Massey University Library. Thesis Copyright Form

Title of thesis: Light Transmission, Heat Retention and Mechanical Strength Property Evaluation of Film Plastic Cladding Materials Available in NZ.

(1) (a) I give permission for my thesis to be made available to readers in the Massey University Library under conditions determined by the Librarian.

(b) ~~I do not wish my thesis to be made available to readers without my written consent for ________ months.~~

(2) (a) I agree that my thesis, or a copy, may be sent to another institution under conditions determined by the Librarian.

(b) ~~I do not wish my thesis, or a copy, to be sent to another institution without my written consent for ________ months.~~

(3) (a) I agree that my thesis may be copied for Library use.

(b) ~~I do not wish my thesis to be copied for Library use for ________ months.~~

Heatley

Signed PRHeatley

Date 30/11/90.

The copyright of this thesis belongs to the author. Readers must sign their name in the space below to show that they recognise this. They are asked to add their permanent address.

NAME AND ADDRESS	DATE
P.R. HEATLEY	30/11/90
10 WINDSOR AVE	
WHANGAREI	

In loving appreciation

of

Kim and Robyn

LIGHT TRANSMISSION, HEAT RETENTION AND MECHANICAL STRENGTH PROPERTY EVALUATION OF FILM PLASTIC CLADDING MATERIALS AVAILABLE IN NEW ZEALAND

A thesis
submitted in partial fulfilment
of the requirement for the degree
of

Master of Horticultural Science

in

Horticultural Engineering

at
Massey University

Philip Reeve Heatley
1990

ABSTRACT

This study was conducted on film plastic cladding materials commercially available from distributors in New Zealand. Laboratory scale experiments were applied to test and evaluate the optical, thermal and mechanical properties of each of the film plastics.

Optical properties tested included PAR transmissivity and the degree of UV radiation transmission through the film plastics. The radiant heat retention property of each product was evaluated through thermal transmission tests. Mechanical property evaluation required application of tear resistance, tensile strength, impact resistance and water vapour permeance tests.

It was recognised that an evaluation and comparison of each of the film plastics as a full functional cladding material would be useful to both greenhouse designers and growers. Consequently, each of the products were ranked according to specific optical, thermal or mechanical properties. Upon combining these rankings, recommendations on the best film plastic cladding material, for specific applications, were supported and presented in tabular form.

Experimental data and analysis consistently indicated that a PVC film plastic, a double layer co-extruded film plastic, woven PE and reinforced EVA film materials and a specific EVA type film plastic, available in New Zealand at the time of this research, will perform particularly well as greenhouse cladding materials. Purchasing evaluation, of any of the film plastics tested in this study, should further involve the cost and the susceptibility of each product to UV degradation as selection criteria.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF PLATES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

λ = wavelength

α = absorptivity

A = surface area

°C = degrees Celsius

C = cost; radiation constant

CO_2 = carbon dioxide

cos = cosine

Σ = sum

ϵ = emissivity

E = emissive power

EVA = ethylene vinyl acetate

FRP = fibre reinforced plastic

g = gram

Gm = Gigametre

h = convective heat transfer coefficient

HALS = hindered amine light stabilizer

I = intensity

IR = infra-red

IREVA = infra-red ethylene vinyl acetate

IRPE = infra-red polyethylene

IR = impact resistance

J = joule

k = thermal conductivity; extinction coefficient

kg = kilogram

l = path length

m = metre
mm = millimetre
MS = combined mechanical strength
MW = Megawatt
n = refractive indicae
nm = nanometre
N = newton
θ = degree angle
σ = Stephan Boltzmann constant
ρ = reflectivity
Pa = Pascal
PAR = photosynthetically active radiation
PE = polyethylene
PEST = polyester
PETh = thermal polyethylene
PVF = polyvinyl fluoride
PT = PAR transmissivity
Q = rate of heat flow; radiation
r = component of reflection
s = second
sin = sine
τ = transmissivity
T = temperature
tan = tangent
TR = tear resistance
TS = tensile strength
TT = thermal transmissivity
μm = micrometre

um = micrometre

UV = ultra-violet radiation

UVB = ultra-violet ‘B’ radiation

UVC = ultra-violet ‘C’ radiation

VA = vinyl acetate

WVP = water vapour permeance

WVT = water vapour transmission

x = distance

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to Dr. Gavin Wall, Acting H.O.D. (Agricultural Engineering) and Mr. Colin Wells. Their assistance in the planning and execution of this study, their 'open door' policy for relaxed discussion and their constructive suggestions during the preparation of this thesis, are gratefully acknowledged.

The author also wishes to acknowledge the advice given by Mr. Ian Painter and Mr. Paul Turner during the construction of testing equipment. Their cooperation throughout the period of equipment preparation, and when experiments were carried out, was very much appreciated.

Many thanks are extended to the staff of the Auckland Institute of Technology and the staff of the D.S.I.R. Industrial Development Division (Christchurch) who carried out thermal and optical tests, respectively, on various film plastic samples.

The financial support of Agpac Plastics (Christchurch) Ltd. and Edwards and Williams (Levin) Ltd. is gratefully acknowledged. Thanks to other primary distributors of film plastics in New Zealand for their cooperation in contributing samples of their products and forwarding relevant information.

The personal financial support of the New Zealand Fruitgrowers Federation, C.Alma Baker Trust, Horticultural Industries (N.Z.) Ltd. Bursaries and the Helen Ackers Scholarship are gratefully acknowledged. The testimonials from Dr. Gavin Wall, Graeme Kerr (A.C.A.) and Margaret Keene which helped obtain this finance were appreciated.

A number of friends have supported the author during the period of this study. In particular, grateful appreciation to Todd Newman, Jeff Rowan and Andrew Metcalfe who provided sanity during times of personal stress. Thanks also to Spin, Phill, Greg and Tess for continued friendship through periods of doubt.

Finally, the author wishes to acknowledge the loving encouragement of his close family, who have made his life complicated ..... but interesting; Anne, Kerry, Warren, Robyn, Kim, Graeme and the one to be.

More particularly, however, his father and mother, Roger and Lynne, who provided him with books on the shelves and an education at an early age. These are loving people who encourage and support with both an open door and sound advice.

CHAPTER ONE

INTRODUCTION

The greenhouse provides a means of creating a more favourable environment for the growth of plants apart from the local external conditions. It is a means of optimising the factors which affect the photosynthesis and therefore the yield of the crop (Mermier and Baille, 1988). The principle external conditions that affect the rate of photosynthesis are temperature, light (intensity, quality and duration), carbon dioxide content of the air and the mineral elements in the soil (Rost *et al.*, 1979). For plants adequately supplied with carbon dioxide, mineral elements and water, the photosynthetic rates are mainly determined by the temperature and light conditions. To optimise the temperature and light conditions the grower should decide on the most suitable geometry of the greenhouse, structural elements and orientation, and make the correct choice of the cladding material.

1.1 Cladding Materials Available

Historically, glass has held an unchallenged position as a greenhouse cladding material because of its light transmission characteristics. Increases in fuel prices, the threat of fuel shortages in the long term, and new developments in plastic technology have prompted re-evaluation of glass as the sole cladding material for greenhouses (MAF, 1981). The development of transparent film plastics and rigid plastic panels has introduced a broad challenge to glass for many greenhouse applications. Consequently, interest in the use of non-glass greenhouses is rapidly increasing throughout the world (MAF, 1981; Landgren, 1985).

Glass is brittle, heavy, increasingly expensive and generally available only in flat sheets of relatively small area (Spice, 1974). A substantial structure is required to support glass because of its weight and greenhouse sealing is difficult as unwanted air exchange takes place through the overlaps, between panes.

Rigid plastic panels can be considered as direct substitutes for glass. Most rigid plastics have the advantage of being lighter in weight, permitting a greenhouse structure with fewer light obstructing supports (Spice, 1974).

Film plastics have revolutionised the few standard designs of greenhouses and have opened up new possibilities in environmental modification. The better film plastics, allied with improved greenhouse design, reduce heat loss (White, 1978; Roberts *et al.*, 1985), improve the sealing (Sturrock, 1981; Hurd, 1983), and because of their light weight, reduce the structural componentry required so that more light is allowed into the greenhouse (O'Flaherty, 1977; White, 1978). While light transmission is normally the limiting factor for rigid plastics, strength properties (especially tearing resistance) are limiting for film plastics (Landgren, 1985). Many film plastic materials have been produced in the past few years but they are not all as suitable for greenhouse cladding as others.

1.2 Criteria for a Successful Film Plastic Cladding Material

To a large extent it is possible to choose a specific film plastic cladding material having the most suitable properties for the application for which it is intended. Most film plastic materials, however, have some limitations which may influence their intended use.

Film properties desired in most greenhouse cladding situations include:

1. Transparency to solar radiation.

2. Opacity to thermal radiation.

3. Good mechanical strength.

4. A fair degree of permanence.

Furthermore, a grower generally considers the initial costs, ease and economy of application, and expected maintenance requirements when selecting a film plastic cladding material.

1.3 Statement and Nature of the Problem

Over the last two decades the number of commercially available film plastic cladding materials on the New Zealand market has increased dramatically. Consequently, many greenhouse designers and growers are confused with the multitude of materials and their range of quality and cost. The whole concept of film plastic greenhouses depends on having a film which is completely reliable and predictable. The availability of lower cost products often leads to the false economies of using inferior film. Generally, growers and designers are aware of these problems and so questions frequently arise as to which is the best film plastic material, or which should be used in a specific situation.

Although manufacturers have a great fund of knowledge on the use of various materials and additives, and usually publish information outlining the inherent characteristics of their product, they have occasionally made mistakes in predicting the product's performance.

It is also difficult to compare, and rely on, findings evolving from the independent testing of film plastic cladding materials. This is because:

1. Thickness variations between competing products are common and manufacturing processes and additives used change from one manufacturer to another.

2. Many of the film plastics utilized in New Zealand are sourced from northern hemisphere manufacturers. Whilst such coverings may perform satisfactorily in the northern hemisphere, the unique environment experienced in New Zealand dictates that northern hemisphere performance evaluations may not be safely extrapolated to the New Zealand situation.

3. The reported optical, thermal and mechanical properties of film plastics are often lacking in detail and the methods used to determine such properties are difficult to compare.

It is recognized that the application of standard testing procedures to all the film plastic cladding materials available in New Zealand, can result in an optical, thermal and mechanical property definition for each film. This definition can be used to evaluate and compare competing products.

CHAPTER TWO

LITERATURE REVIEW

2.1 Film Plastic Cladding Materials Available in New Zealand - a Brief

Those film plastic cladding materials available and used in New Zealand include:

1. Polyethylene.
2. Ethylene Vinyl Acetate.
3. Polyvinyl Fluoride.
4. Polyvinyl Chloride.
5. Polyester.
6. Co-extruded Films.

2.1.1 Polyethylene

Polyethylene (PE) is the most widely used greenhouse film plastic covering material in New Zealand. It is manufactured by mixing together homopolymers of ethylene with or without an ultraviolet (UV) stabilizing package. PE film is considered tough, flexible and is relatively inexpensive. Standard PE (film which is manufactured without additives) has a short life in the sun - 9 to 11 months (Duncan and Walker, 1975) - and will split easily if creased. PE transmits up to 90% of the total solar energy available at the earth's surface and has high transmission in the photosynthetically active radiation (PAR) region of the solar spectrum. PE, however, also readily transmits thermal radiation which means a PE clad greenhouse will cool rapidly at night.

"Fabricon" and "Solarweave" are woven PE films where ribbons of PE are woven in a criss-cross fashion. These films have greater mechanical strength than standard PE films while transmission of PAR is still high (up to 90%). PE film reinforced with synthetic fibres is also manufactured.

Infra-red PE (IRPE) films are manufactured by enriching the PE resin with aluminium or magnesium silicates (mineral fillers). These additives render the PE film more opaque to thermal radiation without PAR transmission being greatly affected. "Infrane X-30" is such a film and is available in New Zealand. Although the manufacturer claims this film retains 84% of incident thermal radiation (given off from the inside of the greenhouse), one independent source (Bailey, unpublished report) states that it retains up to 54%. This latter value is still 35% greater than for most standard PE films, although considerably lower than that offered by the manufacturer. The manufacturers of "Infrane X-30" also claim the film diffuses all light passing through it. This is a beneficial characteristic as shadows in the greenhouse are reduced and a more even light distribution within the greenhouse is generated.

2.1.2 Ethylene Vinyl Acetate

Ethylene vinyl acetate (EVA) films are manufactured by enriching PE resin with vinyl acetate (VA). Increasing levels of VA will result in increasing film transparency, plasticity, compatibility with mineral fillers, water vapour permeability and resistance to splitting (Dartiguepeyrou, 1986). Increasing VA levels will, however, also result in a reduction in yield strength and resistance to stretching (Dartiguepeyrou, 1986). Most EVA film plastics contain approximately 10% VA.

"Agphane 101" is an especially formulated EVA film manufactured in New Zealand. "Dura-film 3" is an EVA film manufactured overseas and is also available in New Zealand. "Durafilm 3" contains the least VA (approximately 4%) of all the EVA film plastic cladding materials available in New Zealand. "Evalyte" and "Permalite" are the other EVA films available in New Zealand. According to the distributors "Evalyte" has a high resistance to dust build-up. This is important with EVA films as a higher percentage of VA in a film formulation will tend to render the film plastic more attractive to dust (Dartiguepeyrou, 1986). "Evalyte" is also available as a film with ventilation holes.

