPF along with percent cover. In this experiment, a polyester knit (5) has a cover of 87% and a high SPF of 32; another polyester knit (4) has a cover of 81% and an SPF of 17. These values suggest that the calculation of cover has some systematic error and underestimates the true cover by a certain amount, as discussed earlier, since an accurate measure of the open space would predict the maximum SPF for fabrics. If the yarns are not opaque, and some transmission goes through the yarns, then SPF is reduced. The only way to increase the SPF is to add more fiber, and this would increase the cover as well.

Structure

No differences were significant between woven and knitted structures; both high and low SPF's were reported for knitted and woven structures. The null hypothesis that structure has no effect on SPF ($p < 0.05$) was accepted when structure was used as an independent variable in an analysis of variance as shown in Appendix F

Count

Fabric count did not provide all the necessary information regarding tightness of a weave, since the size of yarns (linear density) must be considered as well. A fine yarn used in a low count weave will produce a fabric with low cover, and UVR will be expected to pass through spaces between the yarns. If thicker yarns are used, a higher cover will result and less transmission is likely to occur. Precise calculation of linear density of yarns in a fabric is time consuming, however, and direct measurement of UVR transmission would be a simpler method of determining SPF than predicting SPF from calculations of linear density, if such prediction were valid. On the other hand, linear density and yarn diameter could be estimated from count and mass per area, leading to a prediction of cover. The estimated values of cover could be used to predict SPF. This zero-order model has not been tested as it is beyond the scope of this work, but it deserves further consideration. No differences in SPF were indicated between low and high count fabrics because the size and hairiness of yarns, mass, cover and thickness varied for the fabrics.

Color

The low SPF of 13 for the white cotton twill was surprising as previous researchers recommended denim as suitable protection for many sun-sensitive patients. Denim produced high SPF values even in the pre-test conducted for this experiment. (The denim sample had an SPF well in excess of 100.) Since the white twill differs only in color from most denim, it was suggested that dye might be an important UV-absorber.

A small qualitative experiment was conducted to examine the effect of dyes on the SPF of a fabric. One specimen of each of the five cotton samples was cut and dyed with Procion M midnight blue reactive dye. Five specimens were also treated in blank dyebaths, that is, to the dye process without having the dye included in the recipe; this was to account for changes other than dyeing, such as possible shrinkage. UVR transmission was measured through the ten specimens and the results are reported in Table 9. Dyeing increased the SPF by more than a factor of three for all specimens. Pailthorpe (1993b) described the importance of dyestuffs on the SPF of fabrics, noting that dye molecules can absorb UVR and contribute to a fabric's protectiveness.

Table 9.

SPF's for dyed and treated cotton specimens

Description	*SPF*
Bleached cotton print cloth (11) - Treated	4
Bleached cotton print cloth (11) - Dyed	14
Cotton jersey knit (13) - Treated	4
Cotton jersey knit (13) - Dyed	18
Cotton twill weave (12) - Treated	12
Cotton twill weave (12) - Dyed	166
Cotton lacoste knit (14) - Treated	4
Cotton lacoste knit (14) - Dyed	12

Summary of Statistics

Table 10 shows the descriptive statistics (minimum, maximum, mean and median) for mass, count, cover and SPF. Of the twenty eight samples in this study, nineteen had an SPF of less than 15. The range was 3 to 139 and the median value was 9. This indicates that most of the white fabrics tested offered less protection than a sunscreen with an SPF of 15. Pailthorpe (1993) reported that, of 250 fabrics tested (data with respect to fiber types and colors were not provided), approximately 120 offered less protection than an SPF of 15.

Table 10

Descriptive Statistics for measured variables

	Mass (g/m^2)	Count[1]	Cover (%)	SPF
minimum	61.5	13 (knit) 30 (woven)	75	3
maximum	343.6	60 (knit) 86 (woven)	100	139
mean	157.6	n/a	87	23
median				9

[1]yarns/cm (warp) plus yarns/cm (weft) for wovens; courses/cm plus wales/cm for knits; average of 5 counts.

A three-way and a two-way analysis of variance were performed using SPSSx for Windows to determine the influence of mass, fiber type and structure (individually and for combined effects) on SPF of the fabrics. (Structure was excluded in the two-way ANOVA.) Sun Protection Factors were used for statistical purposes rather than percent transmission of UVR since SPF provides a description of protection offered by the fabrics. Mass was found to have a significant effect on SPF. It is clear that the addition of extra mass (additional fiber) to a fabric, keeping other variables constant, will increase the cover of the fabric. Thus it is obvious that mass and cover should have an effect on SPF. The three independent variables (mass, structure and fiber type) together also had a significant effect at p=0.05, but fiber type and structure were not significant individually. It was observed that within polyester, wool, nylon and acrylic fiber type groups both high and low SPF's could be obtained. All ten cotton, linen, acetate, rayon and blended samples provided low SPF's in this study. To compare individual groups (by fiber type) scatter plots of SPF versus mass for the fiber types were used. The sample sizes were very small (4 fabrics to 9 fabrics), but high positive correlations were indicated by using least squares quadartic regression to fit a line to the data points. The scatter plots and ANOVA tables are in Appendix F. A larger number of samples of each fiber type must be tested to determine if this relationship between mass and SPF will hold for a larger population.

The twenty-eight samples used in this study were not representative of summer-weight clothing, since all were white and many were quite heavy. While they are not likely choices for sun-protection, they were useful as a basis for comparison of the various fiber types and structures.

Spectrophotometry confirmed that there is a dependence on wavelength for transmission. The spectral transmission was distinctive for polyester, nylon and cotton fabrics. Cellulosic (cotton, rayon, linen) fabrics were similar in that they showed a uniform increase in transmission across the range of 250 nm to 400 nm.

An increase in SPF was generally noted with increases in mass and/or cover. Pailthorpe (1993b) notes that cover is increased by adding extra fiber (i.e. mass) to a fabric, thus these two variables are intimately related. This research suggests that cover can not be used to predict the SPF directly for fabrics, since a wide variation from the theoretical SPF was noted. Most of the fabrics offered less protection than a sunscreen with an SPF 15 rating.

Previous research was difficult to compare to this study since not all other researchers used the spectrophotometric methods and samples were not adequately described in the literature. Robson and Diffey (1990) tested over sixty fabrics and did use similar methods to those described in this study. Their results appeared to be much higher for white fabrics than were the results of this experiment. Reasons for such discrepancies are not clear.

While the sample size was small, a strong positive relationship between mass and SPF was noted within fiber types, but not as highly positive across fiber types combined. In general, SPF also increased with increases in percent cover.

CHAPTER V

Summary, Conclusions and Recommendations

Medical experts have endorsed the use of clothing as UVR protection. Studies have shown that fabrics can provide a wide range of protection from very little to practically complete protection. The majority of studies previously conducted did not systematically examine the effects of fabric variables, such as mass, fiber type, color and construction, on the UVR protectiveness of the fabrics. Various methods of measuring UVR transmission and various ways of reporting results made comparisons difficult.

Spectrophotometric measurements of UVR transmission through fabrics showed that fiber types had specific patterns of transmission over the range 250 to 400 nm. Some of these patterns of transmission had previously been reported by Robson and Diffey (1990). It was found that many fabrics provide less protection than that available from sunscreens.

This study was an examination of fabric variables, namely fiber type, mass, cover, structure and fabric count, and their effect on the SPF of fabrics. A general increase in SPF was observed with increases in mass, but this was not consistent throughout the twenty-eight samples. Mass and SPF were strongly related within fiber types. Other fabric variables including fiber type and cover had some effect on SPF as well. It is suggested that direct calculation of SPF from percent transmission measurements, measured spectrophotometrically, is the best method for rating solar-protective fabrics. A small qualitative analysis proved that the effects of color deserve more attention since dyes promote an increase in protection.

Conclusions

There were four objectives stated for this research. The four objectives have been met and conclusions are listed in this section.

Objective 1

The first objective was to measure UVR transmission, spectrophotometrically, through various fabrics and determine if transmission was wavelength dependent. It was determined that there is great dependence of transmission on wavelength. Considerable differences in transmission were noted when comparing wavelengths in the UVC, UVB and UVA ranges. Spectral transmission was distinctive for most fiber type groups. A uniform increase in transmission was noted from 250 nm 400 nm for cotton. Step increases were noted at different wavelengths for polyester and nylon. All three wool samples were characterized by different patterns of transmission over the range 250 nm to 400 nm. It is important, then, that determination of protection ratings be based on measurements over a broad range of wavelengths. Menzies et al. (1990) agreed that the range must encompass all erythemally active radiation, including both UVB and UVA wavelengths.

Objective 2

The second objective was to calculate Sun Protection Factors for the twenty-eight fabrics in this study. The calculation was performed by weighting the UVR transmission data with functions for the biological action spectrum (McKinlay & Diffey, 1987) and the solar action spectrum representing Edmonton atmospheric conditions in late June and early July. An average of 5 SPF's was reported for the fabrics. Nienteen of the fabrics had SPF's of 15 or less. Thus, most of the fabrics in this study provided less protection than sunscreens with ratings of SPF 15 .

Objective 3

Fabric variables (fiber type, mass, cover, count and structure) were examined for their relationship to the SPF of the fabrics in this study. While different fiber types had specific patterns of transmission over the range of wavelengths tested, SPF's varied greatly for many fiber types. For example, polyester fabrics had SPF's ranging from 7 to 77; wool fabrics ranged from 8 to 139. Polyester samples consistently offered higher protection than comparably constructed cotton fabrics. All cotton, linen, acetate, rayon and blended samples had SPF's less than 15. With respect to mass, a positive correlation was observed. SPF generally increased with increases in mass, but the relationship was not linear. Cover was also observed to influence SPF. The method used to measure cover is not refined and must be tested for repeatability and accuracy. Therefore, it is recommended that SPF be calculated from direct measurements of UVR transmission rather than predicted from cover, mass and/or fiber type. Other fabric variables, such as thickness and color, could be examined to design a simple and accurate predictive model.

Objective 4

A rating scheme is necessary to enable consumers to compare fabrics. The majority of fabrics in this study offered less protection than a sunscreen with an SPF of 15. Yet, the influence of dyes may increase the protection provided by fabrics substantially enough to warrant higher protection factors. It would be reasonable to use some limiting of SPF such as the limits placed on sunscreens, that is, that ratings will not exceed SPF 30 (FDA, 1993). While some manufacturers wish to rate fabrics with SPF's up to 100, this study does not support the need for such high ratings.

An SPF rating system would be equivalent to the *in-vivo* assessment of sunscreens, is familiar to some consumers already and is likely to gain rapid approval from consumers and regulators. Standard biological and solar action spectra need to be identified to ensure equivalence of ratings.

Recommendations

Based on the results of the literature review and the experiment presented in this thesis, several recommendations can be made for future studies in the area of clothing as sun protection. The recommendations are broken into three main areas of research: (1) textile research, (2) co-operative research with dermatologists and textile experts, and (3) advocacy research and development.

Textile Research

Color

The obvious beneficial effects of dyes on the SPF of the cotton fabrics in this experiment indicate that a much more detailed analysis is worthy of study. In particular, the differences in effect among shades and hues should be examined. Since nylon exhibited consistently low SPF's for three different fabrics, it would be interesting to see if the SPF could be increased by adding dye to the fabric.

Thickness

Density of fabrics may have some influence on the SPF of fabrics.

Other Fibers

In particular, microfibers are worthy of study due to the impact they are making in fashion. It is expected that the denser packing of microfibers would reduce direct transmission to a negligible amount, assuming that the generic fiber used is opaque to UVR. Spandex has been noted as a fabric with a very high SPF and is often used in summer athletic and beach wear. This relationship between spandex and high SPF should be confirmed.

Visible light Transmission

Many dermatologists recommend the "light bulb" test to their patients. Visible light transmission through the fabric should be measured quantitatively and compared to qualitative assessment of visible light transmission by human subjects. The correlation between UVR and visible light transmission should be measured.

Layers

Spectrophotometric analysis of layers should be studied as this emulates how garments are worn. Samples should be tested in contact with each other and with some separation between them. Functional design studies would contribute in this area as well.

In-vivo Comparison

More comparative studies should be performed to determine the correlations between spectrophotometric and *in-vivo* measurements.

Consumer and Educational Research

Research in this area would include market surveys to evaluate sun protective clothing currently available to consumers as well as development of standard test methods for measuring and rating the protection of fabrics. It is imperative that educational campaigns accompany the efforts to provide more protective clothing. Many people need education about the hazards of over-exposure to UVR and methods of preventing such occurrences.

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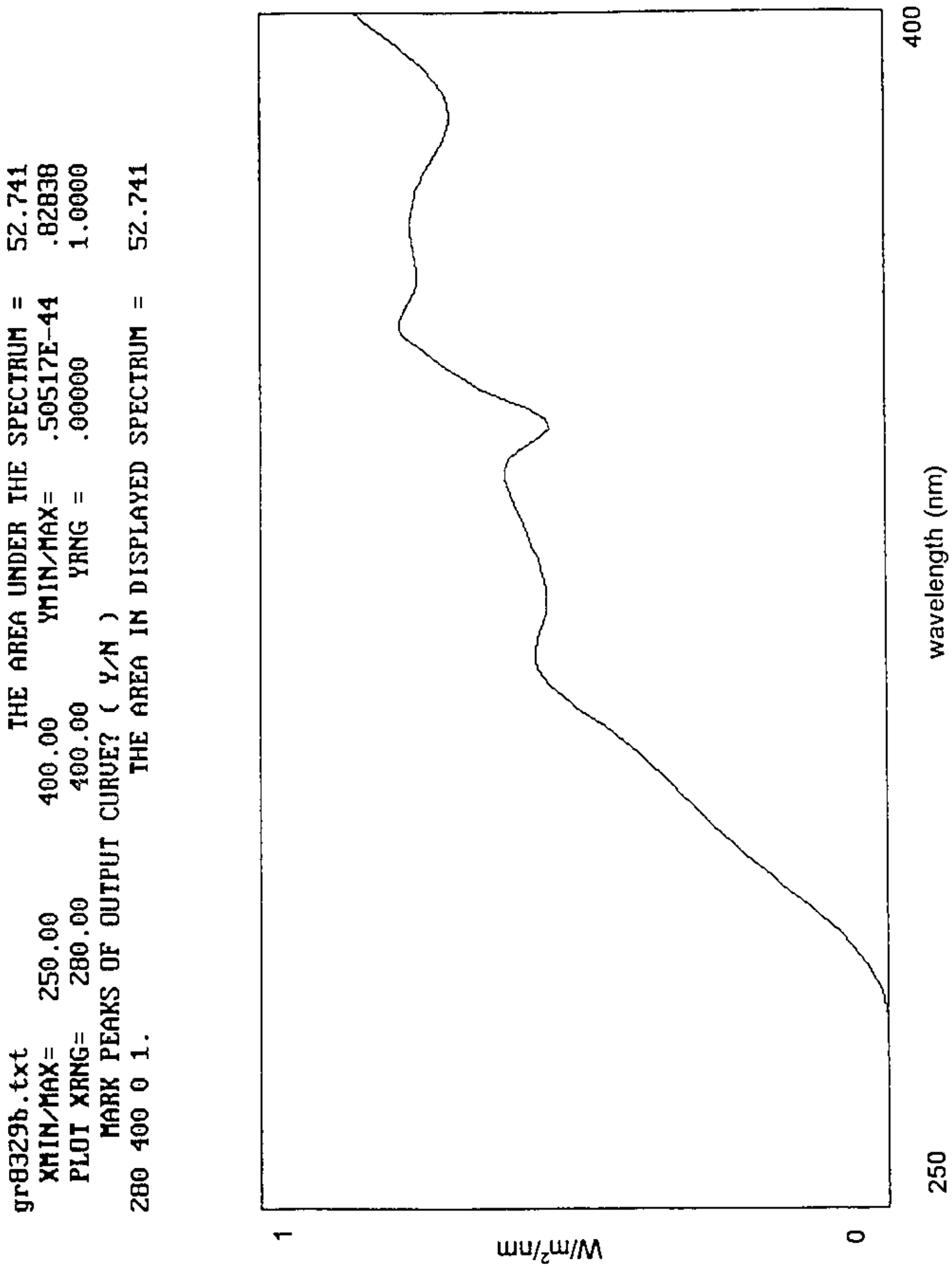
Appendix A
Description of Fabric Samples

No.	Description	Catalogue Number
1	polyester batiste filament plain weave	733
2	spun polyester plain weave	n/a
3	polyester (Dacron 56) taffeta	738
4	polyester rib knit	n/a
5	texturized Dacron 92 double knit	729
6	texturized Dacron 56T double knit	720
7	filament nylon 6.6 semi-dull taffeta	306A
8	spun nylon 6.6 DuPont type 200 woven	361
9	filament nylon 6 tricot dull	322
10	texturized nylon 6.6 stretch fabric	314
11	bleached cotton print cloth	400
12	bleached, mercerized 1.23 cotton twill	423
13	bleached cotton t-shirt fabric, tubular	439W
14	bleached cotton knit - sport shirt weight, tubular	459
15	worsted wool challis, chlorinated	530
16	worsted wool gabardine	541
17	wool jersey knit fabric	532
18	spun viscose challis	266
19	handkerchief linen	L-61
20	linen suiting	L-54
21	Creslan acrylic type 61 plain weave	981
22	Orlon acrylic type 75 100% spun yarn plain weave	864
23	spun Acrilan 16 acrylic jersey knit	867
24	spun Orlon type 42 acrylic knit sweater body	860
25	spun acetate suiting, bright luster	154
26	acetate tricot, all delustered filament	122
27	Dacron 35/Wool, 55/45 blend suiting (contains brightener)	7509
28	Dacron 54W/cotton, 65/35 bleached broadcloth (contains brightener)	7409

Note: All fabrics with catalogue numbers were ordered from Testfabrics, Inc. P.O. Box 420, Middlesex, New Jersey, 08846

Appendix B
Biological and Solar Action[2] Spectra



[2] Greene's (1983) model best fit (rms fit) to combined 1992 and 1993 peak solar action spectra for Edmonton (average of 13 days between June 21st and July 11th, 1992 and 13 days between June 14th to July 10th, 1993). Model uses 290 Dobson Units ozone.

Relative Erythemal Effectiveness EE(λ) of Proposed Reference Erythemal Action Spectrum

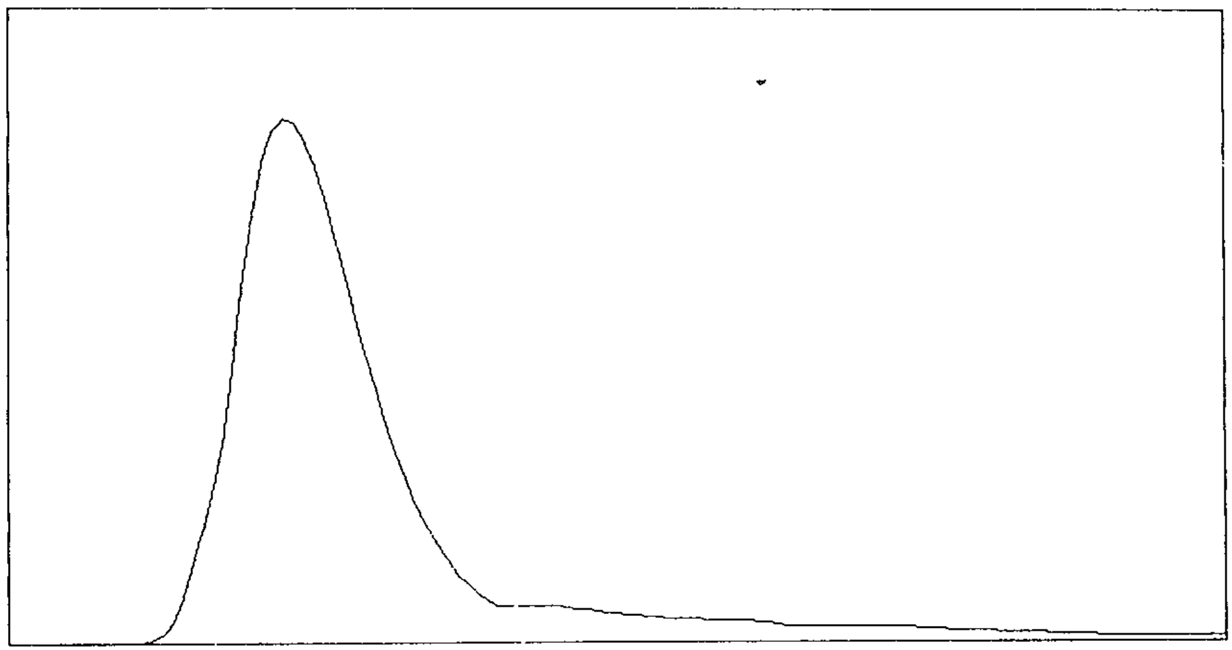
λ (nm)	EE (λ)
250 - 298	1.0
300	0.65
310	7.4×10^{-2}
320	8.6×10^{-3}
330	1.4×10^{-3}
340	9.7×10^{-4}
350	6.8×10^{-4}
360	4.8×10^{-4}
370	3.4×10^{-4}
380	2.4×10^{-4}
390	1.7×10^{-4}
400	1.2×10^{-4}

Calculated normalized values of relative erythemal effectivness EE(λ):

$EE(\lambda) = 1.0$ $(250 < \lambda < 298)$
$EE(\lambda) = 10^{.094\,(298 - \lambda)}$ $(298 < \lambda < 328)$
$EE(\lambda) = 10^{.015\,(139 - \lambda)}$ $(328 < \lambda < 400)$

Reprinted with permission from McKinlay & Diffey (1987). A reference action spectrum for ultraviolet induced erythema in human skin. In W.F. Passchier & B. F. M. Bosnjakovic (Eds.), Human exposure to Ultraviolet Radiation: Risks and Regulations, Proceedings of a seminar held in Amsterdam, 23-25 March 1987 (pp. 83-87). Elsevier Science Publishers, Amsterdam.

```
uvmck29.txt                              THE AREA UNDER THE SPECTRUM =   .17532
  XMIN/MAX=   275.00        400.00       YMIN/MAX=    .10072E-25   .98948E-02
  PLOT XRNG=   280.00        400.00         YRNG =    .00000       .12000E-01
                    3         THE AREA IN DISPLAYED SPECTRUM =   .17532
.5                  0
                    7
                    0
                    0
```



Combined response function of Biological and solar action spectra. Peak absorbance is at 307 nm.

Appendix C
Pre-test Results and Precision Calculations

Description	Structure	Count[1]	SPF
navy cotton/polyester	jersey knit	13 x 13	>100
taupe wool/synthetic pant	plain weave	20 x 18	90
blue striped cotton/poly shirting	plain weave	37 x 30	6
black synthetic/wool	felt		>1000
unbleached cotton	plain weave	33 x 37	6
bleached cotton print cloth	plain weave	33 x 34	4
red & white cotton	plain weave	46 x 30	8
white polyester	satin weave	46 x 76	5
white cotton voile	plain weave	36 x 30	2
spun polyester	plain weave	25 x 23	15
nylon taffeta	plain weave	36 x 42	5
Frogwear® nylon microfibers	plain weave	48 x 32	37
blue cotton denim	twill weave	19 x 20	>1000
red lycra blend swimsuit	double knit	27 x 27	>100

[1]for wovens: yarns/cm in warp x weft; for knits: wales/cm x courses/cm

Determination of Precision, CAN/CGSB No. 1-M87.

Results of ten scans of one cotton (11) specimen

Number	SPF
1	2.95
2	2.93
3	3.08
4	3.01
5	2.97
6	3.07
7	3.71
8	3.79
9	3.10
10	3.68

Coefficient of variation $$\nu = (\sigma / mean) \times 100$$

where,

υ = coefficient of variation,

σ= standard deviation, and

Mean is average of specimen SPF's

From ten scans of one specimen of bleached cotton:

mean = 3.229

Standard Deviation = σ= 0.349

Coefficient of variation = υ = 10.81%

A coeffecient of 11% suggests reasonable repeatability for specimens. Therefore, it was decided that each specimen would be scanned only once.

Determination of Number of Specimens Needed, CAN/CGSB No. 1-M87.

Results of scans of fifteen cotton (11) specimens

Number	SPF
1	3.53
2	3.53
3	3.34
4	3.55
5	3.36
6	3.54
7	3.30
8	3.18
9	3.60
10	2.85
11	2.87
12	2.85
13	2.90
14	2.93
15	2.95

Coefficient of variation

$$\nu = (\sigma/mean) \times 100$$

where,

υ = coefficient of variation,
σ= standard deviation, and
Mean is average of specimen SPF's

Determination of Sample size

$$N = (\nu/\mathrm{E})^2$$

where,

N = number of specimens, and
E = maximum % difference allowed in mean

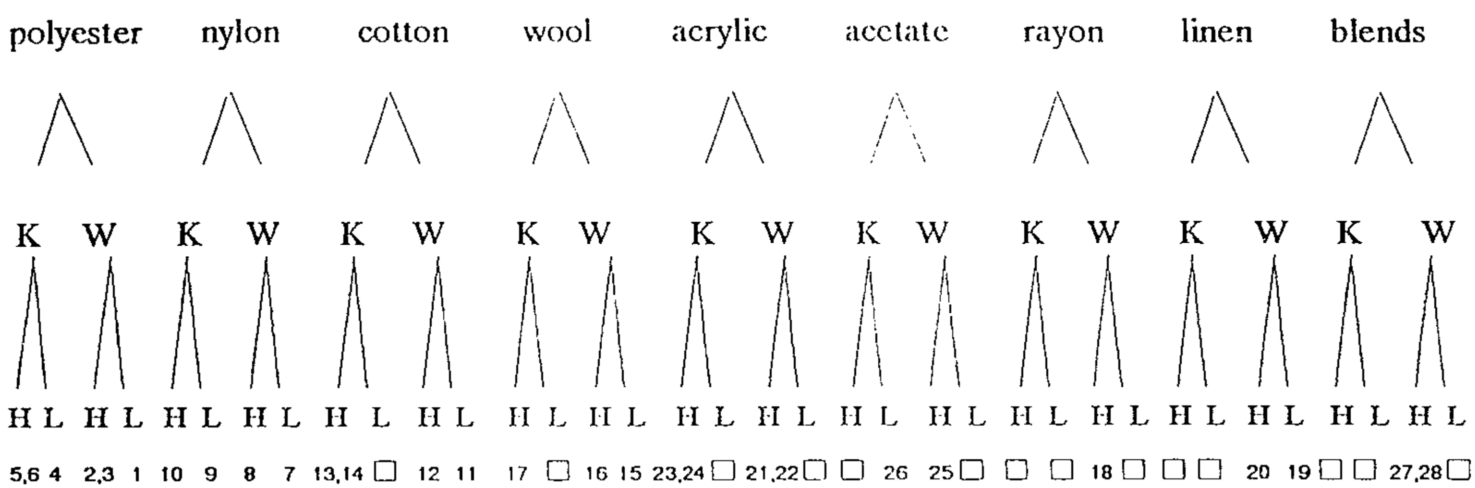
From test of 15 bleached cotton specimens:

mean = 3.5207
Standard Deviation = σ= 0.33
Coefficient of variation = υ = 9.32%
Sample size = N = 3.47 = 4, where E is 5%.

Therefore, when determining SPF, a minimum of 4 specimens per sample is needed to ensure that the estimated mean SPF of the sample will have a standard error no greater than 5% of the mean.

Appendix D
Factorial Experimental Design

9 x 2 x 2 Factorial Experimental Design



1st level: 9 fiber types

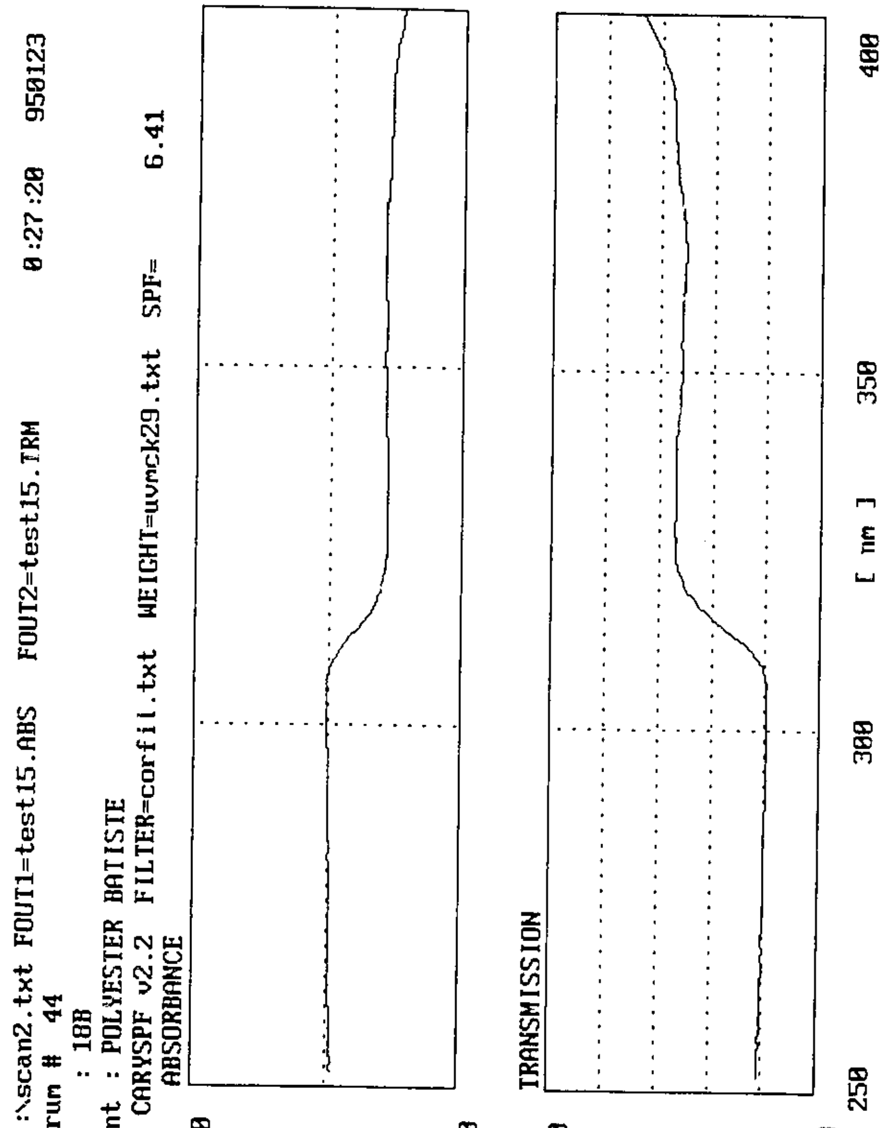
2nd level: 2 structures: K = knit, W = woven