"Duratherm" is an infra-red EVA (IREVA) film which, as a cladding, will successfully retain heat within the greenhouse. Such a film, containing both VA and infra-red (IR) absorbing additives, is also known as a 'thermal PE' (PETh) type film. "Duratherm" is manufactured overseas and available in New Zealand.

EVA films that are reinforced with polyester strands are also made available to New Zealand growers. "Graphlon" is such a film. "Graphlon" is UV stabilized and can be purchased as a green tinted (as well as clear) film for reduced transparency.

2.1.3 **Polyvinyl Fluoride**

Polyvinyl fluoride (PVF) films have outstanding optical properties (Hare *et al.*, 1984) and weather extremely well (Waaijenberg, 1985). PVF is most actively marketed under the trade name "Tedlar PVF". The PVF film plastics are not popular as they can only be manufactured in small widths, they cannot be welded and the material is generally very expensive.

PVF can be used for surface coating fibreglass reinforced plastic (FRP) panels. "Durolite-f" FRP panels, available in New Zealand, are coated with "Tedlar PVF" film.

2.1.4 Polyvinyl Chloride

Polyvinyl chloride (PVC) films generally have good transmission in the PAR region for both direct (up to 90%) and diffuse (74% to 84%) light (McNaughton *et al.*, 1981; Landgren, 1985). The value of transmissivity in the thermal region is low compared with most other film plastics (e.g. PE, EVA). Transmissivity may reach up to only 30% (i.e. 30% thermal radiation loss through the film) at night. Unfortunately, PVC film plastics have a higher relative cost than PE or EVA film plastics, PVC films are only manufactured in narrow widths, and they tend to attract dust.

"Hyperlyte" PVC film is manufactured and distributed in New Zealand.

2.1.5 Polyester

The polyester (PEST), or terephtalate of PE, films allow excellent PAR transmission and exhibit high strength. According to Landgren (1985) PEST films have a very high tensile strength, but have poor tear resistance. PEST film plastics are not often used in New Zealand as they are very expensive and can only be manufactured in very small widths. Polyester, however, is used as reinforcing in other film materials (e.g. "Graphlon").

"Melinex" PEST film is a tough, durable film which is UV stabilized. It is used to coat the inner side of "Durolite-f" FRP panels.

2.1.6 Co-extruded Films

These films are made up by co-extrusion of raw materials into parallel layers. They usually consist of 2 to 5 layers of different materials. "Polycrop" is a double layer co-extruded film available in New Zealand. "Infrasol 226" is a triple layer co-extruded film available in New Zealand.

2.2 Optical Properties of Film Plastics

Light is the most important of all the factors which control the physiological activities of the plant (Mermier and Baille, 1988). Often light is the limiting factor on the rate of photosynthesis and subsequent plant yield. The optical properties of a film plastic cladding material largely determine the intensity and quality of light incident on the plant. Therefore, it is important that the cladding material transmits as much of the light incident on the greenhouse as possible, in order to obtain the full benefit of environmental light levels. Yields are often maximised where excellent cladding transmission enables the optimum light intensity, for the plant, to be reached.

Although the greenhouse is often subject to high levels of incident light, not all of it is useful. The greenhouse cladding material may be required to screen harmful wavelengths as well as transmitting high levels of desirable wavelengths. It is important to recognise the nature of the available light, so that the function of the film plastic cladding material can be more sharply defined.

2.2.1 Available Light

The sun has a surface temperature of around 6000 °C and emits 64.2 MW/m^2. It is nearly spherical with a diameter of 1.38 Gm. The sun-earth distance is on average 1.50×10^{11} m. As radiant energy travelling from the sun moves across space, it is spread across a larger and larger area. Consequently, the energy becomes less intense according to an inverse square law. Thus, the intensity of the solar radiation at the top of the earth's atmosphere is represented by:

$$\text{Intensity} = \frac{\text{Heat flux} \times (\text{sun radius})^2}{(\text{sun-earth distance})^2} \tag{2.1}$$

$$= \frac{64.2 \text{ MW} \times (6.90 \times 10^8 \text{m})^2}{(1.50 \times 10^{11} \text{m})^2}$$

$$= 1360 \text{ W/m}^2$$

The actual intensity of the solar radiation at the earth's surface, however, is somewhat smaller than this value, due to the affect of absorption and scattering of rays within the earth's atmosphere (Figure 2.1). In fact, the radiation intensity decays in an exponential manner according to Beer's Law (Incropera and DeWitt, 1985).

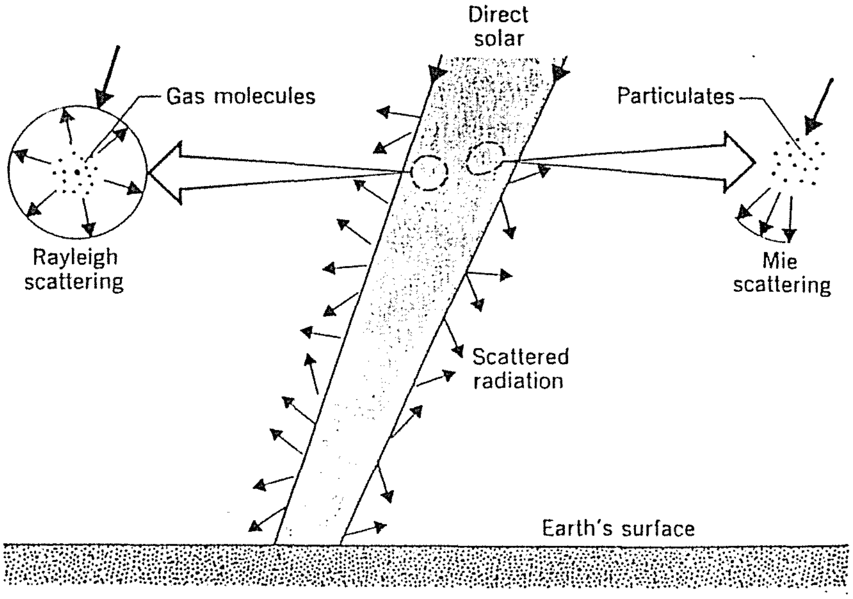


Figure 2.1 Scattering of solar radiation in the earth's atmosphere (Incropera and DeWitt, 1985).

The position of the sun in the sky at various times of the year and the location of the greenhouse, influence the quantity of solar radiation available for plant growth. The latitude of the greenhouse site and the season of the year govern the angle at which the sun rays strike the surface of the earth. When the rays strike the ground at an angle the intensity is reduced, since the energy is spread over a wider area.

The more northern the latitude, the higher the sun is above the horizon during mid-winter (from the southern hemisphere perspective). As the angle of the sun rays become more acute, (i.e. during winter conditions) less energy per unit area reaches the earth surface. Also, the position of the sun above the horizon changes from sunrise to sunset, affecting the distribution of solar radiation during the day. Irradiance varies from a low level during the early morning to a maximum around mid-day, then diminishes to a low level in the late afternoon. This is largely due to the effect of the solar angle.

The earth's atmosphere also has a considerable affect on the radiation intensity at different latitudes, different seasons and at different times of the day. As the angle of the sun rays become more acute, sunlight must pass through more of the earth's atmosphere where a considerable portion of the energy is absorbed and scattered. In addition to radiation intensity, a change in spectral quality occurs, as the atmosphere selectively scatters more of the shorter (blue and UV) wavelengths than the longer (red and IR) wavelengths (Coulson, 1975). The thicker layer of atmosphere that sunlight passes through early in the morning and late in the afternoon, at more northern and southern latitudes and during the winter months, filters the sun rays. This results in direct radiation incident on the ground that is richer in the red wavelengths and the diffuse light is, spectrally, predominantly blue (Coulson, 1975).

The number of sunlight hours also changes with the latitude and the season of the year.

2.2.1.1 Direct and Diffuse Light

Solar radiation enters the greenhouse from many different directions. Direct light comes from the single sun source. Diffuse light comes from varying directions due to radiation reflection off the ground or off particles in the air. At noon, on a clear day, only 12.5% of the energy received on a flat surface comes from diffuse light (Mastalerz, 1977). This ratio changes during the day and also depends on weather conditions (Table 2.1).

Table 2.1 Proportion of Direct and Diffuse Light at Different Times of the Day

Period	Direct Light (%)	Diffuse Light (%)
Clear day		
Sunrise	<50.0	>50.0
Mid-morning	80.0	20.0
Noon	87.5	12.5
Mid-afternoon	80.0	20.0
Sunset	>50.0	>50.0
Completely overcast	100.0	0.0

Adapted from Mastalerz (1977).

Diffuse radiation entry into the greenhouse will result in more uniform distribution of light and, consequently, the degree of shading of lower plant leaves will be reduced. Therefore, an important factor in the design and orientation of greenhouses is the transmission of diffuse light as well as direct light. The highest transmission of light is possible when the light is directed perpendicular to the glazing material. If the light strikes at an angle other than that perpendicular to the material, then more light is reflected and less is transmitted (MAF, 1981). Diffuse light tends to strike the greenhouse at random angles. It is possible to design a greenhouse that will intercept a large portion of the diffuse radiation at angles close to perpendicular.

2.2.1.2 Photosynthetically Active Radiation

Photosynthetically active radiation (PAR) is that specific portion of the total solar spectrum considered usable by green plants for growth (Ting and Giacomelli, 1987a). The light energy from other parts of the spectrum may become useful as free heat, which can speed up those biochemical processes leading to plant growth. PAR is the portion of electromagnetic radiation approximately within the 380nm to 780nm wavelength band (Figure 2.2).

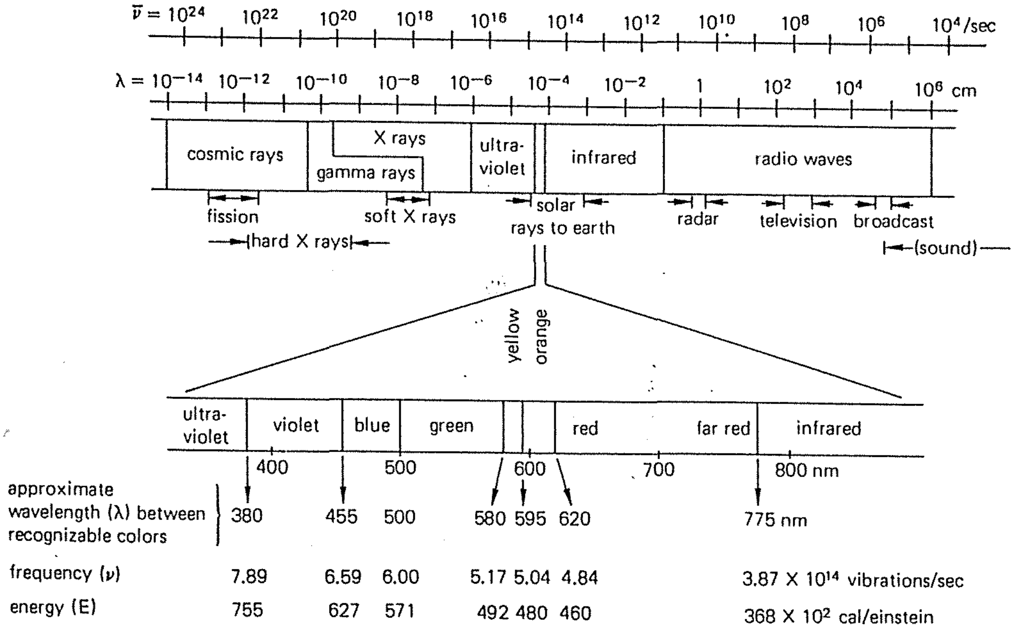


Figure 2.2 PAR portion of the spectrum (Salisbury and Ross, 1978).

Approximately 38% of the solar radiation measured outside the earth's atmosphere is PAR (Thekaekara, 1971; Ting and Giacomelli, 1987b). The quantity of PAR actually reaching the ground, however, can be expected to be slightly less than that outside the atmosphere. This is due to scattering of the blue wavelengths by the atmosphere and the absorption of UV and near IR (refer 2.2.1 Available Light). The portion of PAR reaching the ground that is transmitted into the greenhouse is determined by the film plastic cladding material. Different film plastics allow different levels of PAR into the greenhouse (Table 2.2).

Table 2.2 **Total % PAR Transmission (Assumed equivalent to total visible light transmission)**

Material	Thickness (um)	McNaughton *et al.* (1981)	Fuller and Cooper (1983)	Hare *et al.* (1984)
PE				
Standard	150	-	90.0	90.0
Woven	230	-	85.0	-
EVA				
Normal	150	90.0	-	-
Reinforced	250	80.0	-	-
PVF	100	-	-	92.0
PVC	400	89.0	88.0	-
Polyester	80	-	-	95.0

2.2.2 Transmission Theory

When radiation, visible or IR, falls on a surface a fraction ρ is reflected, a fraction α is absorbed and the remainder τ is transmitted (Figure 2.3), so that:

$$\rho + \alpha + \tau = 1 \tag{2.2}$$

(Bailey, unpublished report; Wells, 1989).