3rd level: 2 masses: H = high, L = low

Numbers indicate fabric samples from Table 2

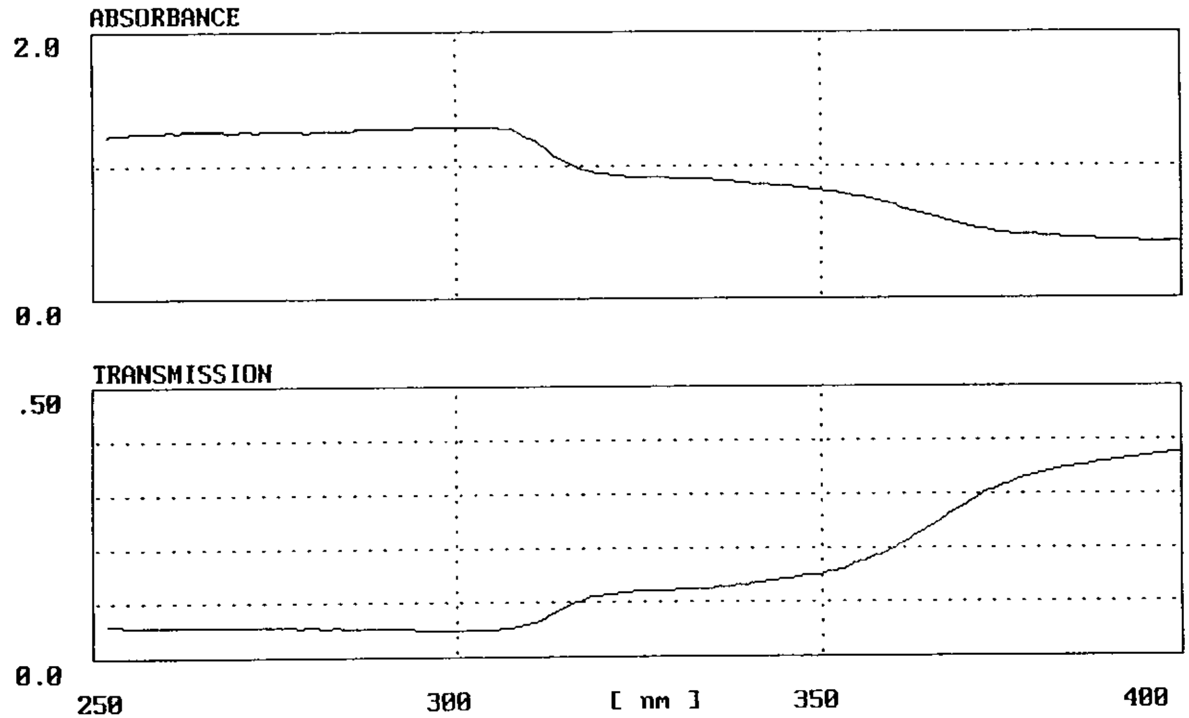
☐ indicate empty cells

Appendix E
Distribution of UVR Transmission for each Fabric

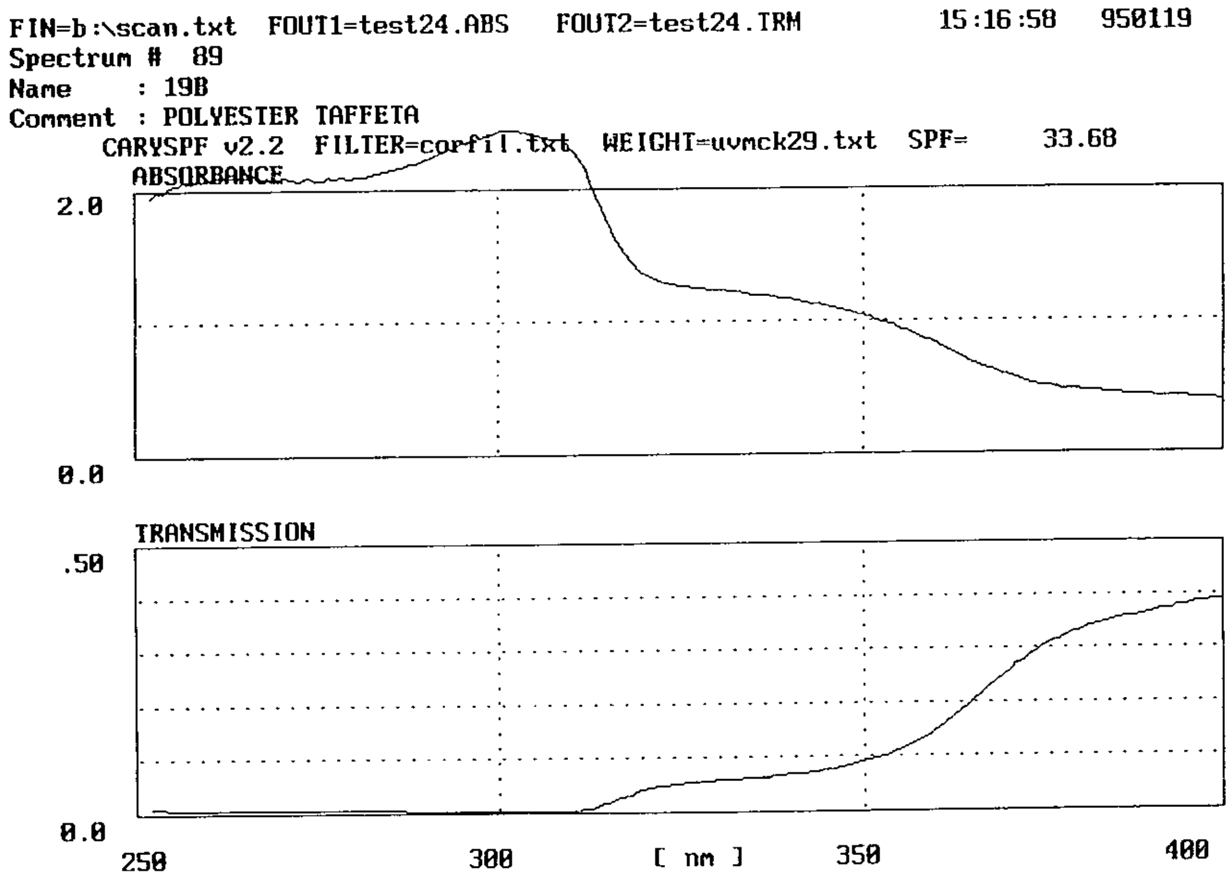


1. Polyester plain woven 68.1 g/m^2 87% cover $\overline{SPF}$ = 7

FIN=b:\scan.txt FOUT1=test04.ABS FOUT2=test04.TRM 15:05:32 950119
Spectrum # 69
Name : 10B
Comment : SPUN POLYESTER
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 11.73

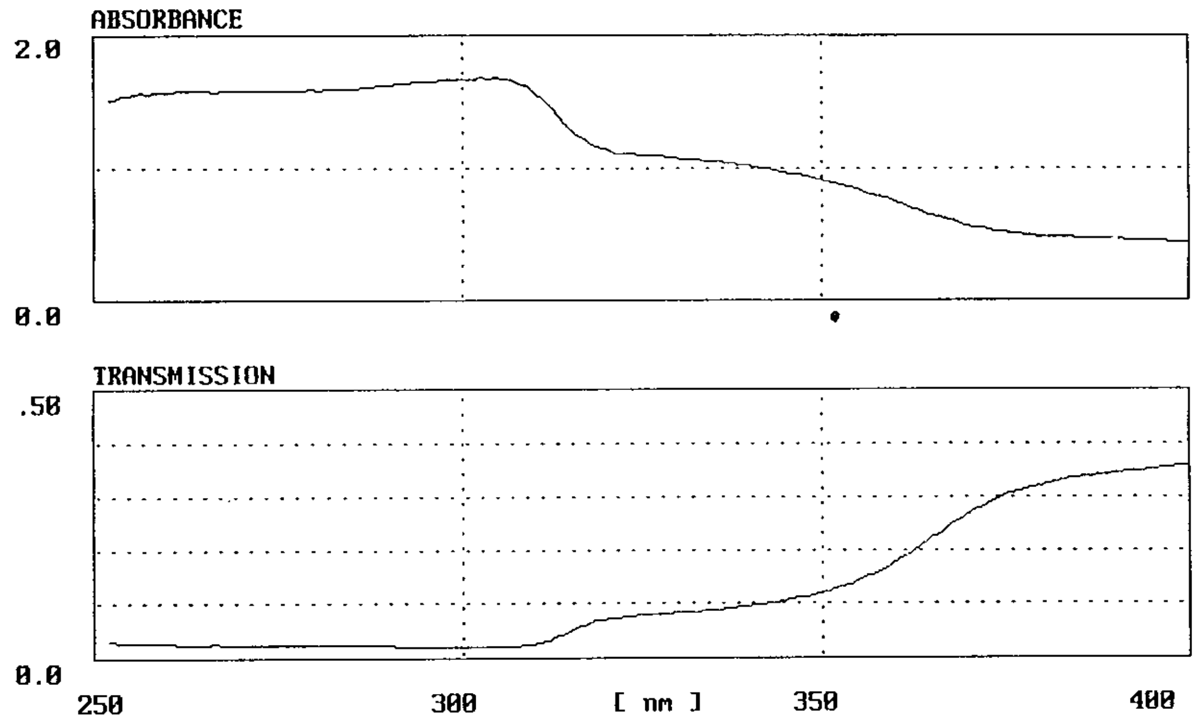


2. Polyester plain woven 132.8 g/m^2 83% cover $\overline{SPF}$ = 12

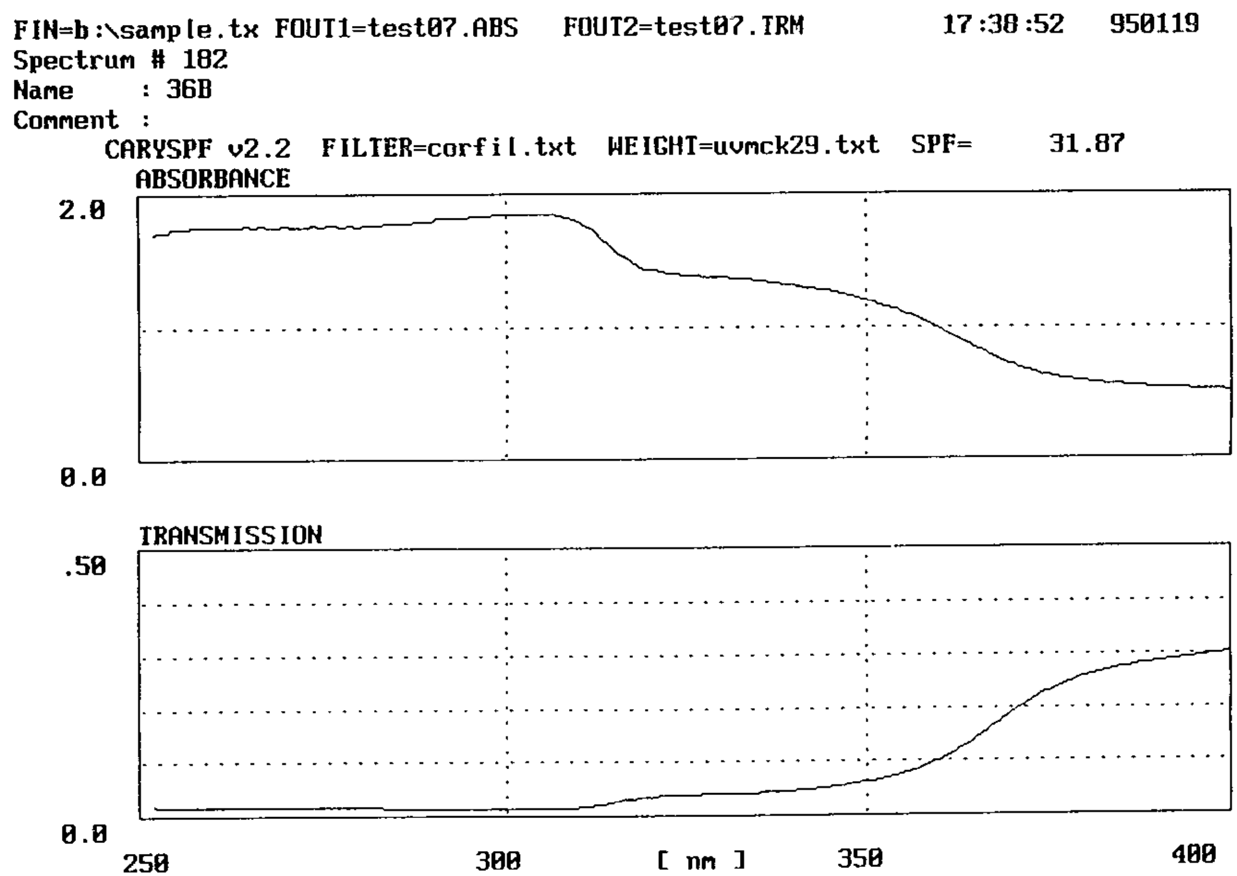


3. Polyester plain woven 149.2 g/m^2 98% cover $\overline{SPF}$ = 34

FIN=b:\sample.tx FOUT1=test14.ABS FOUT2=test14.TRM 16:28:33 950119
Spectrum # 113
Name : 25B
Comment : POLYESTER KNIT
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 19.33

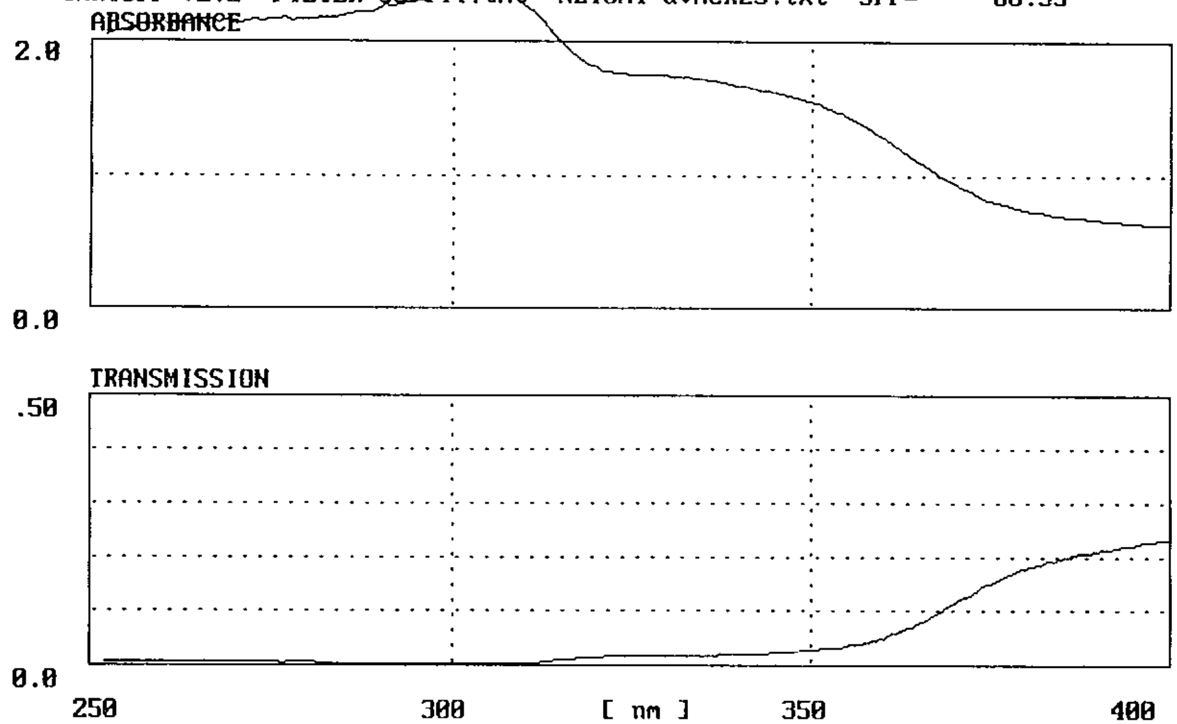


4. Polyester rib knit 105.9 g/m^2 81% cover $\overline{SPF}$ = 17



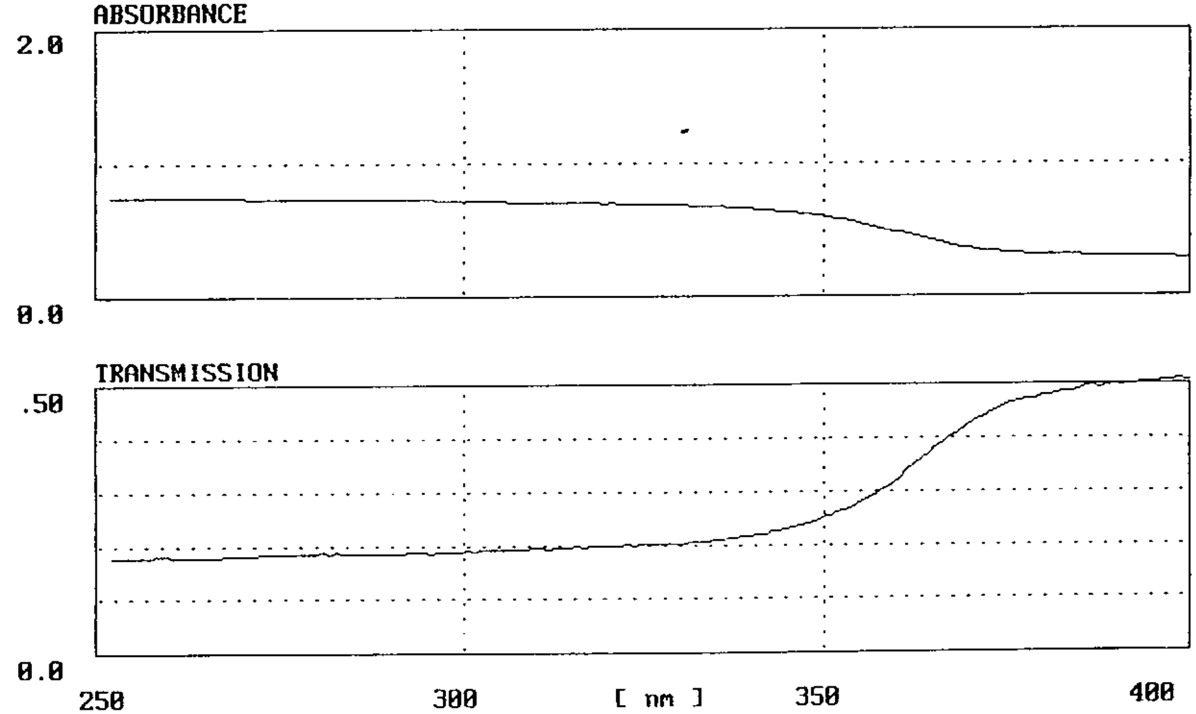
5. Polyester double knit 198.1 g/m^2 87% cover $\overline{SPF}$ = 32

```
FIN=a:\scan2.txt FOUT1=test17.ABS   FOUT2=test17.TRM          0:28:15   950123
Spectrum #  50
Name     : 20B
Comment  : POLYESTER KNIT
     CARYSPF v2.2  FILTER=corfil.txt  WEIGHT=uvmck29.txt  SPF=     68.99
```