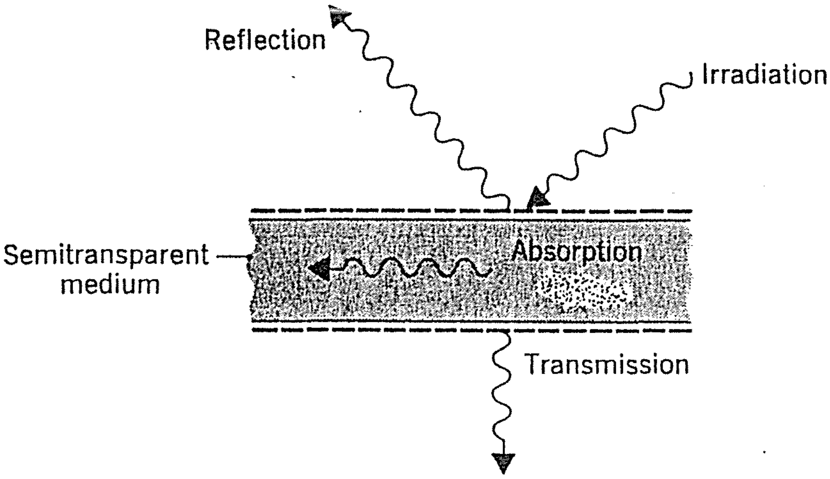


Figure 2.3 Reflection, absorption and transmission processes associated with a semi-transparent medium (Incropera and DeWitt, 1985).

The quantities ρ, α, and τ are known as the reflectivity, absorptivity and transmissivity, respectively. These properties of a surface vary with the material and the wavelength of the incident radiation. The properties can be assumed to be constant over the solar and terrestrial wavelength bands (except with tinted materials) although they may vary from band to band.

2.2.2.1 Reflection

Theoretical calculations show that up to 4% of incident light is reflected at each glass glazing air interface (MAF, 1981). Less incident light is reflected by film plastic materials. This suggests a maximum of approximately 95% light transmission is possible for a single layer of film (the maximum is considerably less for twin walled cladding systems). Since some films transmit up to 95% of incident radiation, this indicates that a major loss of light is due to reflection rather than absorption.

The amount of reflection is dependant on the angle of incidence and the refractive index of the covering material with reference to air (Tesi *et al.*, 1986; Bailey, unpublished report). Figure 2.4 illustrates the dependence that the degree of reflection has on both the cladding material's unique characteristics and the angle of incidence. As the latter increases, so does the reflectivity (ρ) of the material.

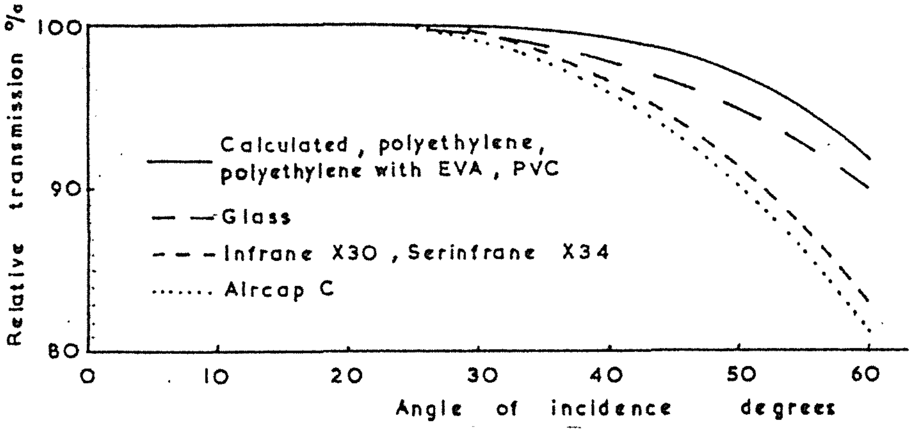


Figure 2.4 Effect of angle of incidence on light transmission (Adapted from Bailey, unpublished report).

For smooth surfaces Fresnal (Duffie and Beckman, 1980) has derived expressions for the reflection of unpolarised radiation on passing from medium 1 with refractive index n_1, to medium 2 with refractive index n_2 (Figure 2.5). These are as follows:

$$r_\perp = \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)} \tag{2.3}$$

$$r_\parallel = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)} \tag{2.4}$$

$$r = \frac{I_r}{I_i} = \frac{(r_\perp + r_\parallel)}{2} \tag{2.5}$$

where $r_\perp$ = parallel component of unpolarized radiation

$r_\parallel$ = perpendicular component of unpolarized radiation

r = reflection as an average of $r_\parallel$ and $r_\perp$

I_i = intensity of the incident radiation (W/m^2)

I_r = intensity of the reflected radiation (W/m^2).

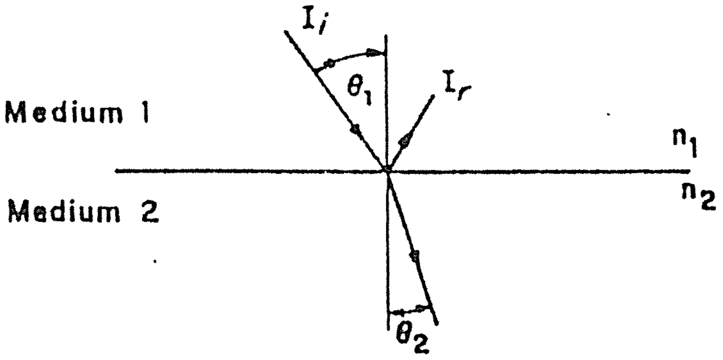


Figure 2.5 Angles of incidence and refraction in media having refractive indices n_1 and n_2 (Duffie and Beckman, 1980).

The angles θ_1 and θ_2 are related to the indices of refraction by Snells Law:

$$n_1 = \sin\theta_1 \tag{2.6}$$

$$n_2 = \sin\theta_2 \tag{2.7}$$

The reflectivity of a single cover, allowing for both reflection and absorption losses, for the parallel component of polarisation is:

$$\rho_{\parallel} = r_{\parallel} + \frac{(1 - r_{\parallel})^2 . \tau_a^2 . r_{\parallel}}{1 - (r_{\parallel} . \tau_a)^2}$$

$$= r_{\parallel} . (1 + \tau_a . \tau_{\parallel}) \tag{2.8}$$

where $\rho_{\parallel}$ = reflectivity for the parallel component

τ_a = represents the transmission through the medium when only absorption losses have been considered

$\tau_{\parallel}$ = transmissivity for the parallel component

(Duffie and Beckman,1980).

A similar equation can be found for the perpendicular component of polarisation ($\rho_{\perp}$). For incident unpolarized radiation, ρ can be found by the average of the two components $\rho_{\parallel}$ and $\rho_{\perp}$ (Duffie and Beckman, 1980).

2.2.2.2 Absorption

Absorption of radiation is described by Beer's Law, which is based on the assumption that the absorbed radiation is proportional to the local intensity in the medium and the distance (x) the radiation travels in the medium (Duffie and Beckman, 1980). By integrating along the actual path length of the medium we obtain:

$$\tau_a = \frac{I_r}{I_i} = e^{-kl/\cos\theta} \tag{2.9}$$

where τ_a = represents the transmission through the medium when only absorption losses have been considered

I_r = intensity of the transmitted radiation (W/m^2)

k = extinction coefficient (m^{-1}) (e.g. $k = 4\ m^{-1}$ for water white glass and $k = 32\ m^{-1}$ for poor glass)

l = path length (m)

The absorptivity for a single cover allowing for both reflection and absorption losses, for the parallel component of polarization is:

$$\alpha_{\parallel} = (1 - \tau_a) . \frac{1 - r_{\parallel}}{1 - r_{\parallel} . \tau_a} \tag{2.10}$$

where $\alpha_{\parallel}$ = absorptivity for the parallel component

(Duffie and Beckman, 1980).

A similar equation can be found for the perpendicular component of polarisation ($\alpha_{\perp}$). For incident unpolarised radiation, α can be found as the average of the two components $\alpha_{\parallel}$ and $\alpha_{\perp}$.

2.2.2.3 **Transmission**

Transmission through an opaque surface is nil. In such a situation:

$\tau = 0$, and

$\rho + \alpha = 1$.

The transmissivity for a single cover, allowing for both reflection and absorption losses, for the parallel component of polarization is:

$$\tau_{\|} = \frac{\tau_a.(1 - r_{\|})^2}{1 - (r_{\|}.\tau_a)^2}$$

$$= \tau_a . \frac{1 - r_{\|}}{1 + r_{\|}} . \frac{1 - r_{\|}^2}{1 - (r_{\|}.\tau_a)^2} \qquad (2.11)$$

(Duffie and Beckman, 1980).

A similar equation can be found for the perpendicular component of polarisation ($\tau_{\perp}$). For incident unpolarised radiation, τ can be found as the average of the two components $\tau_{\|}$ and $\tau_{\perp}$.

For double cladding systems, with covers not necessarily identical, the following equations for determining the reflectivity (ρ) and transmissivity (τ) may be used:

$$\rho = \tfrac{1}{2} . \left(\rho_1 + \frac{\tau_1 . \tau . \rho_2}{\tau_2} \right) . \left(\rho_1 + \frac{\tau_1 . \tau . \rho_2}{\tau_2} \right) \tag{2.12}$$

$$\tau = \tfrac{1}{2} . \left(\frac{\tau_1 . \tau_2}{1 - \rho_1 . \rho_2} \right) . \left(\frac{\tau_1 . \tau_2}{1 + \rho_1 . \rho_2} \right) \tag{2.13}$$

where subscript 1 refers to the outer cover and
subscript 2 refers to the inner cover

(Duffie and Beckman, 1980).

Note that the reflectivity from the outer cover system depends upon which cover is first to intercept the radiation.

The preceding analysis applies to the direct component of solar radiation. Solar radiation incident on a cover material also consists of diffuse radiation from the sky and ground. In principle, the amount of diffuse radiation that passes through a cover system can be calculated by integrating the transmitted radiation over all angles. It is easiest, however, to use the equivalent angle of approximately 60° which gives the equivalent direct radiation transmissivity value as diffuse radiation (Duffie and Beckman, 1980). The equivalent angle depends on the surface slope of the cladding material, particularly when ground reflected radiation is involved.

2.2.3 Actual Light Transmission

Many authors (Grafiadellis, 1985; Landgren, 1985; Mognani, 1987; Nijskens *et al.*, 1988; Bailey, unpublished report) and manufacturers have published reports giving the transmissivity of most available cladding materials. Data is readily available showing the transmission properties of various film plastics with respect to radiation incident at different angles and at normal incidence (Figure 2.4). Transmissivity of cladding materials to PAR (Table 2.2), diffuse radiation, total solar energy data, and data showing the transmissivity of the films with respect to different light bands, is also readily available.

The reflectivity or transmissivity may be identified by a preceding adjective such as specular, diffuse, total, directional, or fractional, thereby identifying the basis for the measurement scale. Directional indicates that the light reflected or transmitted in specified directions only was included for measurement and that the measurement scale was relative to that of the ideally and completely diffusing standard measured under the same conditions of incidence and viewing. Directional values depend on the angle of incidence and viewing.

Haze is a term which describes the diffusing characteristic, or clarity, of a material. Reported haze is that percentage of transmitted light which, in passing through the material, deviates from the incident beam by forward scattering. Cladding materials that diffuse light are generally considered beneficial, as diffuse light in the greenhouse will reduce plant shading.

In practice, the degree of light transmission through any greenhouse cladding material is largely dependent on the material characteristics, dimension (thickness), age, cleanliness, the presence of condensation, and the number of material layers. Therefore, the effects of age, dirt, condensation and double cladding need to be considered. The effect of each of these treatments is to reduce the transmissivity value (with the exception of the presence of a thin, uniform layer of condensation).

Most transmission data is for newly manufactured material.

2.2.4 Cladding Aging and Degradation

Accelerated film aging occurs as a result of solar radiation (photodegradation) and high temperatures (thermodegradation) (Goldsberry, 1984), high humidity (Duncan and Walker, 1975), exposure to some chemicals (Barahona and Vasquez, 1985) and various mechanical constraints. The environmental factors often cause yellowing and haziness of the film plastic cover, which results in a loss of light transmission capability of the material (as well as a reduction in impact and tensile strength). Table 2.3 gives the life expectancy (as a solar radiation transmitting material) of various greenhouse cladding materials. The expected life should always be treated as a general estimate, as prevailing environmental conditions largely influence the aging process.

Table 2.3 **Properties of Cladding Materials for Greenhouses**

Material	Thickness (mm)	% Transmissivity of Visible Light (380um to 780um)	Life Expectancy (Years)
Glass	3.000	92.0	20
FRP Panels	1.500	85.0	8
PE	0.150	90.0	2
PVF	0.100	91.5	15
Polyester	0.075	95.0	7

Adapted from Hare *et al.* (1984).

Photodegradation describes the inevitable chemical degradation of all plastic (rigid and film) greenhouse cladding materials exposed to the action of sunlight (McLean, 1982). With film plastics long term exposure to the UV fraction of the sun energy may cause the conversion of a normally elastic material into a brittle film that tears easily (Duncan and Walker, 1975; McLean, 1982; Goldsberry, 1984). UV light is the main damaging agent to plastic films (Nijskens *et al.*, 1988). The UVB range (280nm to 320nm) is a very active area for degradation to occur, and film plastics should ideally have zero transmissivity in this region. The UVC fraction (320nm to 400nm) is also an active area especially around 350nm to 360nm for PE (Mitchell, pers. comm.). Ideally, transmission of the UVC fraction should be of the order of 15% or less.

A film plastic cladding material should, ideally, contain UV stabilizers to control incident UV radiation, and so prevent the degradation of the polymer. Addition of certain chemicals (UV stabilizers) to the film plastic resins, such as UV absorbers or UV quenchers, allows the possibility of increasing the useful life of a film plastic by a significant margin.

2.2.4.1 Ultra-violet Stabilizers

According to Stepek and Daoust (1983), UV stabilizers must meet the following basic conditions:

1. They should absorb 300nm to 400nm wavelength radiation more readily than the polymer.

2. They should not react with the polymer.

3. They should transform absorbed energy into harmless energy (i.e. energy corresponding to high wavelengths or thermal energy that does not heat the polymer above its decomposition temperature).

4. They should be stable (i.e. capable of absorbing radiative energy without undergoing decomposition).

UV absorbers (e.g. hydroxy-benzophenone or benzotriazole types) are stabilizers which absorb the energy associated with UV light. They then dispose of this energy by radiation, by conversion into heat or by chemical changes leading to stable products (Brydson, 1982). Unfortunately, chemical changes over a long period of time may render the absorbers inactive and, subsequently, the film material may again become prone to photodegradation.

UV quenchers (e.g. HALS or nickel chelate) themselves do not absorb UV light. Their effectiveness is due to their conversion into the stabilizer following reaction with excited polymer molecules damaged by UV light (Scott, 1980). Once in the stabilizer form, the quencher catalyses the repolymerization of the broken chain polymers of the film material. HALS (hindered amine light stabilizers) not only moderate the effect of UV on film materials but can also divert (i.e. act as anti-oxidants) the free radicals originating from UV light (Brydson, 1982; Son, 1990). Since HALS are converted into the actual stabilizer form in the early stages of photo-oxidation, their loss is a prerequisite for their effectiveness as UV stabilizers (Scott, 1980). Some HALS exhibit both UV light and thermal radiation stabilization properties (Son, 1990).

Selection of absorbers and quenchers largely depends on the nature of the resin (Son, 1990). UV inhibitor formulations containing both a UV absorber and a UV quencher are most successful (Nijskens *et al.*, 1988).

Some of the PE films have high concentrations of UV stabilizers which create a yellowish-green tint in the material (Goldsberry, 1984). Although the film life expectancy is increased, the films have poorer light transmission properties. Care is taken upon manufacture of such films to ensure the light transmission capabilities are not greatly affected.

Like the clear film plastic cladding materials, green tinted materials tend to darken with time due to photo and thermodegradation (Goldsberry, 1984). PVC does not appear to change colour as it ages but it does gradually lose its tear resistance properties.

Thermodegradation generally occurs where the film is in contact with the supporting greenhouse structure, as the hot structure tends to heat the film plastic in contact with it. Although this heating does not affect light transmission (as the structure blocks the light at these points anyway) mechanical failure is likely to occur in these areas.

2.2.5 Dust and Dirt

The age of greenhouse glass has little effect on greenhouse transmission as long as the glass is clean. The presence of dust and dirt on film plastic materials not only reduces light transmission, but often creates a visual yellowing of the material as well. Periodic cleaning of the cladding material is essential in industrial areas, areas of low rainfall, and where light conditions are less favourable. Table 2.4 presents data which demonstrates the importance of removing dust and dirt accumulation on PE film.

Table 2.4 Single Layer Transmissivity (%) of Claddings When New and After 18 Months on the Greenhouse (Perpendicular PAR)

Greenhouse Number and Material		Cladding Condition		
		New	Exposed (Before cleaning)	Exposed (After cleaning)
1.	IRPE	86.0	82.0	85.0
2.	IRPE	86.0	82.0	84.0
3.	PE	87.0	80.0	83.0
4.	PE	87.0	80.0	83.0

Adapted from Roberts *et al.* (1985).

The electrostatic charge usually associated with vinyls causes dust particles to adhere to polyvinyl films (Duncan and Walker, 1975; MAF, 1981) and EVA films high in VA content (Dartiguepeyrou, 1986). This necessitates regular cleaning of these film plastics.

2.2.6 Condensation

When the warm, moist air within the greenhouse structure is cooled at the cladding surface, to a temperature close to the cladding itself, condensation may form. Condensation will form if the cover temperature drops below the dew point temperature of the greenhouse air. Such a temperature drop commonly occurs at night. Horiguchi and Hirano (1988) reported that the ease at which vapour adheres to the film is closely related to the formation of condensation, the density of the film and the quality of the film.

Condensation on the cover will cause a reduction in heat energy losses from the inner greenhouse space as the transmissivity of water in the thermal radiation domain has a zero value (White, 1978; Nijskens *et al.*, 1984; Nijskens *et al.*, 1985; Halleux *et al.*, 1985). This reduction in heat loss during night time is beneficial in most situations. When the water layer reaches a certain thickness, however, it can alter the optical properties of the transparent material that it covers (Nijskens *et al.*, 1984). When the condensation appears in the form of drops the solar transmissivity tends to decrease for those parts of the film that are under water (White, 1978; Nijskens *et al.*, 1988). When condensation forms a thin uniform layer, solar transmission improves (Table 2.5).

Table 2.5 The Effect of Condensation on the Diffuse Solar Transmissivity of Film Plastic Claddings

Transmissivity (%)		
Dry Film	Wet Film (Droplets)	Wet Film (Anti-fog)
79.0	76.0	82.0
77.0	74.0	83.0

Adapted from Nijskens *et al.* (1988).

Anti-fog films contain additives within the film mass which prevent formation of condensation in drop form and cause film layer condensation to develop. Anti-fog films will, therefore, increase the solar transmissivity of the film when condensation forms. The additives are added to the polymers during processing, and are often blended in various combinations to achieve optimal anti-fog performance. Typical anti-fog use levels range from 0.5% to 4% (Vanzin, 1990). Factors involved in the selection of the correct anti-fog additive include film thickness, polymer processing conditions and the additives physical form, thermal stability and compatibility (Vanzin, 1990).

The application of surfactants (surface active agents) to the plastic film cladding surface, will also cause condensation to form into a uniform layer rather than into drops (Halleux *et al.*, 1985; Horiguchi and Hirano, 1988). The external application (topical or full coating), achieved through dip, spray or gravure techniques, is economical and leads to an immediate anti-fog effect (Vanzin, 1990). Figure 2.6 illustrates the effect of treating PE film with a surfactant. The water of condensation completely covers the film when PE is treated with a surfactant. With ordinary PE, however, the water condenses in the form of droplets of varying size, side by side.

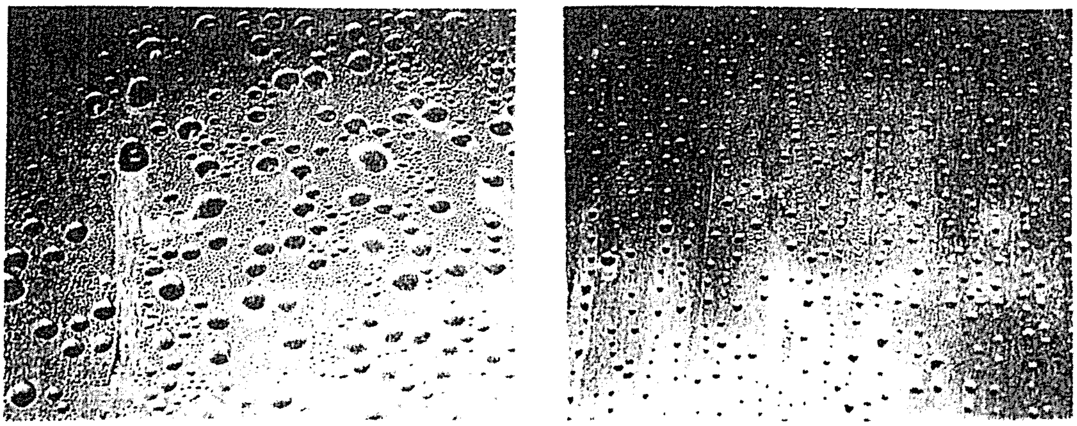


Figure 2.6 Condensation on standard PE film (left) and on PE film treated with a surfactant (right) (Halleux *et al.*, 1985).

Since they are externally applied and are easy to remove, surfactants only work for a limited period. On the other hand, the internal additives in anti-fog films provide a reservoir to continually replace the additives that migrate to the film surface. As a result, internal anti-fog film additives provide longer lasting performance than surfactants.

Anti-drop film additives and surfactants can also provide additional benefits such as lubricating, cling and anti-static properties (Vanzin, 1990).

The major benefit gained from encouraging the build up of condensation (i.e. a reduction in thermal radiation loss) should be weighed up against the following disadvantages:

1. Loss of PAR transmission capability when droplets form.

2. Added cost of using anti-fog films or surfactants.

3. Relatively small benefits gained when the cladding material used allows little transmission of thermal radiation anyway (e.g. as with PVC or double cladding systems).

2.2.7 Double Cladding

A double clad greenhouse consists of a normal type of structure where a transparent film is stretched over a conventional frame, but a second film is placed over the first skin and air is blown between the films with a low pressure fan (McLean, 1982). The films may also be mechanically separated by structural supports and correct film tensioning. In both situations, the air between the two films acts as very effective insulation. In some designs polystyrene beads can be pumped between the layers at night to obtain a very high energy saving (OARDC, 1979; Breuer, 1985).

The benefits of double cladding a greenhouse structure are:

1. Enhancement of the heat retaining performance of the cover.

2. Better air-tightness of the greenhouse.

3. Increases in humidity within the greenhouse, due to the higher temperature of the inner skin (this may or may not be beneficial).

One can also expect there to be less condensation build-up, on the interior film surface, when a double cladding system is employed rather than a single film covering (Weimann, 1989).

The transmission of PAR, however, is adversely affected by double cladding. The loss effect of multiple layer cladding is cumulative (Balls, 1986) due to the greater number of reflecting surfaces. Several authors (Godbey *et al.*, 1979; Hurd, 1983; Mognani, 1987) have reported that:

1. Visible radiation, transmitted by various cladding materials, drops significantly for each successive cladding layer.

2. The degree to which transmission decreases changes according to the type of materials used.

Mognani (1987) suggested 10% to 30% of the visible radiation may be prevented from entering the greenhouse when a double cladding system is employed. By carefully combining films of different characteristics, high transmission of PAR may still be obtained, while transmission of thermal radiation is kept to a minimum. The order (i.e. outside or inner placement) as well as the combination of the films, determines the transmission characteristics of a double cladding system (Godbey *et al.*, 1979).

The double cladding also serves to increase the air tightness of the greenhouse, reducing water vapour and gas exchange. This is most beneficial when CO_2 enrichment techniques are employed, as less gas is lost to the outside environment. An increase in humidity of the interior air may reduce crop irrigation requirements, will probably not affect the percentage yield, but can be expected to make the plants more susceptible to wilting once ventilators are opened (Hurd, 1983). A high humidity environment may also promote disease development and spread.

2.3 Thermal Properties of Film Plastics

A major function of the greenhouse cladding material is to prevent thermal radiation loss from the greenhouse interior to the outside environment. Heat transfer occurs across glazings via conduction, convection and radiation.

2.3.1 Conduction

Conduction is the transfer of heat between adjacent molecules of a substance without the gross movement of the molecules within the substance. According to Fourier's principle (refer to Incropera and DeWitt, 1985; Holman, 1986), the rate of heat conduction through a film plastic material is directly proportional to the temperature gradient in the film and the cross sectional area of the film perpendicular to the direction of heat flow.

The rate of heat flow (Figure 2.7) is represented by:

$$Q = k.A. \frac{T_2 - T_1}{x_2 - x_2} \tag{2.14}$$

where Q = rate of heat flow (W)

k = thermal conductivity (W/m.°C)

A = cross sectional area (m^2)

T = temperature (°C)

x = distance (m)

(Incropera and DeWitt, 1985; Wells, 1989).

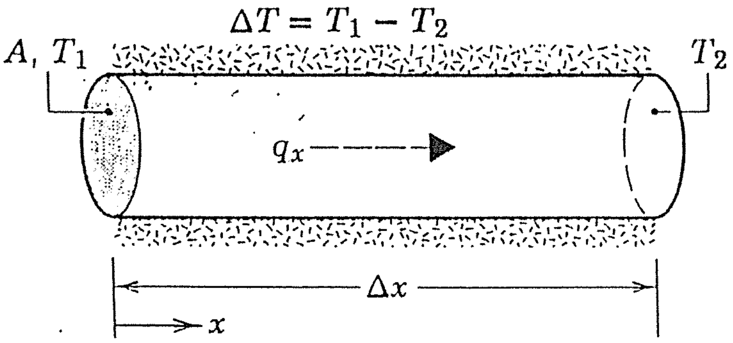


Figure 2.7 Steady-state heat conduction (Incropera and DeWitt, 1985).