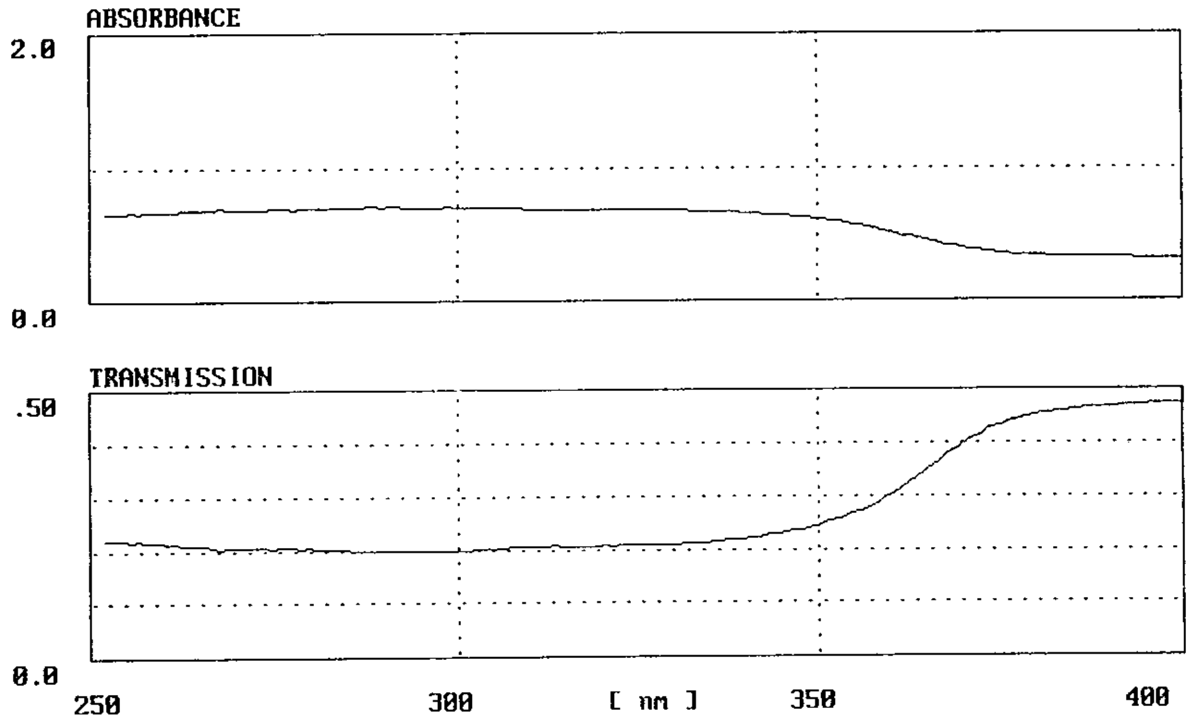
6. Polyester double knit 256.9 g/m^2 93% cover $\overline{SPF}$ = 77

FIN=b:\scan.txt FOUT1=test09.ABS FOUT2=test09.TRM 15:08:14 950119
Spectrum # 74
Name : 11B
Comment : NYLON TAFFETA
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 4.80



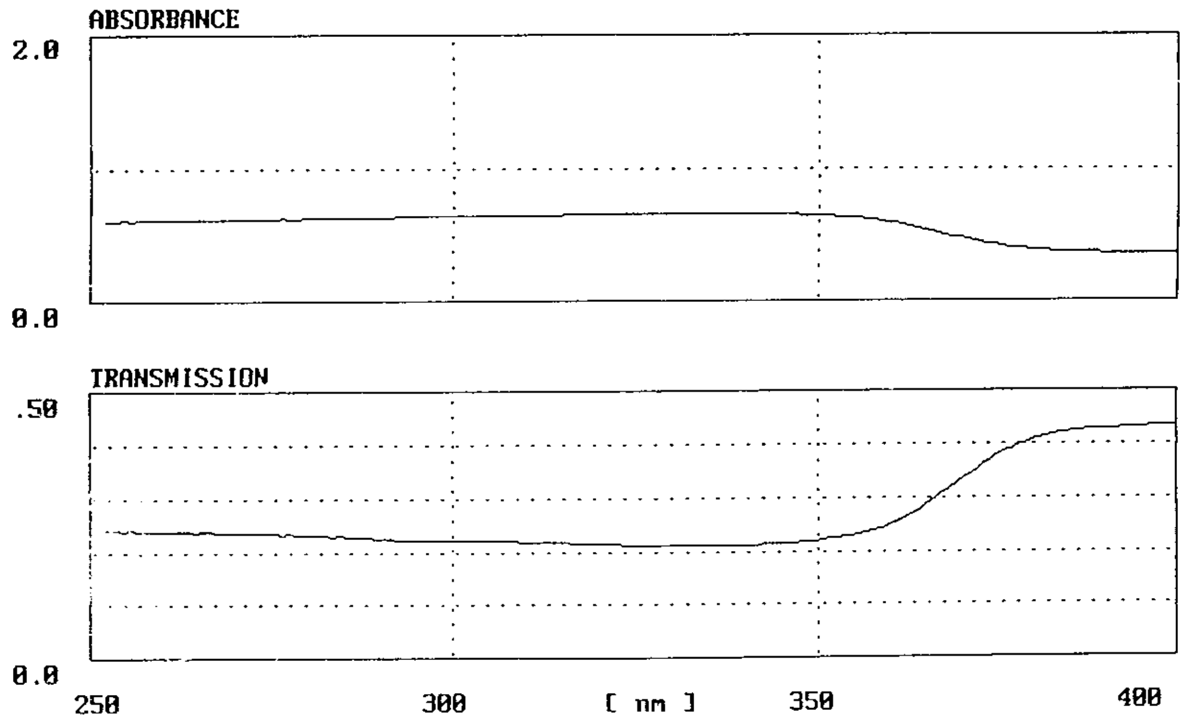
7. Nylon plain woven 61.4 g/m^2 96% cover $\overline{SPF}$ = 5

FIN=b:\scan.txt FOUT1=test29.ABS FOUT2=test29.TRM 15:19:40 950119
Spectrum # 94
Name : 21B
Comment : SPUN NYLON
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 4.61



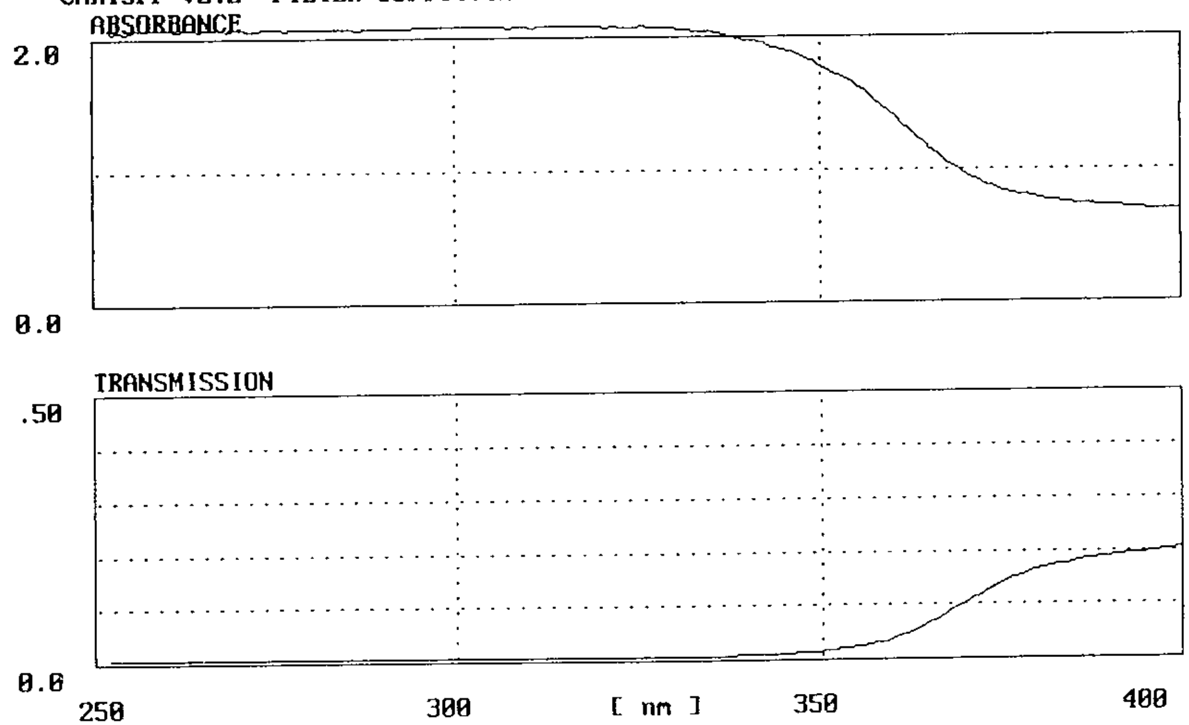
8. Nylon plain woven 124.9 g/m^2 81% cover $\overline{SPF}$ = 5

FIN=b:\run.txt FOUT1=test12.ABS FOUT2=test12.TRM 17:47:31 950119
Spectrum # 197
Name : 39B
Comment :
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 4.42



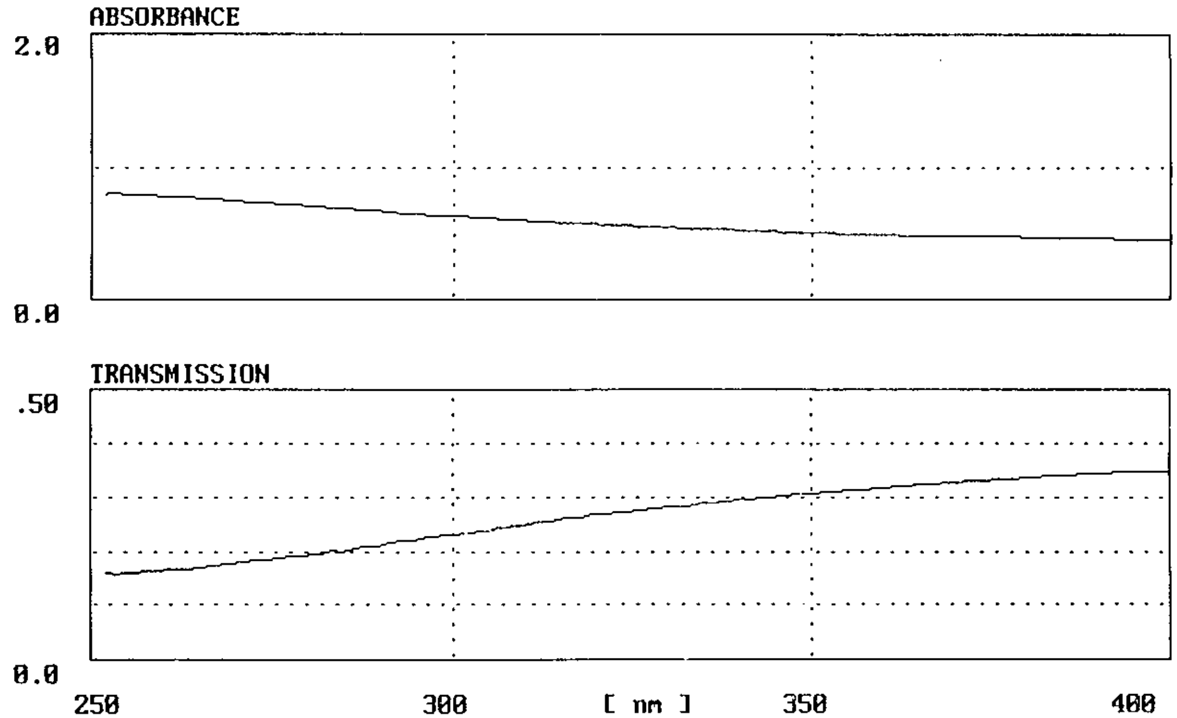
9. Nylon tricot knit 73.0 g/m^2 85% cover $\overline{SPF}$ = 4

FIN=b:\scan.txt FOUT1=test12.ABS FOUT2=test12.TRM 17:16:26 950119
Spectrum # 212
Name : 40B
Comment : NYLON KNIT
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 71.81



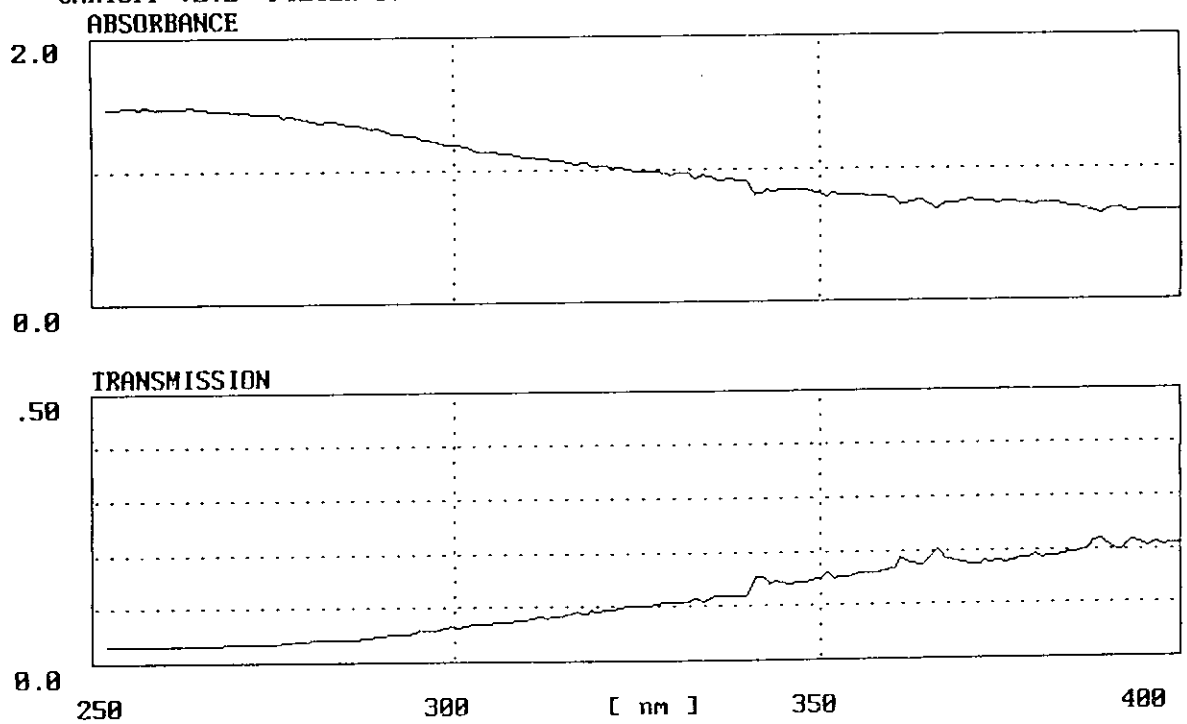
10. Nylon double knit 235.7 g/m² 99% cover $\overline{SPF}$ = 77