The thermal conductivity is a property of a material and a function of temperature (Monteith and Unsworth, 1990).

The temperature drop across a film plastic material is generally insignificant compared with the temperature difference between the inside air surface layer and the outside air surface layer (as the film thickness is very small). Therefore, the rate of thermal radiation loss from the greenhouse is much less dependant on the heat transfer via conduction through the film than the heat transfer via convection.

2.3.2 Convection

Convection is a form of heat transfer where energy is transported by movement of a heated fluid adjacent to a solid material. Heat exchange occurs between the solid and the fluid when there is a temperature difference between them. Unlike the solid, the fluid molecules are free to move and mix relative to one another. The rate of convective heat transfer across a film covering is represented by the equation:

$$Q = h_c.A.(T_s - T_{ao}) \tag{2.15}$$

where Q = rate of heat flow across the film surface (W)

hc = convective heat transfer coefficient ($W/m^2.°C$)

A = surface area (m^2)

T_s = temperature of the film surface (°C)

T_{ao} = temperature of the outside air (°C)

(from Newtons Law of Cooling - refer to Incropera and DeWitt, 1985).

The value of h_c depends on several factors. They include the type of fluid involved; the velocity of the fluid across the surface; the temperature difference between the surface and the fluid; and the shape, orientation, and size of the surface (Incropera and DeWitt, 1985; Wells, 1989).

For formulae used to estimate the convective heat transfer coefficient refer to Monteith and Unsworth (1990).

2.3.3 Radiation

The transmissivity (refer 2.2.2 Transmission Theory) and emissivity of film plastics greatly affect the greenhouse temperature, and are largely dependant on the chemical construction of the materials (Horiguchi *et al.*, 1982).

2.3.3.1 Emissivity

The emissivity (ε) is the property of a surface which determines how well it radiates (Wells, 1989). The emissivity of a surface can be anywhere between zero and one. Surfaces with emissivities close to one are good radiators, whereas surfaces with emissivities close to zero are poor radiators.

Emissivity affects the surface temperature of a greenhouse cladding material and, consequently, the temperature of the greenhouse interior (Horiguchi *et al.*, 1982). A film with low emissivity is desirable for heat conservation. A film plastic with a low emissivity, however, has a high transmissivity if it reflects little radiation. Transmissivity is more important than the emissivity for the fall of night time temperatures (Horiguchi *et al.*, 1982).

Table 2.6 Emissivity of Cladding Materials to Thermal Radiation

Material	Thickness (um)	Emissivity (%)
PE	100	14.2
IRPE*	-	70 - 80
EVA	100	35.7
PVC	100	63.8
Polyester	100	70.8

Adapted from Horiguchi *et al.* (1982),
(* Raviv and Allingham, 1983).

Table 2.6 lists the emissivity values for the more common film plastic materials used for cladding greenhouses. PVC type films and IR films have very high emissivities (Table 2.6) and, therefore, transmit only a small portion of thermal radiation incident on their surface. Hence, both films are employed where heat retention within the greenhouse is particularly important.

Problems with condensation formation are common when low emissivity films are used to clad greenhouses. Films with low emissivities will not absorb thermal radiation to any great extent and, thus, emissivity effects film surface temperature. The temperature of low emissivity covers may drop below the dew point temperature of the greenhouse air, causing condensation.

2.3.3.2 Reflectivity

The quantity of incident radiation reflected changes very little with varying film plastic materials and the differences are in the range of ± 2% (Horiguchi *et al.*, 1982). Therefore, upon changing transmissivity and emissivity, reflectivity can be considered constant.

2.3.3.3 Transmissivity

A cladding material should be transparent to radiation in the near IR range of the spectrum to produce heating and should be opaque to far IR wavelengths (thermal radiation) to prevent heat loss from the greenhouse interior (Bailey, unpublished report; Tesi *et al.*, 1986). Thermal transmission characteristics are most important in cases where there are extreme radiating surfaces within the greenhouse, such as an IR heating system. Energy is wasted when it is first introduced to the greenhouse environment via radiators, but then lost through a cladding material with a high thermal transmissivity value.

Figure 2.8 shows the spectral characteristics desirable in a film plastic cladding material in the situations discussed above. The importance of having acceptable transparency in the PAR region and screening of near UV radiation is also illustrated in figure 2.8.

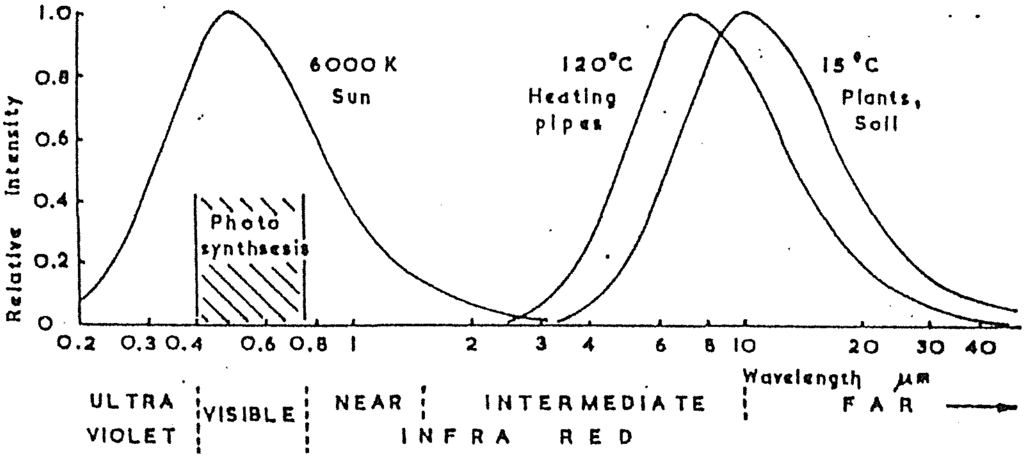


Figure 2.8 Spectral characteristics of radiation of interest in greenhouses (Bailey, unpublished report).

The amount of thermal radiation transmitted through a film covering is expressed by equations 2.16 and 2.17. It is assumed here that the cover material is opaque to thermal radiation. This is true for almost all materials, the notable exception being PE film, which has a transmissivity to thermal radiation of about 77% (Garzoli, 1985).

The amount of internal thermal radiation intercepted by the cover is given by:

$$Q_i = \sigma.\varepsilon.A_f.(T_i^4 - T_c^4) \tag{2.16}$$

where Q_i = intercepted radiation (W)

σ = Stephan Boltzmann constant (5.67×10^{-8} W/m^2.°C^4)

$$\varepsilon = \frac{1}{1 + (A_f/A_c).(1/\varepsilon_c - 1)}$$

A_f = greenhouse floor area (m^2)

A_c = cladding surface area (m^2)

T_i = temperature of the internal surfaces (°C)

T_c = temperature of the cover (°C)

ε_c = cover emissivity value

(Garzoli, 1985; Wells, 1989).

The amount of thermal radiation given up by the cover to the sky is given by:

$$Q_s = \sigma . \varepsilon_c . A_c . (T_c^4 - T_s^4) \qquad (2.17)$$

where Q_s = radiation to the sky (W)

T_s = temperature of the sky (°C)

(Garzoli, 1985; Wells, 1989).

The thermal transmissivity, emissivity, thermal conductivity, and convective heat transfer coefficient are all useful parameters for evaluating the thermal properties of a film plastic cladding material. A 'U value' may also be obtained which represents the overall transfer of convective, conductive and radiative heat through a film. For film plastics, the U value decreases greatly with a reduction of transmission of thermal radiation (Nijskens *et al.*, 1984).

Table 2.7 lists the U values for common film plastic cladding materials. PVC has a relatively low U value as it transmits very little thermal radiation (refer 2.3.3.1 Emissivity). Double cladding systems have extremely low U values because the air layer between the films acts as insulation, preventing convective heat transfer to the outside environment, and thermal radiation must pass through two films instead of only one.

Table 2.7 **Total Thermal Transmission (dependant on wind speed)**

Material	Pacini (1985)		Nijskens et al. (1984)	
	Thickness (um)	U Value ($W/m^2.^oC$)	Thickness (um)	U Value ($W/m^2.^oC$)
Single layer				
PE	200	13.4	100	9.0
EVA	180	10.8	100	7.8
PVC	200	9.0	100	7.6
Double cladding				
PE/PVC	-	3.4	-	-

The rate of heat loss is also governed by the outside air temperature, degree of cloudiness and the wind speed. Both Garzoli (1985) and Halleux *et al*. (1985) reported that the rate of heat loss increases with decreasing outside air temperature and a decreasing degree of cloudiness. Garzoli (1985), however, concluded that the rate of heat loss increases with increasing wind speed whilst Halleux *et al*. (1985) expanded this idea, suggesting radiative heat losses are decreased and convective losses are increased with increasing wind speed when the total heat flow remains constant. The Mediterranean countries, parts of North and Central America, Asia, Australia and New Zealand all have climates bringing about much calmer and clearer nights than those experienced in Europe. This means that thermal radiation, rather than convection, accounts for a large proportion of night time heat losses from greenhouses in the former group of countries (Garzoli, 1985).

Condensation also has a marked affect on the rate of heat loss through a film plastic cladding material.

2.3.4 Condensation

Condensation formation on a greenhouse film plastic cladding material will result in a reduction of heat energy losses from the greenhouse space, as the condensed water is opaque to thermal radiation (refer 2.2.6 Condensation). Dry PE film, in particular, has a high thermal transmissivity, providing the opportunity for much radiant heat loss from within the greenhouse via direct transmission. With dry PE film a direct radiative heat exchange takes place between the internal greenhouse bodies and the external surroundings, as well as the radiative and convective exchanges and the conductive transfer (Figure 2.9). When condensation is formed, the direct radiative flux disappears and a latent heat flux is added to the inner side (Nijskens *et al.*, 1985). The latent heat flux is in fact the latent heat of condensation. This creates a change in the film surface temperature and, consequently, a change in the flow of heat by both radiation and convection.

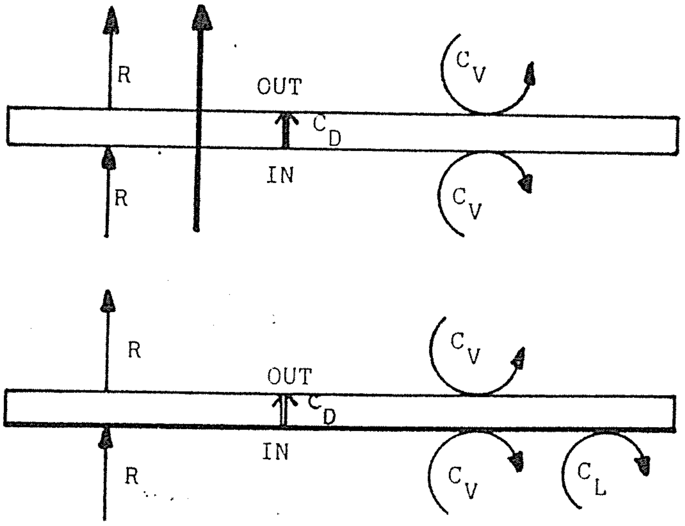


Figure 2.9 Radiative (R), convective (C_V), conductive (C_D) and latent heat flux (C_L) for dry (top) and wet (below) PE film (Nijskens *et al.*, 1985).

The increased losses due to the latent heat flux are more than made up by the removal of the radiative flux. Nijskens *et al.* (1985) reported that the U value improved from 10.2 $W/m^2.°C$ to 8.1 $W/m^2.°C$ when condensation formed on PE film. Halleux *et al.* (1985) suggested that the decrease in the U value can be largely attributed to the difference in the thermal radiation transmission between the dry and the wet film.

As EVA film is predominantly made up of PE (approximately 90%) the effects of condensation build-up on EVA, whether it be drop-wise or in a thin film layer, can be expected to be similar to those on PE film.

The rate of heat loss through film with condensate formed on its surface is also dependant on the outside air temperature, degree of cloudiness, and wind speed. The presence of condensation on PE film is generally favourable with regard to the heat balance if the weather is not cloudy with an outside temperature of 0°C and when the wind speed is in excess of 5 m/s (Halleux *et al.*, 1985).

It is important to realise that although condensate on a greenhouse film plastic cladding material reduces heat loss and perhaps increases diffuse solar transmission, a reduction in the quantity of PAR transmitted is inevitable (refer 2.2.6 Condensation). The latter may be more important, in terms of return, to the grower.

2.3.5 Double Cladding

With all things being equal, a greenhouse clad with two layers (or multiple layers) of film plastic will retain heat much more affectively than a greenhouse clad with a single layer (Allen, 1975; Sherry and Goldsberry, 1978; Tzeklev *et al.*, 1984; Mognani, 1987). A heat loss reduction of at least 20% is not uncommon when greenhouses are clad with two layers of most film plastic materials. Sherry and Goldsberry (1978) reported a fuel saving of 28% when a single layer cladding system was replaced with a double layer of PE. The degree of heat loss is largely dependant on the type of film plastics used and, to a lesser extent, on the external environmental conditions. A film plastic's polymeric composition, thickness and light transmission characteristics are all important (Mognani, 1987).