FIN=a:\scan2.txt FOUT1=test05.ABS FOUT2=test05.TRM 0:21:52 950123
Spectrum # 34
Name : 6B
Comment : BLEACHED COTTON, 2ND SCAN
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 3.90



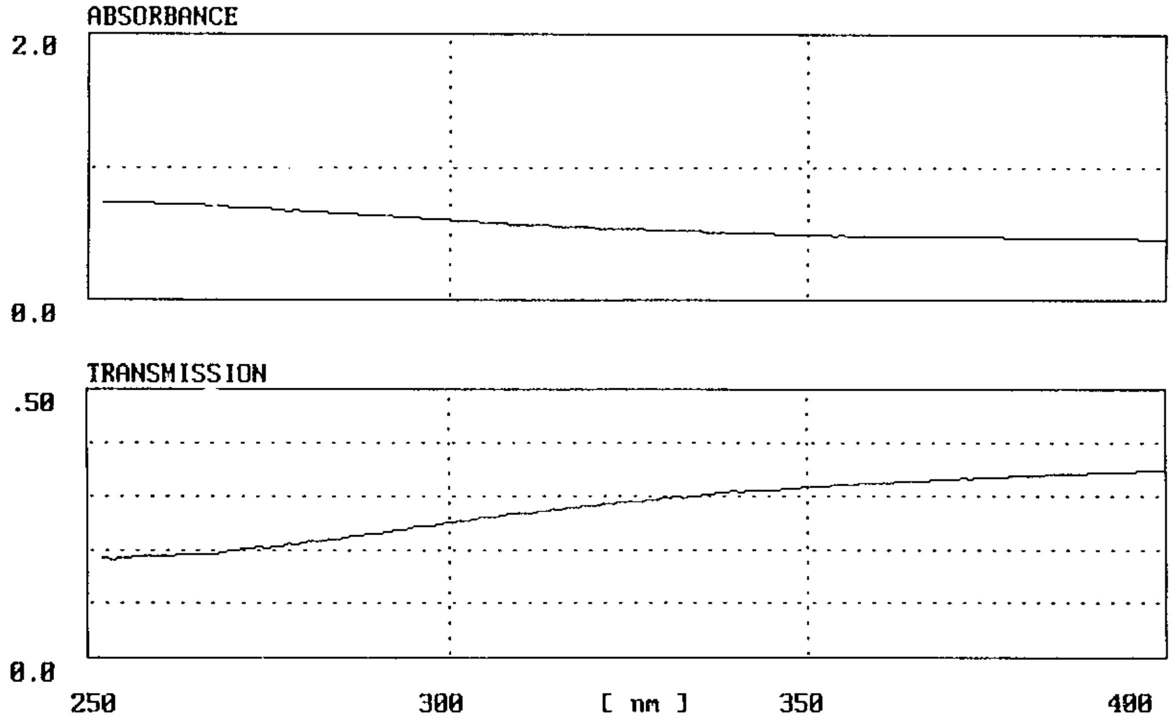
11. Cotton plain woven 106.1 g/m^2 81% cover $\overline{SPF}$ = 4

FIN=b:\scan.txt FOUT1=test14.ABS FOUT2=test14.TRM 15:11:01 950119
Spectrum # 79
Name : 16B
Comment : COTTON TWILL
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 11.29



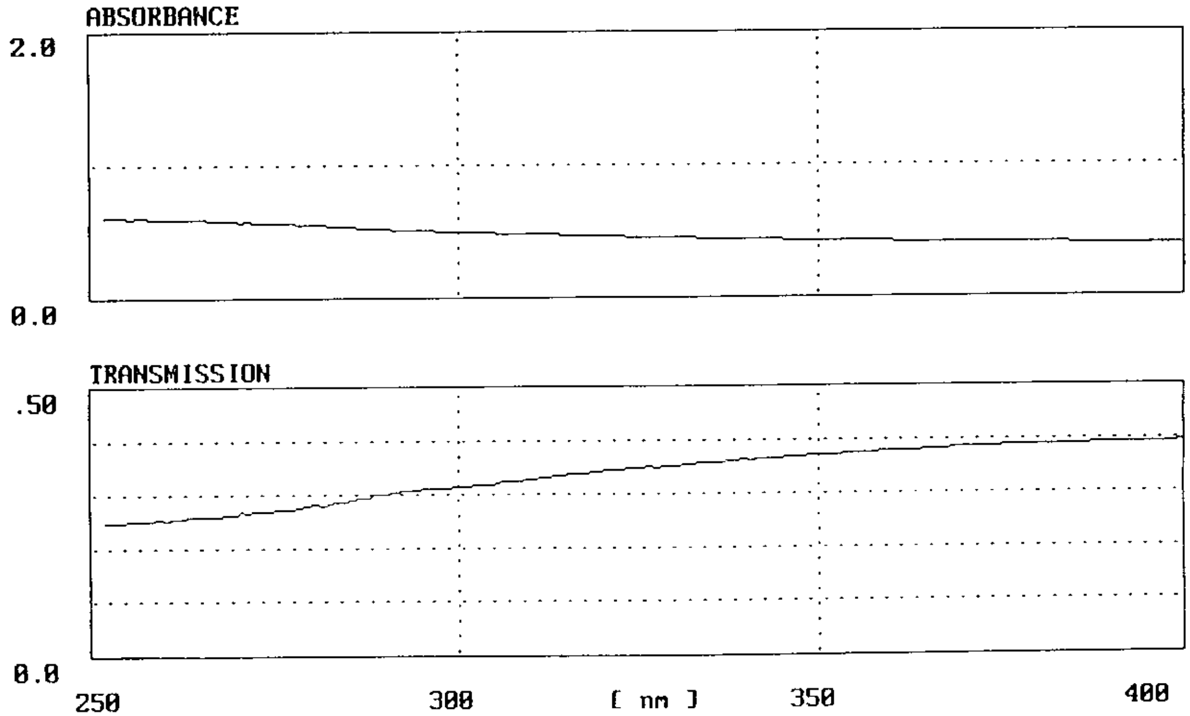
12. Cotton twill woven 264.8 g/m² 100% cover $\overline{SPF} = 13$

FIN=a:\scan2.txt FOUT1=test10.ABS FOUT2=test10.TRM 0:24:29 950123
Spectrum # 39
Name : 15B
Comment : COTTON JERSEY KNIT
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 3.65



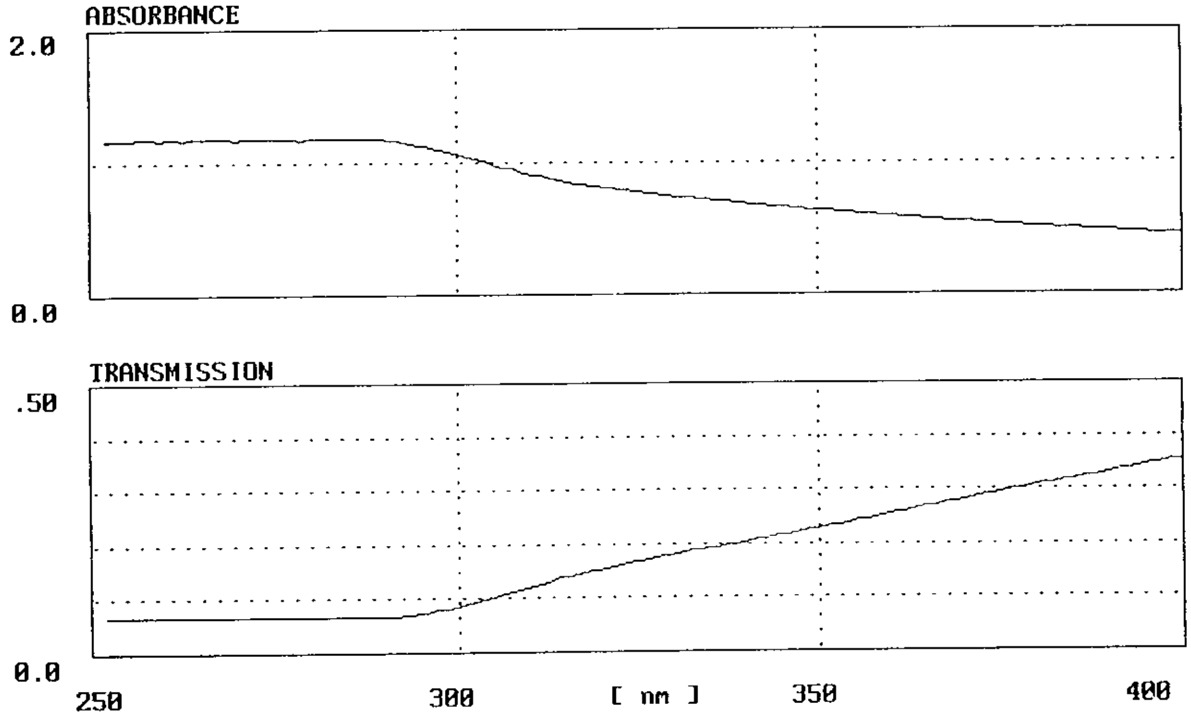
13. Cotton jersey knit 123.9 g/m^2 83 % cover $\overline{SPF}$ = 4

FIN=b:\scan.txt FOUT1=test19.ABS FOUT2=test19.TRM 15:13:41 950119
Spectrum # 84
Name : 17B
Comment : COTTON KNIT
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 2.99

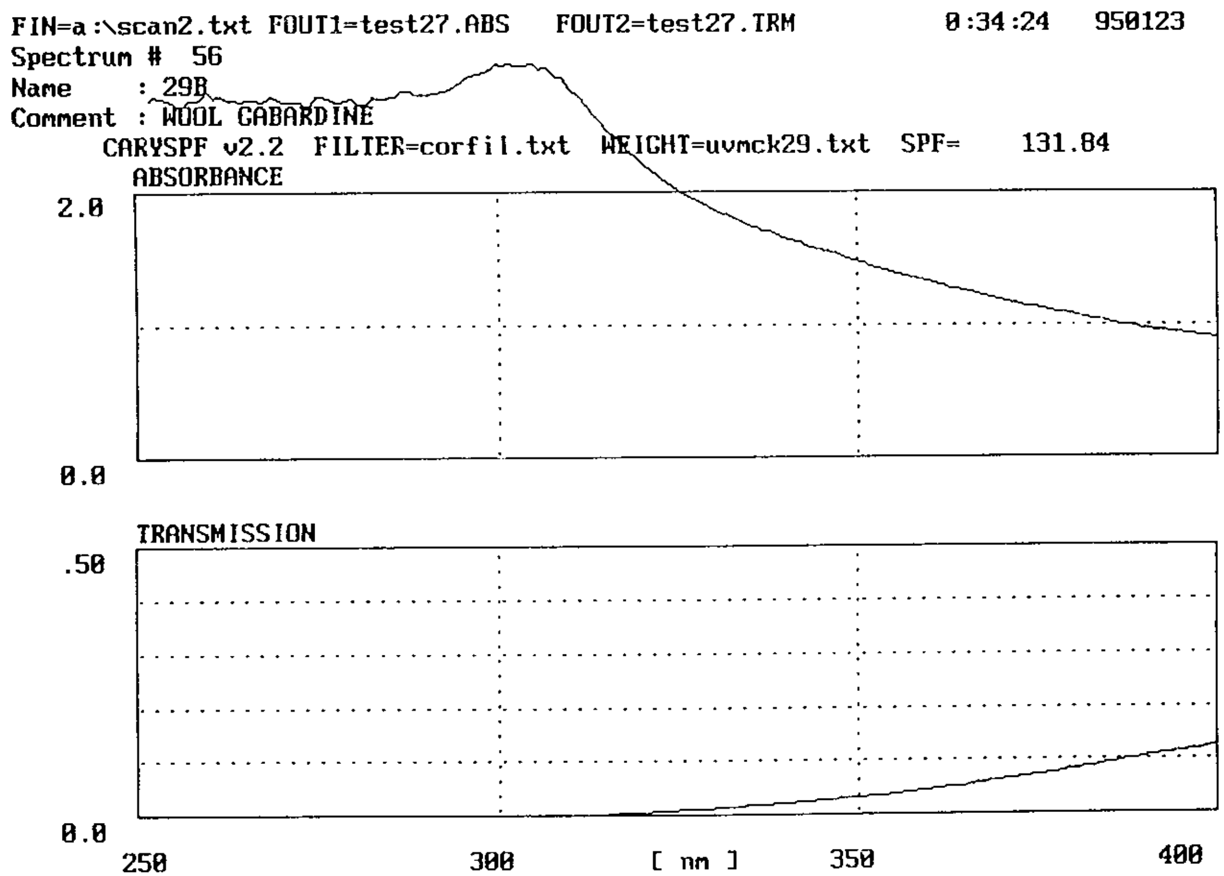


14. Cotton "lacoste" knit 141.1 g/m^2 86% cover $\overline{SPF}$ = 3

FIN=b:\sample.tx FOUT1=test04.ABS FOUT2=test04.TRM 16:05:22 950119
Spectrum # 103
Name : 22B
Comment : WOOL CHALLIS
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 7.42

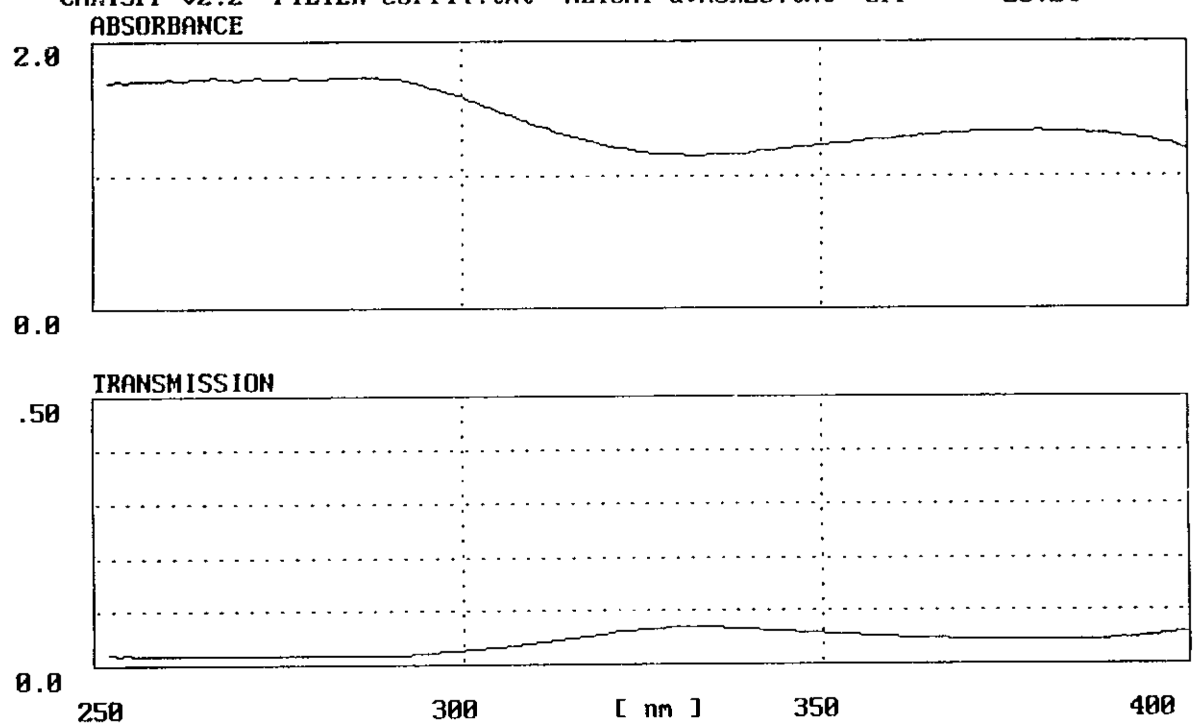


15. Wool plain woven 117.5 g/m^2 82% cover $\overline{SPF}$ = 8



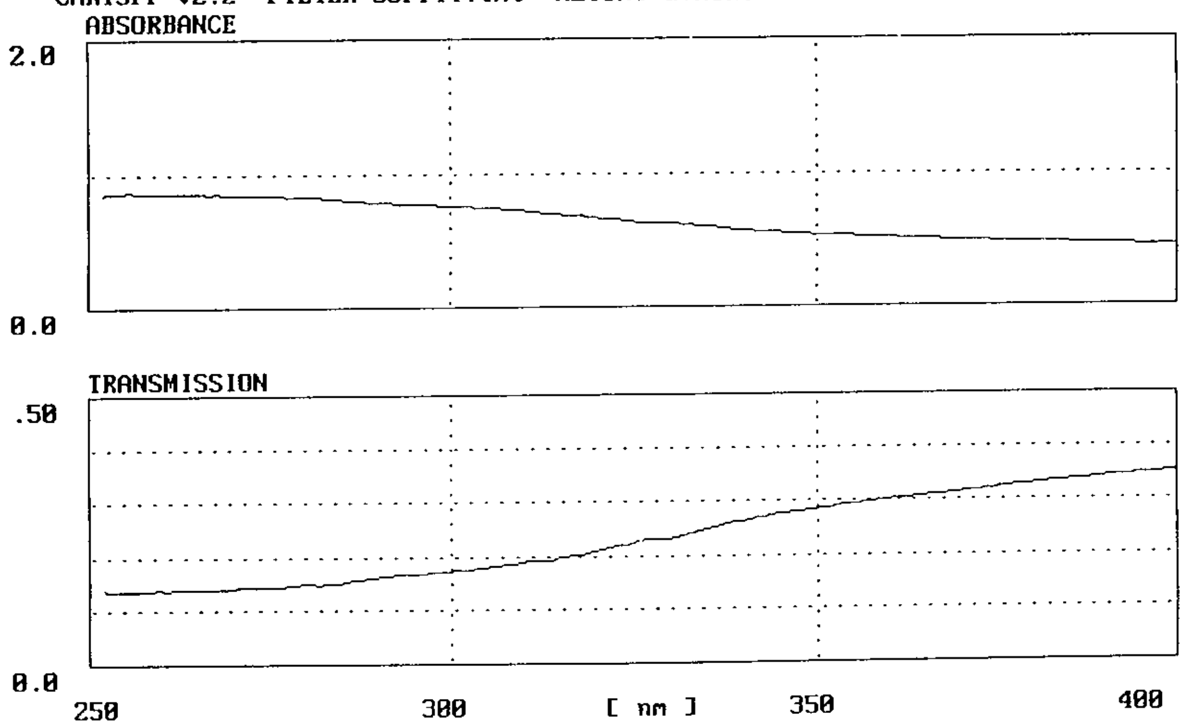
16. Wool twill woven 263.4 g/m² 100% cover $\overline{SPF}$ = 139

FIN=b:\scan.txt FOUT1=test17.ABS FOUT2=test17.TRM 17:20:53 950119
Spectrum # 217
Name : 41B
Comment : WOOL JERSEY KNIT
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 23.24



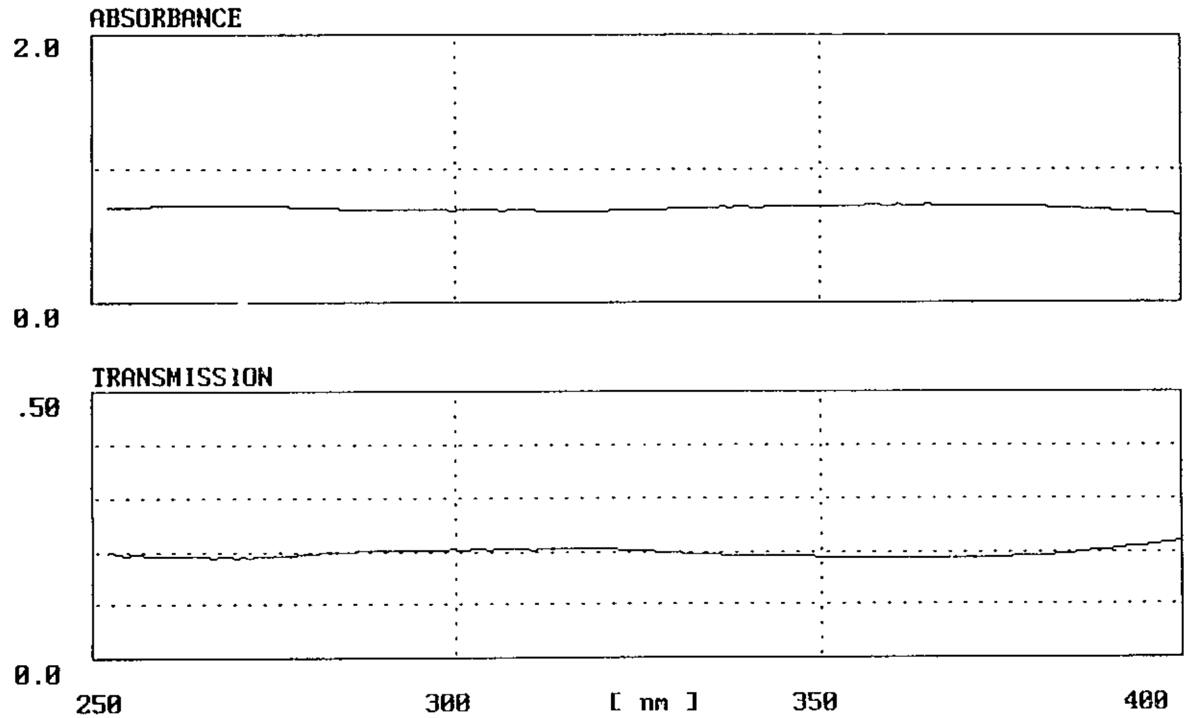
17. Wool jersey knit 194.1 g/m^2 95% cover $\overline{SPF}$ = 22

FIN=b:\sample.tx FOUT1=test09.ABS FOUT2=test09.TRM 16:08:37 950119
Spectrum # 108
Name : 23B
Comment : SPUN VISCOSE CHALLIS
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 4.97



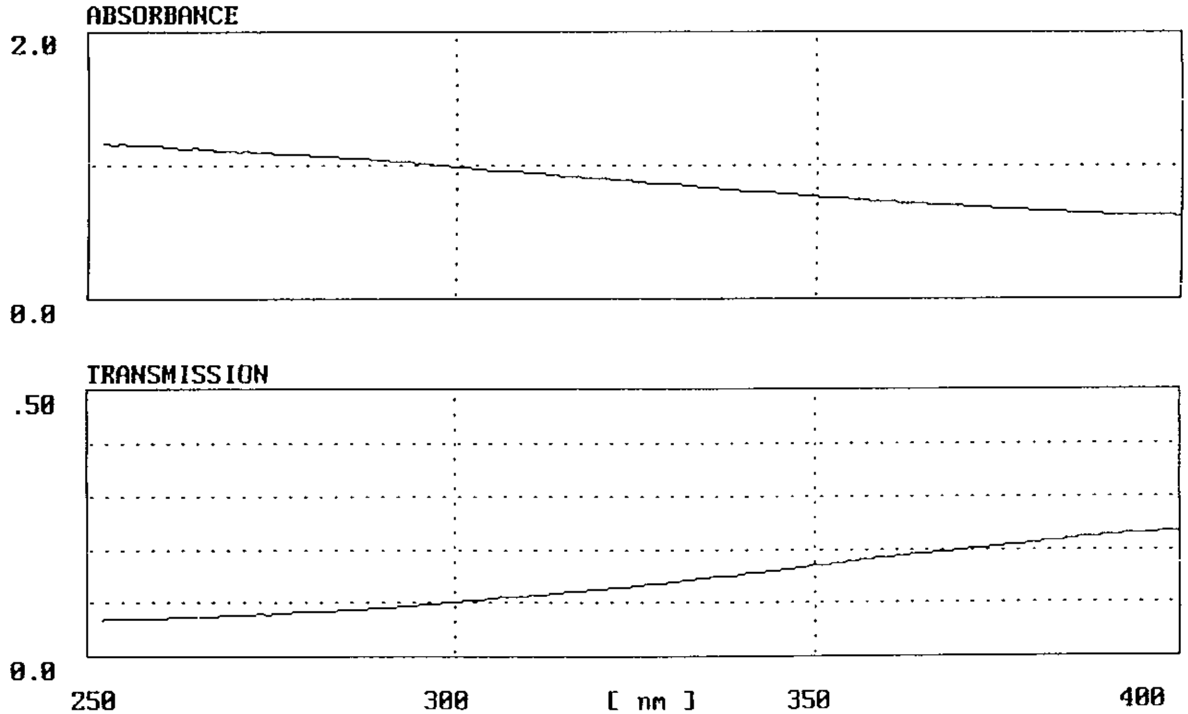
18. Rayon plain woven 139.6 g/m^2 86% cover $\overline{SPF}$ = 5

FIN=b:\sample.tx FOUT1=test09.ABS FOUT2=test09.TRM 16:40:21 950119
Spectrum # 127
Name : 28B
Comment : HANDKERCHIEF LINEN
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 4.91



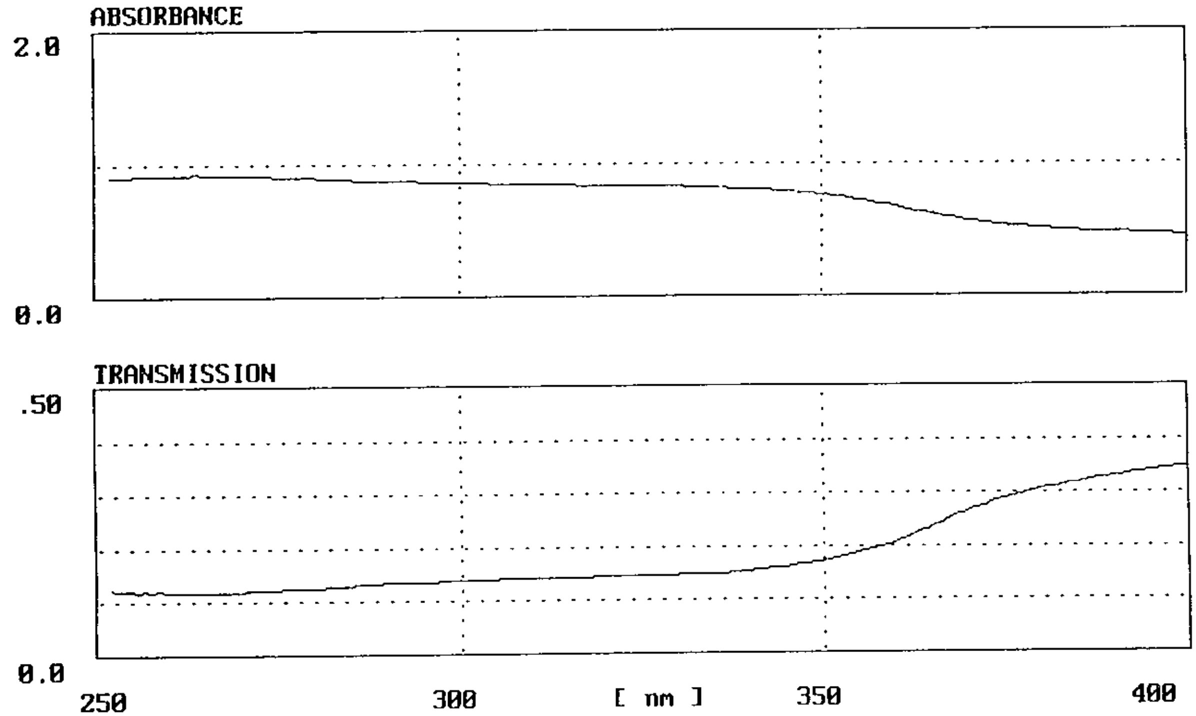
19. Linen plain woven 107.1 g/m^2 79% cover $\overline{SPF}$ = 5

FIN=b:\sample.tx FOUT1=test04.ABS FOUT2=test04.TRM 16:37:15 950119
Spectrum # 122
Name : 27B
Comment : LINEN SUITING
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 8.21



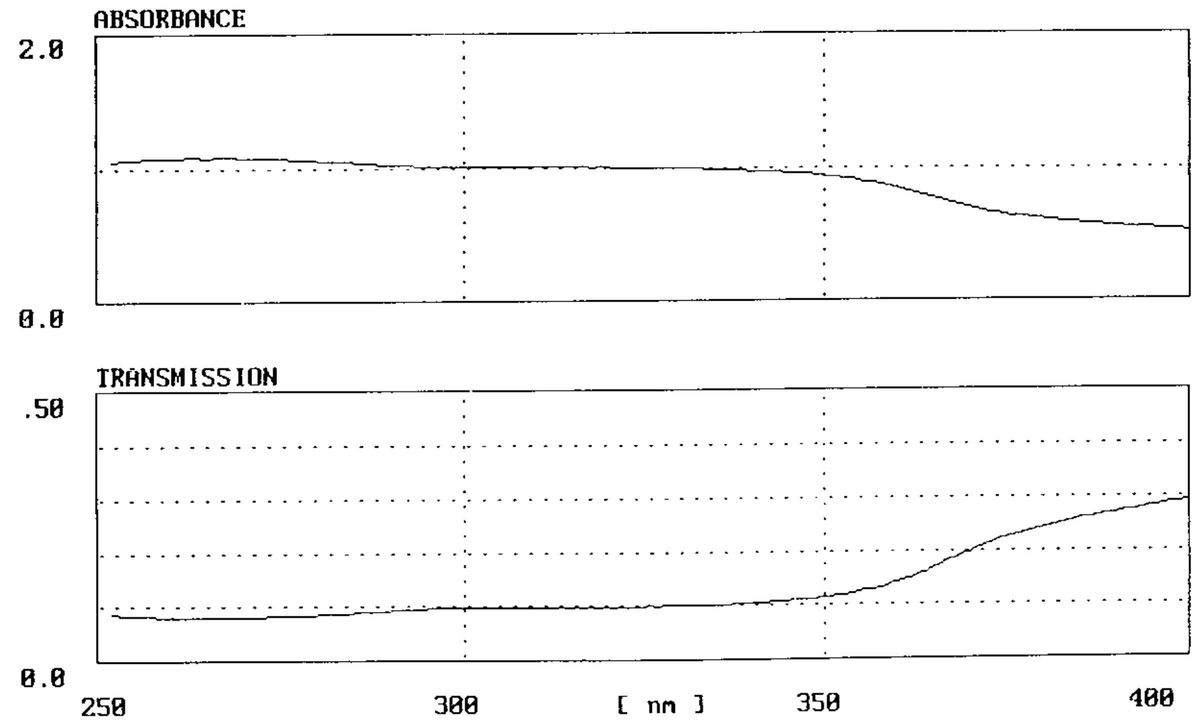
20. Linen plain woven 237.3 g/m^2 92% cover $\overline{SPF} = 9$

FIN=b:\scan.txt FOUT1=test11.ABS FOUT2=test11.TRM 17:33:20 950119
Spectrum # 172
Name : 34B
Comment :
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 6.65