Tzeklev *et al.* (1984) suggested that the most promising feature of multi-layer cladding systems was their stabilization effect on the thermal conditions inside the greenhouse (via insulation), as regards to both extreme cold and excess of heat. The stabilized state is obtained through a buffering action where there is a reduction of solar energy admitted into the greenhouse (refer 2.2.7 Double Cladding) during the day and less heat loss during the night. Soil temperatures may also be increased by the use of multi-layer cladding systems. This may improve earlier plant growth when combined with higher air temperatures (Tzeklev *et al.*, 1984).

Film plastic materials are much lighter than rigid materials. Even multi-layers of film plastic can be supported by a much less massive structure than is required for one layer of rigid cladding. Using a double layer film plastic instead of a glass cladding system, for heat loss reduction, should result in lower costs and less PAR transmission losses, as there is a low bulk of structural componentry.

Although reports justify the value of a double cladding system with regards to heat retention, the choice of cladding system should not be made only on this basis. Factors such as the requirement for heat loss during light periods, crop responses, durability, and the adverse effect on PAR transmission, all determine the overall potential of a double cladding system.

2.4 Mechanical Properties of Film Plastics

The failing of many of the modern film plastic cladding materials is due to their poor resistance to weathering (Duncan and Walker, 1975). The relatively short life expectancy of PE film (Table 2.3) is a notable example (Duncan and Walker, 1975; Hare *et al.*, 1984). Consequently, growers often conclude that producing crops under film plastics involves a risk of greater proportion than that associated with production under rigid materials. This reasoning is based on:

1. The inflammable nature of many film plastic products.

2. Expected mechanical damage of film plastics which may place the entire crop under high risk during very windy, or wet, conditions.

3. Reports of decreased performance, following material degradation and aging, with respect to light transmission and heat retention.

2.4.1 Inflammability

When considering the possibility of fire damage to a greenhouse,a grower should first differentiate between the "cause" and the "spreading" of the fire. The inflammability characteristic of a material is generally only relevant for the latter.

Secondly, it is important that the grower distinguishes highly, normal and hardly inflammable materials. Most plastic formulations, both rigid and film, used for cladding purposes are normally inflammable (Bruns, 1985). Often raw materials are considered hardly inflammable. Since the final formulation has gained additives and has aged, it is considered normally inflammable. Several of the rigid fibreglass plastics have a highly inflammable characteristic. The addition of flame retardant ingredients to the plastic formulation is possible, but this may impair weathering performance.

Although aluminium and steel framework is not flammable, it may be effectively destroyed owing to twisting and buckling induced by the heat of a fire.

Insurance premiums can be expected to be higher on greater risk structures (e.g. timber frame structures) than for those clad with glass and/or supported with aluminium or steel. Often insurance coverage for plastic clad greenhouses cannot be obtained.

2.4.2 Mechanical Damage

The degree of protection of persons, the crop and equipment offered by the greenhouse cladding varies from product to product. The physical characteristics of a film plastic cladding material are of most relevance in determining its limitations of resistance to mechanical damage.

The extent of wind damage to the cladding, under standard environmental conditions, is generally determined by the design and strength of the supporting structure (and ventilation system), rather than solely on the performance of the cladding material itself (Orliac, 1981; Bruns, 1985). The possibility of storm damage is, however, increased with increasing cladding sheet sizes and at those points where suction forces occur. The use of twin skinned structures (double cladding) prevents contact between the outer skin and the structure, as the outer skin is supported by an air layer. The air pressure between the two films keeps the outer layer taught so that wear and damage to the inner layer, due to wind, is largely prevented.

The elasticity of films is influenced by the temperature, humidity and the creep of the material. The creep characteristic describes the stretch which occurs when a constant tension works on the film over an extended time (Waaijenburg, 1985). Impact strength, tear resistance and tensile strength also describe mechanical properties of the film.

Impact strength is usually presented as the impact resistance (energy to rupture) of a film plastic test specimen. The impact resistance property determines the capability of the film plastic material to withstand hail or stone damage. The hail resistance of film plastic cladding materials depends not only on the raw materials used, but also on the film thickness, finish, age and on the environmental temperature (Bruns, 1985). For film plastic materials there is a distinct visible difference between the appearance of the first damage due to hail and that of successive damages. For rigid materials this is not the case. This is significant, as even if there is only a few unrepairable hits, large film plastic sheets still have to be totally replaced (Bruns, 1985). The economic losses due to hail damage of film plastics are more serious than that of glass because of the larger size of the single sheet requiring replacement, following damage.

Tear resistance is another important mechanical property. Most tear damage to film plastics from snow or ice pressure occurs in combination with damage to greenhouse framework. Plastics often fail at fixing centres where inadequate fastening elements or sharp edged supports are present.

Tensile properties of film plastics are of interest to the industry because films used as greenhouse claddings are subject to tensile loads. Extreme loads arise when the films are tensioned during installation and when wind pressure and precipitation (rain and snow) loadings are great. The following tensile properties of film plastics are usually considered important:

Maximum Tensile Strength: The maximum tensile load per unit area sustained by a specimen during a tension test. It is calculated by dividing the maximum load by the original cross-sectional area of the specimen.

Tensile Strength at Break: Calculated in the same way as the maximum tensile strength except that the load at break is used in place of the maximum load. In many cases the tensile strength and the tensile load at break are identical.

Tensile Strength at Yield: The yield point is defined as the first point on the stress-strain curve at which an increase in strain does not result in an increase in stress (Figure 2.10). Where applicable, it is calculated by dividing the load at yield point by the original cross-sectional area of the specimen.

Percentage Elongation at Break: The percentage elongation at the moment of rupture of the test specimen. It is calculated by dividing the elongation at break by the initial gauge length of the specimen and multiplying by 100.

Elastic Limit: The greatest stress which a material is capable of sustaining without any permanent strain remaining upon completed release of the stress.

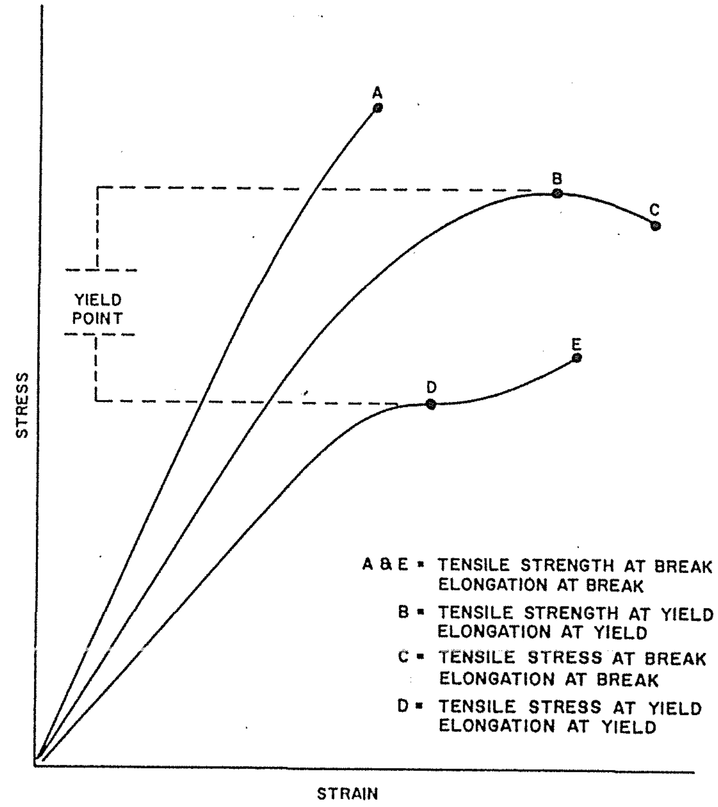


Figure 2.10 Tensile designations (ASTM, 1984).

Woven film plastic materials are manufactured in such a way as to provide excellent mechanical strength (especially tensile) in-situ.

2.4.2.1 Tests

Tests are continually being conducted by those interested in the performance of film plastic cladding materials. Photo and thermodegradation may greatly affect the overall kinetics of film aging and the subsequent loss of mechanical strength. For accelerated aging tests, correct predictions of weathering resistance can only be made when the dependence of the degradation rate on such factors as the light intensity and temperature are known (Scott, 1980).

Those long range tests carried out under natural outdoor weathering conditions provide the most accurate information, as opposed to accelerated weathering tests.

2.4.3 Degradation

Higher than normal temperatures can cause rapid excessive yellowing and breakdown of most plastic materials when combined with UV light (McLean, 1982). Thermodegradation is often augmented when growers close their greenhouses for extended periods while they are not in use.

'Hotspots' are also generated in the film where it is in contact with the supporting structure. Solar energy tends to heat up the structure which in turn raises the temperature of the film in contact with it. The hot film will weather more quickly, for any given quantity of UV light, than film at air temperature (McLean, 1982). Although this action does not affect light transmission (refer 2.2.4 Cladding Aging and Degradation) mechanical failure is likely to occur in these areas.

There are several methods of reducing the incidence of hotspots:

1. Protection of the metal hoops by the use of felt, which insulates the cover from the hoop.

2. Covering of the hoops with a white tape so that the sun's rays are reflected and heat build-up is minimised.

3. Applying a strip of paint over the film plastic cover where it is in contact with the frame. The paint will protect the film material from UV radiation.

4. Applying protective tape on the film over the supports.

Certain pesticides are also active in accelerating the process of degradation of PE products, resulting in a reduction of their useful life by up to 50% (Barahona and Vasquez, 1985).

Photodegradation and the presence of dust and dirt will also cause mechanical weakening of many film plastics.

2.4.4 Water Vapour Permeability

The internal greenhouse environment, to which the crop is exposed, can be modified by gas and water vapour exchange with the outside atmosphere. Relative humidity changes within the greenhouse atmosphere can affect plant growth and disease spread (refer 2.2.7 Double Cladding). The energy 'locked up' in water vapour can also significantly affect and alter the greenhouse thermal condition. The degree of exchange depends on the integrity of the cladding system (including its seals and closures) and on the permeability of the film plastic cladding material itself. Under steady state conditions, a gas or vapour will diffuse through a polymer film at a constant rate if a constant pressure difference is maintained across the film. There are two processes by which gases and vapours may pass through polymeric film materials:

1. A pore space effect, in which the gases and vapours flow through microscopic pores, pinholes and cracks in the materials.

2. A solution-diffusion effect, in which the gases and vapours dissolve in the polymer at one surface, diffuse through the polymer by virtue of a concentration gradient, and evaporate at the other surface of the polymer (Robertson, unpublished report).

The barrier properties of a film plastic depend on the specific molecular structure of the polymer involved. A structure that provides a good barrier to gases may provide a poor water vapour barrier. Although the sorption of ambient vapours or liquids may result in a decrease in mechanical properties (Robertson, unpublished report), the transmission of water through film plastic materials is also of importance to the grower.

From test results the following properties can be calculated:

Water Vapour Transmission Rate (WVT) - the steady water vapour flow in unit time through unit area of the film, normal to specific parallel surfaces, under specific conditions of temperature and humidity at each surface.

Water Vapour Permeance (WVP) - the time rate of water vapour transmission through unit area of flat film material induced by unit vapour pressure difference between two specific surfaces, under specified temperature and humidity conditions. WVP is a performance evaluation rather than a property of the material.

2.5 Film Plastic Cladding Materials Available

A cladding material should offer the following optical and mechanical characteristics to be successful in most greenhouse culture situations:

1. Transparency in the PAR region (380nm to 780nm wavelength band) to promote a high level of photosynthetic activity.

2. Screening of the near UV (wavelengths smaller than 380nm) as photosynthesis is inhibited by UV radiation (Tesi *et al.*, 1986).

3. Transparency to the near IR (700nm to 2500nm wavelength band) to ensure sufficient heating of the greenhouse by solar radiation.

4. Screening of long-wave IR (wavelengths greater than 2500nm) so heat is held within the greenhouse space.

5. Good mechanical strength to withstand both hail and wind.

6. Complete resistance to corrosion and rot.

7. Non-flammable.

8. Good retention of all properties described above.

Advantages gained by the implementation of any specific film plastic cladding material should be weighed up against its capital cost and ease of installation.

It is very difficult to compare film plastics with rigid cladding materials as capital costs and life expectancies are very different. Table 2.8 offers a very general comparison summary of those cladding material categories used for greenhouses.

Table 2.8 A General Comparison Between the Various Types of Cladding Materials

Catagory	Initial Costs	Long Term Costs	Energy Costs	Lifetime
Glass	high	high	high	high
Rigid plastics	medium to high	medium	medium	medium
Film plastics	low	low	low	low

Adapted from Breuer (1985).

The properties of the many film plastic materials available, and their costs and life expectancies, can be successfully compared. The common film plastic cladding materials available today are:

1. Polyethylene.

2. Infra-red Polyethylene.

3. Thermal Polyethylene.

4. Ethylene Vinyl Acetate.

5. Polyvinyl Fluoride.

6. Polyvinyl Chloride.

7. Polyester.

8. Co-extruded Films.

2.5.1 Polyethylene

Polyethylene (PE) is manufactured by mixing homopolymers of ethylene with or without a UV stabilizer package (refer 2.2.4.1 Ultra-violet Stabilizers) (MAF, 1981). There are two types of PE: linear and radicular. The latter is obtained through high pressure and high temperature polymerization where extrusion takes place and pressurised air is forced into the PE resin (Nijskens *et al*., 1988). Linear PE requires lower pressures and temperatures for its manufacture. Linear PE has a greater mechanical strength than radicular PE and so can be manufactured in thinner sheets. All PE films are, however, subject to irreversible elongation (stretching - especially above ambient temperatures) and are, therefore, difficult to produce in large widths.