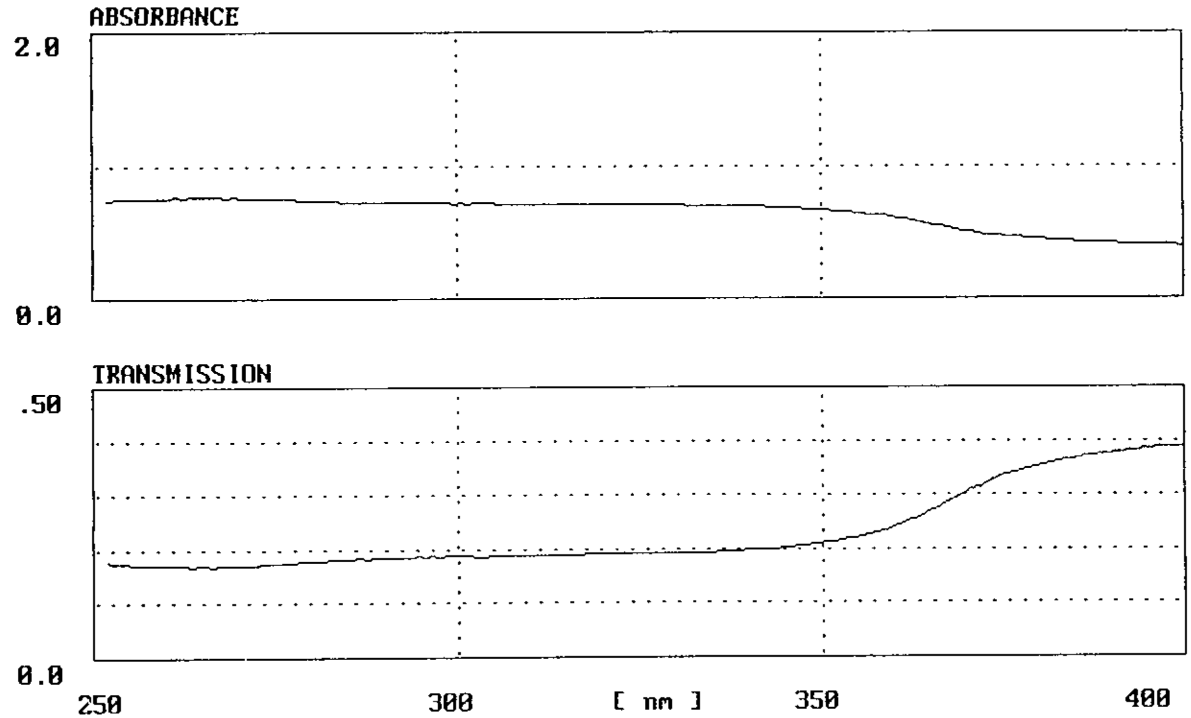
21. Acrylic plain woven 131.1 g/m^2 84% cover $\overline{SPF}$ = 7

FIN=b:\sample.tx FOUT1=test14.ABS FOUT2=test14.TRM 16:43:06 950119
Spectrum # 132
Name : 30B
Comment : SPUN ORLON
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 9.63



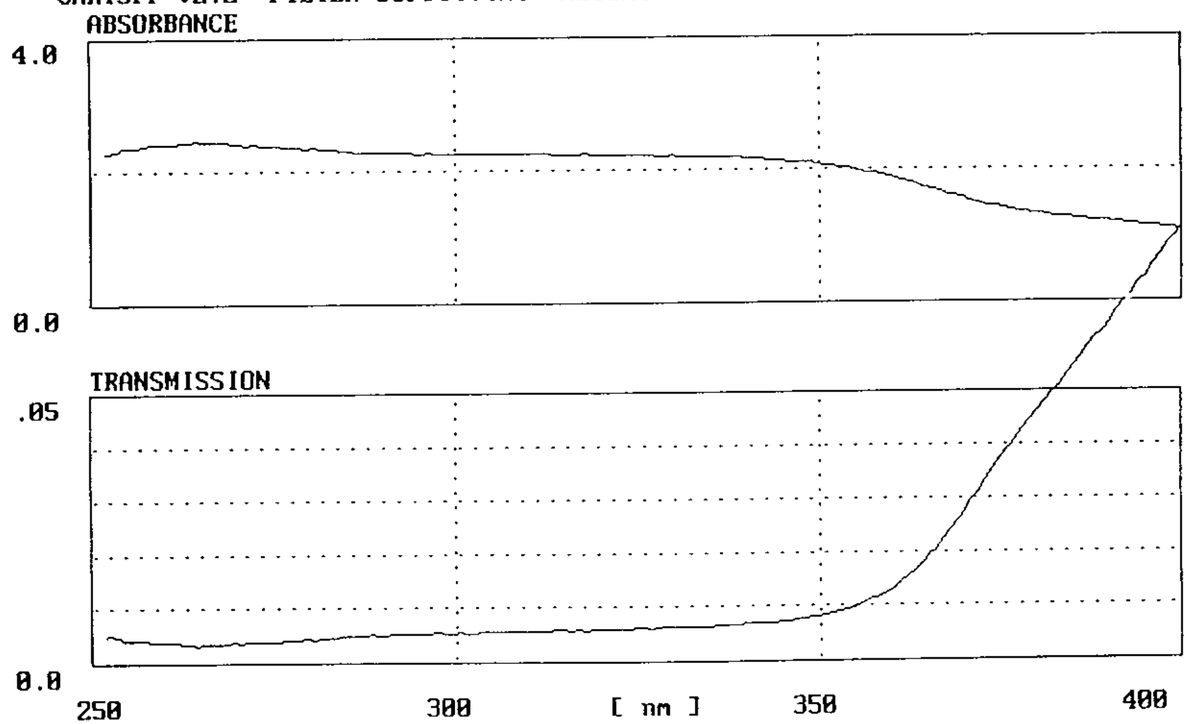
22. Acrylic plain woven 143.1 g/m^2 86 % cover $\overline{SPF}$ = 10

```
FIN=b:\sample.tx FOUT1=test02.ABS    FOUT2=test02.TRM          17:36:09   950119
Spectrum # 177
Name     : 35B
Comment  :
      CARYSPF v2.2  FILTER=corfil.txt  WEIGHT=uvmck29.txt  SPF=      5.12
```



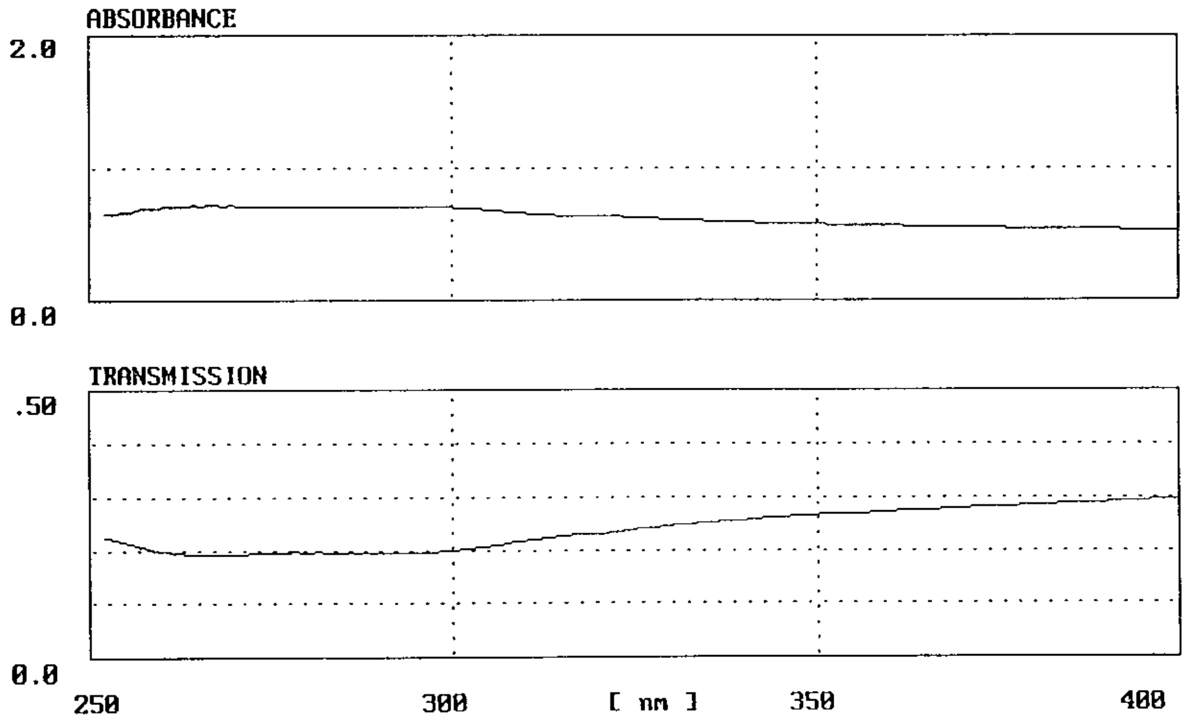
23. Acrylic jersey knit 128.3 g/m^2 75% cover $\overline{\text{SPF}} = 6$

FIN=b:\scan.txt FOUT1=test06.ABS FOUT2=test06.TRM 17:30:38 950119
Spectrum # 167
Name : 33B
Comment :
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 137.46



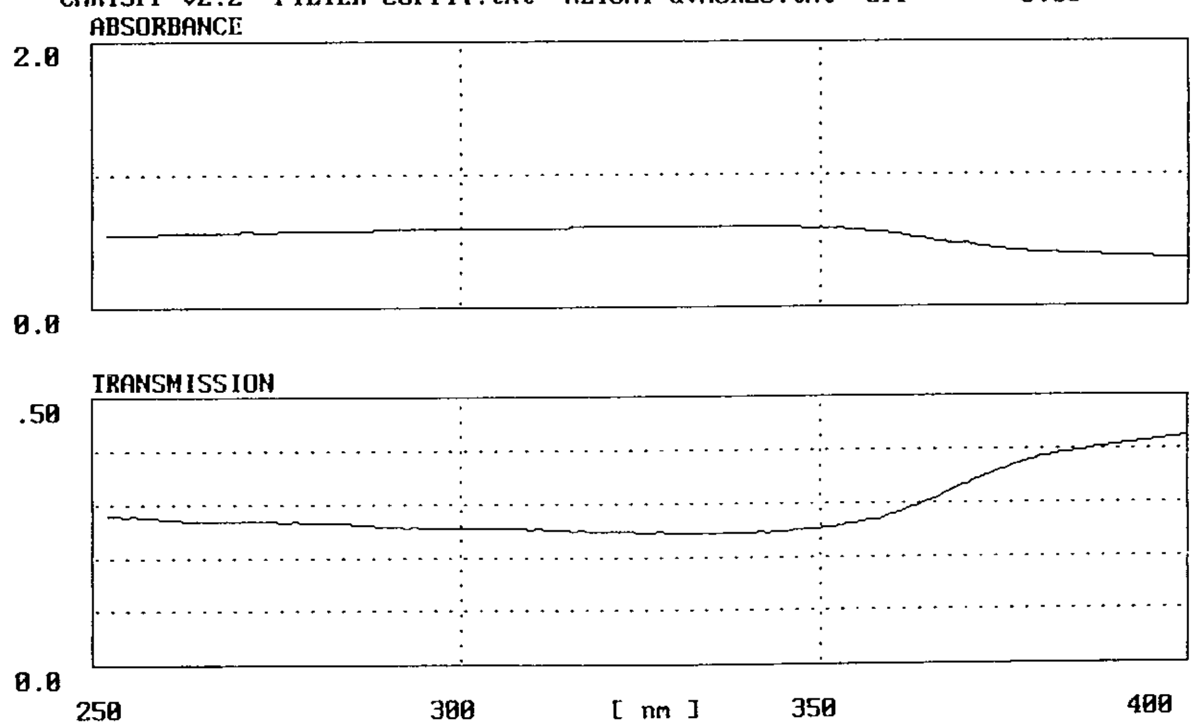
24. Acrylic jersey knit 343.6 g/m^2 95 % cover $\overline{SPF}$ = 104

FIN=b:\run.txt FOUT1=test02.ABS FOUT2=test02.TRM 17:41:45 950119
Spectrum # 187
Name :
Comment :
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 4.48

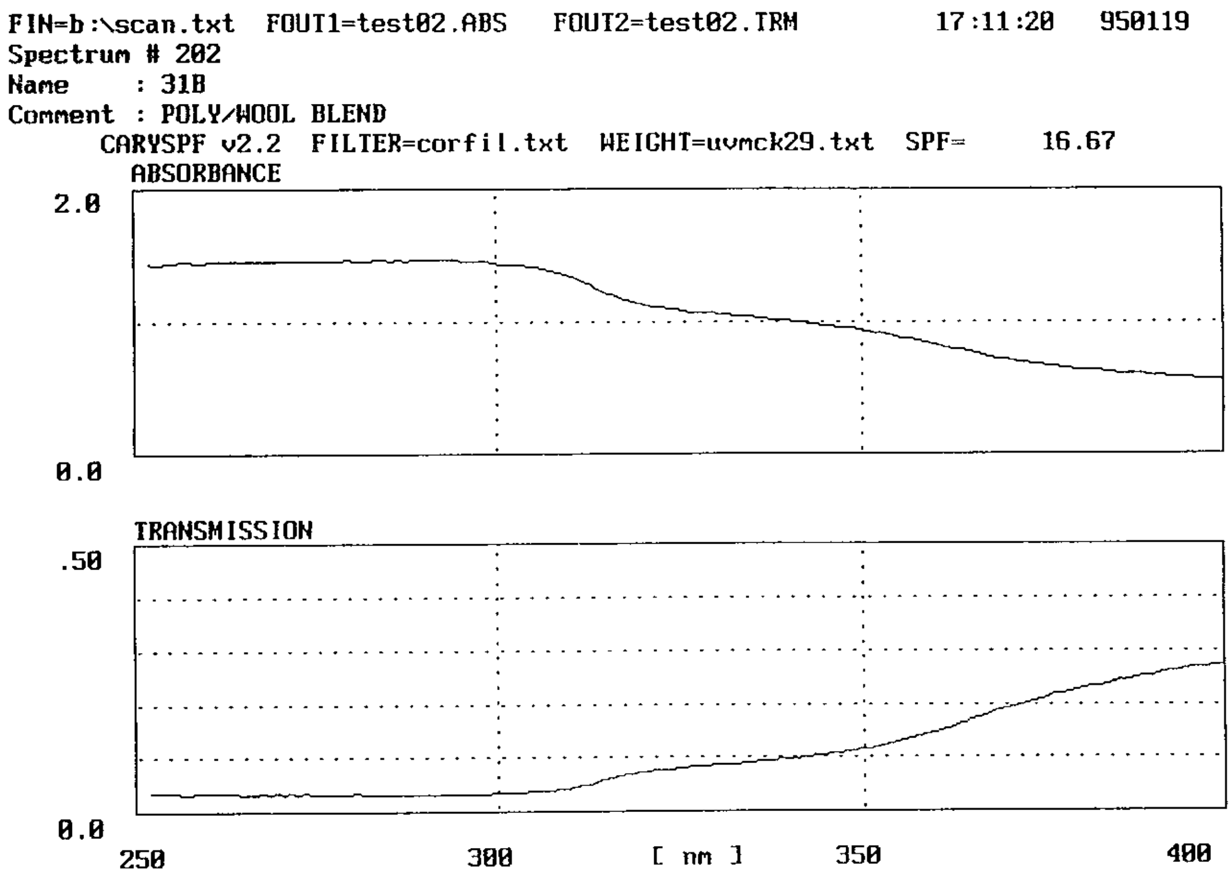


25. Acetate plain woven 192.6 g/m^2 85% cover $\overline{SPF}$ = 5

FIN=b:\run.txt   FOUT1=test07.ABS   FOUT2=test07.TRM   17:44:50   950119
Spectrum # 192
Name   :
Comment :
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF=   3.89