PE film is considered tough, flexible and is relatively inexpensive. Standard PE has a short life in the sun: 9 to 11 months (Duncan and Walker, 1975), and will split easily if creased. PE transmits approximately 85% to 90% of the total solar energy available at the earth's surface (MAF, 1976; Fuller and Cooper, 1983) and has a high transmission in the PAR region of the solar spectrum. PE, however, also readily transmits thermal radiation (up to 80% depending on film thickness) which means a PE clad greenhouse will cool rapidly at night.

Single layered PE clad systems tend to have condensation problems (refer 2.3.4 Condensation) which result in reduced heat loss at the expense of transmitted PAR into the greenhouse. The thickness of the PE film has a large affect on the degree of thermal transmission and subsequent heat loss. Figure 2.11 shows a 10% decrease in film transmissivity for every 0.10 mm increase in thickness. Most film plastic materials are manufactured in thicknesses ranging between 100μm and 250μm.

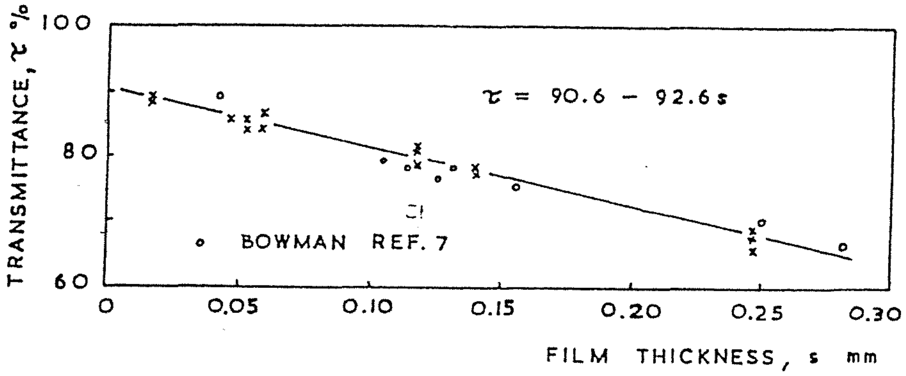


Figure 2.11 Transmission of infra-red radiation by PE film (Bailey, unpublished report).

Double cladding systems, utilizing PE film, may reduce heat loss and prevent condensation build-up. Unfortunately, PAR transmission can be expected to be adversely affected.

2.5.2 Infra-red Polyethylene

Infra-red polyethylene (IRPE) films are manufactured by enriching a standard PE resin with either magnesium silicate or aluminium silicate (Nijskens *et al.*, 1988). These silicates are referred to as mineral fillers and render the PE film more opaque to thermal radiation. Bailey (unpublished report) reported that IRPE films transmit 35% less thermal radiation than standard PE films of the same thickness, and Roberts *et al.* (1985) reported that PAR transmission into the greenhouse is hardly affected when standard PE film is replaced by the IRPE type.

If the dose of mineral filler added to the film is too high there may be film deterioration problems, as aluminium silicate impurities cause film destruction (Nijskens *et al.*, 1988).

2.5.3 Thermal Polyethylene

Thermal polyethylene (PETh) films are manufactured from a low density PE resin enriched with both VA and mineral fillers (Nijskens *et al.*, 1988). The added dose of each of these substances is deemed optimal by the manufacturer. The PETh film plastics are also known as infra-red EVA (IREVA) films.

The PETh films differ widely from the PE and EVA in that their transmissivity of thermal radiation is much less. Consequently, PETh film utilization can be expected to cut fuel costs for night heating. Such films also appear promising, as they offer sufficient durability.

2.5.4 Ethylene Vinyl Acetate

Ethylene vinyl acetate (EVA) films are manufactured by enriching PE resin with vinyl acetate (VA). Bailey (unpublished report) states that the addition of 4% VA renders PE film more opaque to thermal radiation, without measurably altering the quantity of PAR transmitted. The overall thermal transmission (U value) is greatly reduced by the addition of VA to PE resin (Table 2.7). According to Allen (1975) EVA copolymers containing 12% to 16% VA have heat retention properties close to that of PVC. Films with such high concentrations of VA are, however, usually mechanically weak.

Dartiguepeyrou (1986) reported that increased levels of VA in a film result in improved:

1. Tensile strength, elongation at break (Figure 2.12).

2. Impact strength (Figure 2.13).

3. Flexibility and elasticity.

4. Transparency (Figure 2.14).

5. Resistance to splitting.

6. Aging characteristics.

7. Compatibility with mineral fillers.

8. Permeability to oxygen, carbon dioxide and water vapour.

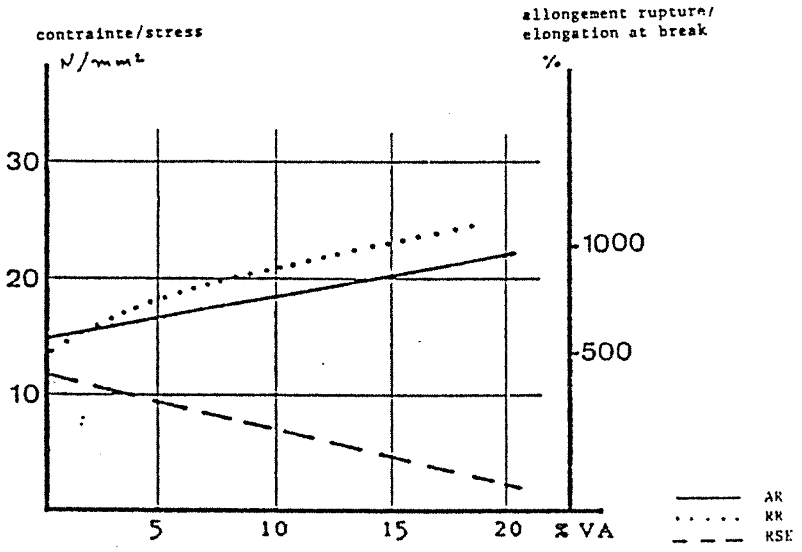


Figure 2.12 Influence of % VA content on the tensile strength property of EVA film plastic (Dartiguepeyrou, 1986).

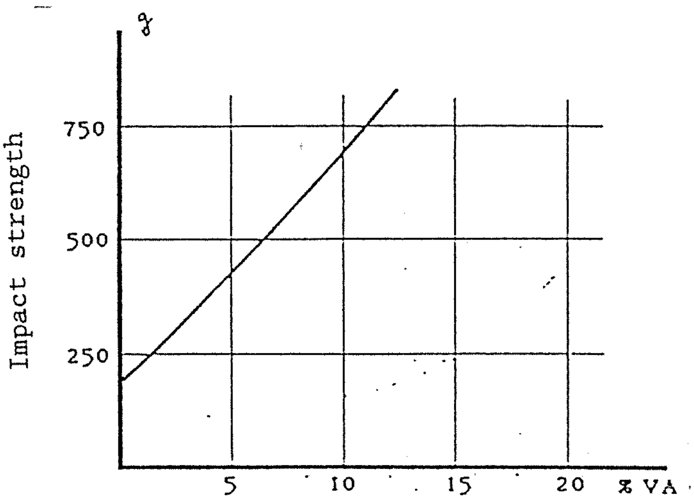


Figure 2.13 Influence of % VA content on the impact strength property of EVA film plastic (Dartiguepeyrou, 1986).

Improved transparency is synonymous with a lesser tendency for the film to diffuse light. Figure 2.14 illustrates the decrease in the diffusing characteristic (% haze) that can be expected when there is an increase in the VA content of PE film. Diffusion of light is generally considered beneficial (refer 2.2.1.1 Direct and Diffuse Light) and so the improved transparency with increasing VA content, reported by Dartiguepeyrou (1986), may not be advantageous.

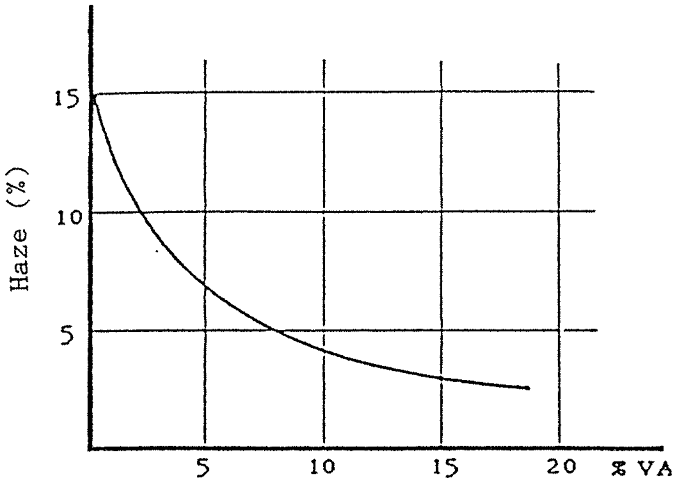


Figure 2.14 Influence of % VA content on the light diffusion property (% haze) of EVA film plastic (Dartiguepeyrou, 1986).

Dartiguepeyrou (1986) also reported a reduction in the following film characteristics with increasing VA content:

1. Rigidity.

2. Hardness.

3. Yield strength.

4. Fusion temperature and softening point.

5. Resistance to stretch.

A VA content of greater than 15% should be avoided as higher doses of VA render the film more attractive to dust. Dust build-up will decrease the film transparency to PAR over time. Generally EVA films contain approximately 10% VA. Such a mix will transmit up to 90% PAR and approximately 40% thermal radiation (McNaughton et al, 1981).

2.5.5 Polyvinyl Fluoride

Polyvinyl fluoride (PVF) films weather extremely well and have excellent optical properties: up to 92% PAR transmission (Hare *et al.*, 1984), and 43% thermal radiation transmission (MAF, 1981). PVF is most actively marketed under the trade name "Tedlar PVF". Waaijenburg (1985) carried out research and experimentation on the "Tedlar PVF" type film and reported it to have the following properties:

1. Sufficient impact strength.

2. At lower temperatures the tear resistance is decreased.

3. The film has an open structure with respect to vapour transfer.

4. There is a negligible decrease in the tensile strength following artificial aging.

5. There is a negligible decrease in the transmission of perpendicular light following artificial aging.

Waaijenburg (1985) used an artificial aging process which corresponded to three years exposure to Dutch outdoor conditions.

Although the mechanical properties discussed above are actively sought in a greenhouse film plastic cladding material, PVF films are not popular with growers. This is because PVF films cannot be produced in large widths and they are very expensive (MAF, 1981). The problem of small widths is particularly relevant when cladding tunnel houses, as PVF films cannot be welded together.

"Tedlar PVF" is usually used as a surface coating for FRP panels. Excellent surface protection is offered to the FRP panelling, as "Tedlar PVF" has exceptional resistance to the known effects of climate and contaminated atmospheres.

2.5.6 Polyvinyl Chloride

There are two types of polyvinyl chloride (PVC) film: those reinforced and those not reinforced. The mechanical properties are also dependant on the plasticizer used (Nijskens *et al.*, 1988). PVC films are more resistant to weathering than are PE films (MAF, 1981) and UV stabilized forms are more resistant to sunlight (MAF, 1976). Condensation problems are uncommon with PVC film plastics.

PVC film plastics generally allow good transmission of PAR. McNaughton *et al.* (1981) reported PVC film plastic samples of 300μm and 400μm thickness as having a transmissivity to direct PAR of 90% and 89% respectively. PAR transmissivity of diffuse light may range between 74% and 84% (Landgren, 1985). Lower PAR transmission is possible in some formulations. PVC has a greater tendency to diffuse incident radiation than PE film plastics (Tzeklev *et al.*, 1984).

Several authors (Bailey, unpublished report; Horiguchi *et al.*, 1982; Nijskens *et al.*, 1984) have reported that PVC film transmits far less thermal radiation than the PE or EVA films. The transmissivity of thermal radiation can be expected to be less than 33% for most PVC film plastic cladding materials available. Furthermore, the total thermal transmission (U value) was reported by both Nijskens *et al.* (1984) and Pacini (1985) to be substantially less through PVC film than through either PE or EVA (Table 2.7). The comparatively low thermal transmissivity and U value mean greenhouses clad with PVC film plastics will not lose heat as rapidly as those clad with PE type films.

For the reasons discussed above, PVC film plastics are used widely in Japan for cladding greenhouses and tunnel houses. They are far less favoured by European growers because they have a higher relative cost than both PE and EVA films. Furthermore, there is a necessity to weld PVC sheets together as the film is only manufactured in narrow widths. Heat sealing, to provide wider spans, is costly and not very reliable for greenhouse glazing purposes (MAF, 1981). In addition, the electrostatic charge usually associated with vinyls causes dust particles to adhere to the film, resulting in a reduction in light transmission.

2.5.7 Polyester

A typical polyester (PEST) film (or tetephtalate of PE) will have good solar transmission characteristics with PAR transmissivity of up to 95% for a film thickness of 80μm (Hare *et al.*, 1984; Gemmel, 1986).