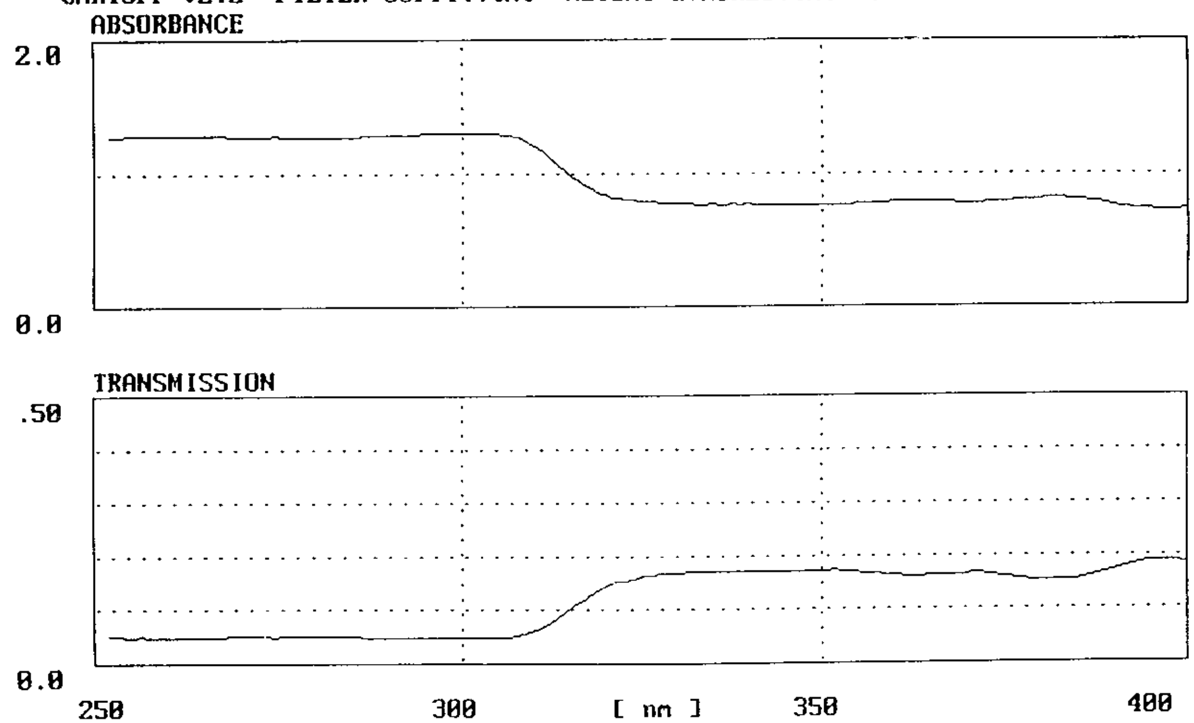


26. Acetate tricot knit   76.8 g/m^2 79% cover $\overline{SPF}$ = 4



27. Poly/wool blend plain woven 166.6 g/m^2 89% cover $\overline{SPF}$ = 17

FIN=b:\scan.txt FOUT1=test07.ABS FOUT2=test07.TRM 17:13:49 950119
Spectrum # 207
Name : 32B
Comment : POLY/COTTON
CARYSPF v2.2 FILTER=corfil.txt WEIGHT=uvmck29.txt SPF= 11.47



28. Poly/cotton blend plain woven 129.8 g/m² 83% cover $\overline{SPF} = 11$

Appendix F
Mass versus SPF for Fiber types and Statistical Analysis

* * * A N A L Y S I S   O F   V A R I A N C E * * *

```
        SPF      Sun Protection Factor
     by MASS2    mass2
        FIBER    FIBER TYPE
        STRUCTUR STRUCTURE

        UNIQUE sums of squares
        All effects entered simultaneously
```

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	20775.261	8	2596.908	2.739	.034
MASS2	11211.638	2	5605.819	5.912	.010
FIBER	5625.872	5	1125.174	1.187	.352
STRUCTUR	114.198	1	114.198	.120	.732
Explained	20775.261	8	2596.908	2.739	.034
Residual	18016.515	19	948.238		
Total	38791.775	27	1436.732		

28 cases were processed.
0 cases (.0 pct) were missing.

Due to empty cells or a singular matrix,
higher order interactions have been suppressed.

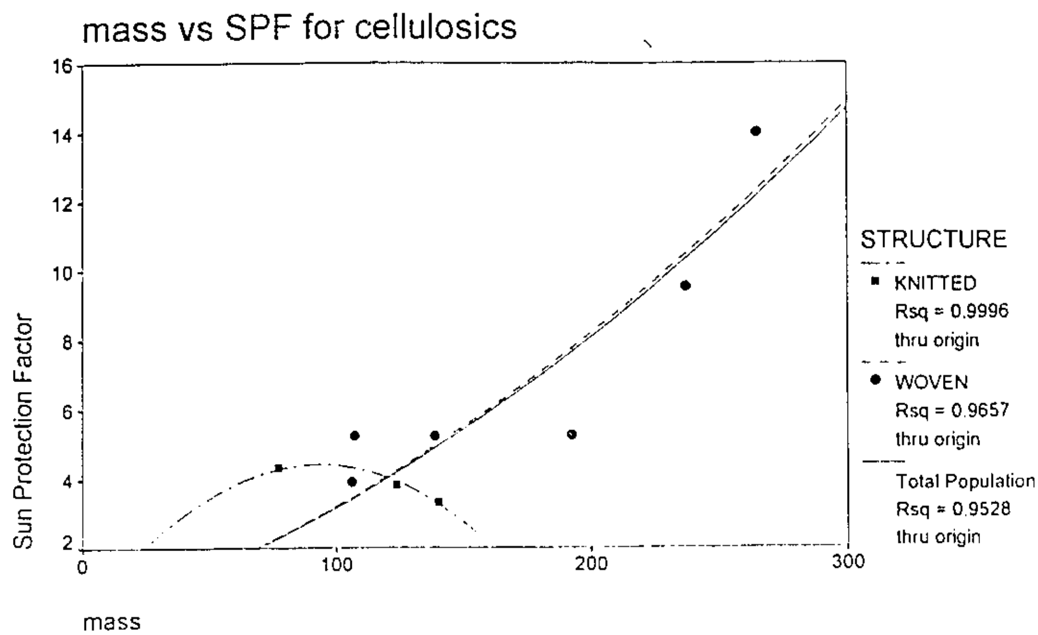
* * * A N A L Y S I S   O F   V A R I A N C E * * *

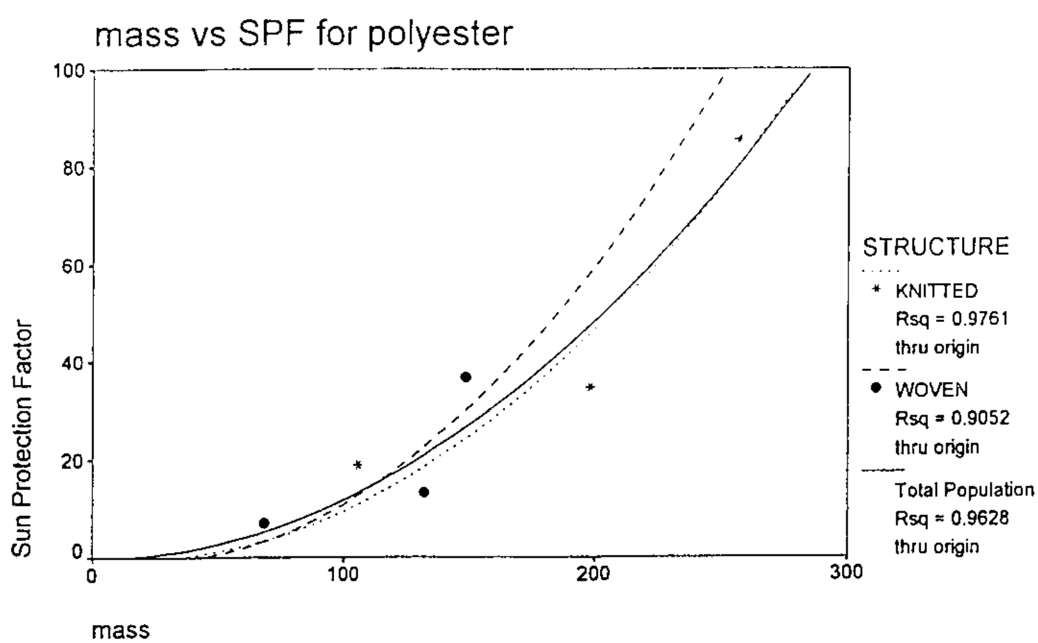
```
        SPF      Sun Protection Factor
     by MASS2    mass2
        FIBER    FIBER TYPE

        UNIQUE sums of squares
        All effects entered simultaneously
```

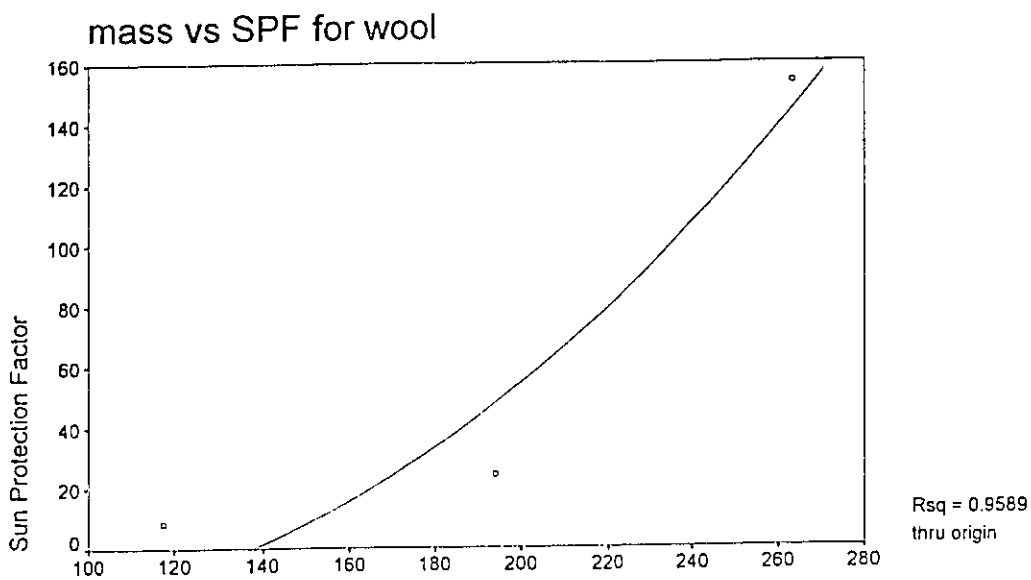
Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	20661.063	7	2951.580	3.256	.018
MASS2	12367.248	2	6183.624	6.821	.006
FIBER	5754.371	5	1150.874	1.270	.316
Explained	20661.063	7	2951.580	3.256	.018
Residual	18130.712	20	906.536		
Total	38791.775	27	1436.732		

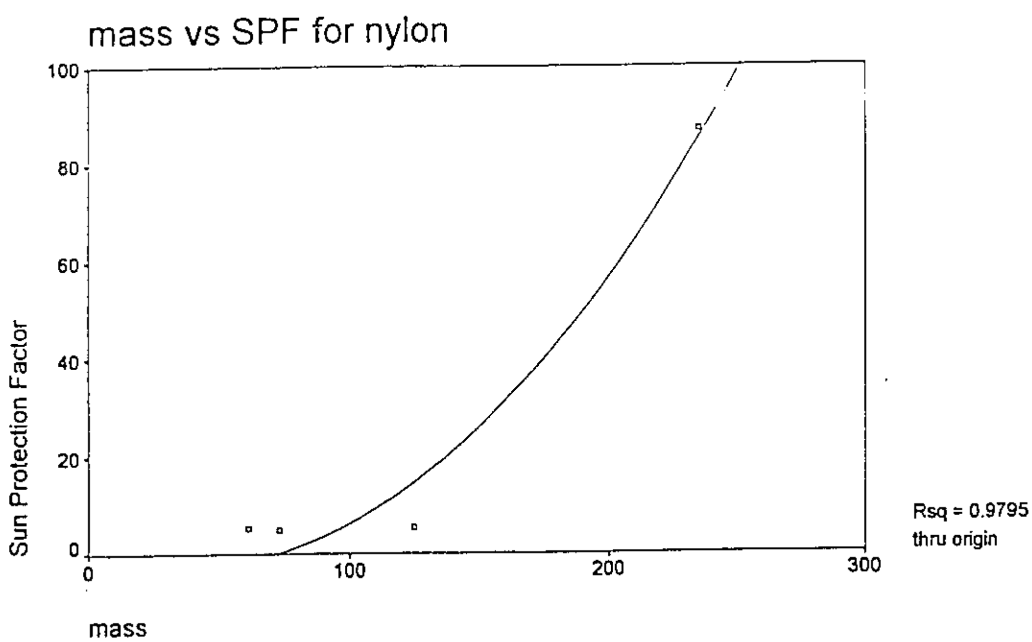
28 cases were processed.
0 cases (.0 pct) were missing.

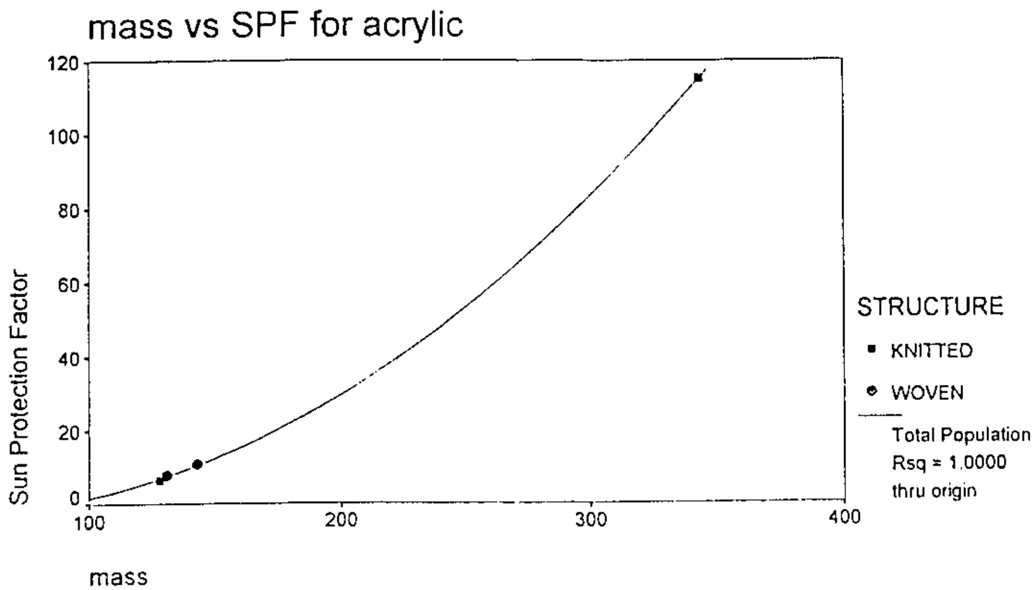
Due to empty cells or a singular matrix,
higher order interactions have been suppressed.


mass vs SPF for cellulosics
Sun Protection Factor
mass
STRUCTURE
KNITTED
Rsq = 0.9996
thru origin
WOVEN
Rsq = 0.9657
thru origin
Total Population
Rsq = 0.9528
thru origin


mass vs SPF for polyester
Sun Protection Factor
mass
STRUCTURE
KNITTED
Rsq = 0.9761
thru origin
WOVEN
Rsq = 0.9052
thru origin
Total Population
Rsq = 0.9628
thru origin


mass vs SPF for wool
Sun Protection Factor
160
140
120
100
80
60
40
20
0
100
120
140
160
180
200
220
240
260
280
Rsq = 0.9589
thru origin


mass vs SPF for nylon
Sun Protection Factor
100
80
60
40
20
0
0
100
200
300
Rsq = 0.9795
thru origin
mass



mass vs SPF for acrylic
120
100
80
60
40
20
0
100
200
300
400
Sun Protection Factor
mass
STRUCTURE
KNITTED
WOVEN
Total Population
Rsq = 1.0000
thru origin