PEST films can be expected to retain much heat within the greenhouse interior. Horiguchi *et al.* (1982) reported that 100μm PEST film transmits only 12% of incident thermal radiation. Sturrock (1981) described a double cladding system, utilizing two layers of PEST film, which can prevent substantial heat loss. At night the layers are separated by air, low in pressure, which reduces heat loss. During the day a slight suction is applied drawing the inner film surfaces together so that they act, optically, almost as one layer. High fuel savings can be gained by using such a double PEST cladding system, although PAR transmission may be reduced as condensation is likely to form on the inner PEST layer (Sturrock, 1981).

PEST films are very strong and may last up to 15 years (MAF, 1981; Sturrock, 1981). According to Landgren (1985) the tensile strength of PEST films is good but the tearing properties are poor. A PEST film may be most useful as a permanent internal second layer inside a rigid plastic clad greenhouse. In such a situation a PEST film's excellent aging properties would be of great benefit while its poor tear resistance would have little consequence (Landgren, 1985).

PEST films may also contain UV stabilizers which enhance their resistance to weathering. Gemmel (1986) described the UV stabilized PEST film "Melinex" as having the following properties:

1. Transmits 95% of PAR incident on its surface.

2. Transmits 93% of the whole solar spectrum.

3. Retains 33% of all thermal radiation falling on its surface.

4. Is a tough and durable film.

5. Will not yield or plastically deform over a temperature range of -50°C to 150°C.

6. Can be cleaned very easily with a weak emulsion in water, but cannot be scrubbed.

7. Is not hydrophobic so a continuous film of water is formed on its surface. Therefore, light transmission is virtually unaffected by condensation.

PEST films are very expensive (MAF, 1981) and can only be manufactured in very small widths. Consequently, PEST film plastics are not very popular at the present time. Polyester, however, is occasionally used for reinforcing other film plastic materials.

2.5.8 Co-extruded Films

These film plastics are manufactured by simultaneously co-extruding raw materials into several parallel layers which, when fused together, are impossible to separate. Co-extruded films usually consist of 2 to 5 layers of different materials. This technology enables selected resins, containing particular properties, to be used in specific layers when producing a purpose designed film (Agpac Plastics Ltd., 1989). Special additives such as UV stabilizers and anti-fog compounds, can also be incorporated into the film. Incorporating additives into those layers of the film where they are most affective will result in maximum benefit.

Data and information on the optical, thermal and mechanical properties of co-extruded films is scarce. Independent reports focusing on these properties are virtually non-existent.

CHAPTER THREE

OBJECTIVES OF THE STUDY

3.1 Objectives

The preceding review of the literature pertaining to the optical, thermal and mechanical properties of film plastic cladding materials revealed a wealth of information. Unfortunately, the bulk of the overseas data was not relevant to film plastics available in New Zealand.

The interest in film plastics, as a viable cladding option for growers, is increasing in this country. The number of products commercially available has increased to match this interest. Consequently, it was decided to conduct research into film plastic cladding materials available in New Zealand with the following objectives:

1. To evaluate the optical properties of each film plastic.
2. To evaluate the thermal properties of each film plastic.
3. To evaluate the mechanical properties of each film plastic.
4. To evaluate and compare each product as a full functional cladding material and rank the films, on a generic basis, accordingly.

3.2 Scope of the Study

This study was limited to laboratory scale experiments to test the performance of the film plastic cladding materials. The film plastic samples tested were obtained directly from the manufacturer or retailer. Consequently, the film plastics were not subject to New Zealand environmental conditions prior to testing and long range weathering tests were not carried out.

Since samples volunteered by distributors of each product were used to conduct the tests, the particular materials tested were selected on the basis of their commercial availability in New Zealand.

CHAPTER FOUR

METHOD AND MATERIALS

4.1 Film Plastic Cladding Materials Under Study

The optical, thermal and mechanical performance of thirteen different film plastic cladding materials (some of varying thicknesses) were evaluated by the methods described below. The film materials were divided into the four following groups based on the materials base resin:

1. Polyethylene.

2. Ethylene Vinyl Acetate.

3. Polyvinyl Chloride.

4. Co-extruded Film.

4.1.1 Polyethylene

One standard polyethylene (PE) film of 125μm thickness was obtained for the tests from a local garden centre. The film came with no warranty and contained no ultra-violet (UV) stabilizing or infra-red (IR) absorbing additives.

One infra-red PE (IRPE) 80μm film was made available for testing. This film had an IR absorbing system and was reported to diffuse light. The IRPE film had no warranty.

Two woven PE films (150μm and 200μm) were made available for testing. Both films were UV stabilized with a hindered amine light stabilizer (HALS) type additive incorporated into a film coating. Only the 200um film, however, had a UV resistant coating on both sides, and was available with a 24 month warrantee.

4.1.2 Ethylene Vinyl Acetate

Four normal ethylene vinyl acetate (EVA) films were available for testing . These were designated normal EVA film 1, 2, 3 and 4. Film 1 was made available in 150μm and 200μm thicknesses. The latter of these had a 33 month warranty. Neither were UV stabilized. Film 2 (150μm) had an expected life of 36 months but came with no warrantee. It was UV stabilized and also had slip additives incorporated into the films surface structure. Film 3 (180μm) had a 36 month warrantee but was not UV stabilized. Film 4 was made available for testing in 125μm, 150μm and 200μm thicknesses. The films had 18, 24 and 36 month warranties, respectively. All three contained anti-dust and anti-fog additives and were UV stabilized.

An infra-red EVA (IREVA) film was made available for testing. This 150μm film had an IR absorption system, a UV stabilizer and came with no warranty, but had an expected life of 36 months (according to the manufacturer).

An EVA film reinforced with woven polyester strands was obtained for testing. The reinforcing was in the form of a mesh held between the sides of two film layers. The EVA film was UV stabilized and was 250μm thick. The reinforced EVA film had a 36 month warranty.

4.1.3 Polyvinyl Chloride

The only PVC film to be tested was available at 400μm thickness and was UV stabilized. This film had a 6 year warranty.

4.1.4 Co-extruded Film

Both double layer and triple layer co-extruded films were obtained for testing. The double layer film was made available in 125μm and 200μm thicknesses. Both layers had UV stabilizing compounds whilst the outer layer also contained an anti-dust additive and the inner an anti-fog additive. The base resin for both layers was EVA. Commercially, the double layer material was available as a 125μm, 150μm or 200μm film with 12, 24 and 36 month warranties, respectively.

The triple layer 150μm co-extruded film had an IR absorption system in the middle layer, an anti-dust additive in the outer layer and an anti-fog additive in the inner. All layers were UV stabilized.

4.2 Test Conditions

The inherent properties of film plastics are influenced by temperature and relative humidity (RH) in a manner that materially affects test results. In order that reliable comparisons may be made between different materials and between different laboratories, it is necessary to standardize the temperature and humidity conditions to which the specimens are subject prior to, and during, testing.

For the light transmission, initial tear resistance, tensile properties and impact resistance tests the respective ASTM standards demanded reference to the relevant sections of ASTM D 618 (1981) and ASTM E 171 (1987). The samples were subjected to the conditioning environment and testing environment described in these.

Consequently, the test specimens were conditioned at 23 ± 2°C and 50 ± 5% RH for not less than 40 hours prior to testing. The tests were then conducted in the standard laboratory atmosphere of 23 ± 2°C and 50 ± 5% RH.

4.3 Light Transmission

This test covered the measurement of the light transmitting properties, and from these, the light scattering properties, of each of the film plastic cladding materials.

This test also included the measurement of UV radiation transmitting properties. UV transmission gives an indication of the films susceptibility to photodegradation, as high UV transmission suggests a film has no UV absorption properties. (The results of the UV transmission measurement are limiting, as films containing UV quencher type stabilizers allow UV light to pass through the film and so the stabilizer presence is not detected).

The test was carried out by technical staff at the D.S.I.R. Industrial Development Division (Christchurch) according to the method outlined in ASTM D 1003 (1977).

The following standards were also referred to:

1. ASTM E 179 "Selection of Geometric Conditions for Measurement of Reflectance and Transmittance".
2. ASTM E 284 "Standard Definitions of Terms Relating to Appearance of Materials".
3. ASTM E 308 "Spectrophotometry and Descriptions of Colour in CIE 1931 System".

The transmissivity factor range 770nm to 380nm was recorded on the Varian Techtron 634S UV/Vis Spectrophotometer, using the diffuse reflectance accessory. These values were taken every 10nm. The collective transmissivity factor values were multiplied by a weighting factor MA_Y, from the 1931 CIE Standard Observer (refer

ASTM E 308). The incident light (C_1), total light transmitted by specimen (C_2), light scattered by instrument (C_3), and light scattered by instrument and specimen (C_4), giving transmissivities τ_1, τ_2, τ_3, and τ_4 respectively, are used to calculate:

$$\text{Total transmissivity, } \tau = (\tau_2/\tau_1) \tag{4.1}$$

$$\text{Diffuse transmissivity, } \tau_d = \frac{\tau_4 - \tau_3.(\tau_2/\tau_1)}{\tau_1} \tag{4.2}$$

$$\text{Haze (\%)} = (\tau_d/\tau) \times 100 \tag{4.3}$$

The Saunderson correction (Equation 4.4) was used for the transmissivity determinations. The Saunderson correction is not used in ASTM D 1003 (1977). This correction was devised to take into account specular reflection and internal reflection which are not allowed for in basic transmission theory.

The Saunderson corrected transmissivity (τ') was calculated from the following equation:

$$\tau' = \frac{\tau - k_1}{1 - k_1 - k_2.(1 - \tau)} \tag{4.4}$$

where k_1 = Fresnal = 0.04

k_2 = empirical constant = 0.40

τ = measured transmissivity

The results could then be reported as the percentage solar transmissivity and PAR transmissivity of each of the film plastics. The percentage UV transmissivity and haze value could also be reported.

4.4 Thermal Transmission

This test covered the determination of thermal radiation transmission characteristics for each of the film plastic cladding materials. Each film was exposed to IR radiation (3μm to 25μm) so the average transmissivity to thermal radiation and then the heat retention properties of the film could be established.

The test was carried out by technical staff at the Auckland Institute of Technology (Faculty of Science and Engineering). A Perkin-Elmar Spectrophotometer (Type 1710 FTIR) was used, according to the standard text method, to produce the spectral transmission data.

Blackbody emission distribution spectra (refer Incropera and DeWitt, 1985) were then implemented to determine the average transmissivity (τ_{avg}), from the transmission data, over the range of wavelengths 3μm to 25μm.

Firstly, the Planck Distribution (Equation 4.5) was used to calculate the rate at which radiation was emitted per unit area from an assumed radiant source (i.e. the emissive power). The total transmitted radiation was calculated by multiplying the transmissivity value (τ) at each wavelength by the emissive power at the same wavelength, and summing over all the wavelengths 3μm to 25μm.

$$E_{\lambda,b}(\lambda,T) = \frac{C_1}{\lambda^5.[\exp(C_2/\lambda.T) - 1]}$$

where $E_{\lambda,b}(\lambda,T)$ = spectral emissive power at wavelength λ (W/m^2)

λ = wavelength of the thermal radiation (ranging between 3μm to 25μm)

C_1 = radiation constant (3.74×10^8 W.μm^4/m^2)

C_2 = radiation constant (1.44×10^4 μm.K)

T = absolute temperature of the blackbody (K)

Secondly, the total transmitted radiation, $\Sigma\ [\tau . E_{\lambda,b}(\lambda,T)]$, was divided by the total emissive power, $\Sigma\ [E_{\lambda,b}(\lambda,T)]$, of the radiation incident on the film material:

$$\tau_{avg} = \frac{\Sigma\ [\tau . E_{\lambda,b}(\lambda,T)]}{\Sigma\ [E_{\lambda,b}(\lambda,T)]}$$

where τ_{avg} = average transmissivity of thermal radiation over wavelengths $3\mu m$ to $25\mu m$

Absolute blackbody (i.e. radiant source) temperatures were set at 20°C and 80°C. The latter value represented the temperature of a radiant source heating system.

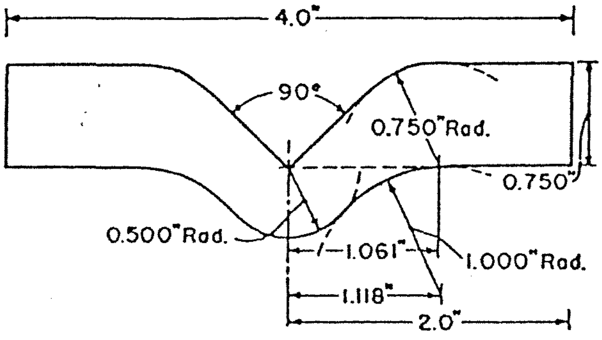
The thermal transmissivity (τ_{avg}) is reported at two radiant source temperatures 20°C and 80°C.

4.5 Initial Tear Resistance

This test covered the determination of the tear resistance of film plastics at very low rates of loading. The test was carried out according to the method outlined in the ASTM D 1004 (1988a).

ASTM D 1004 (1988a) required a minimum of 10 specimens to be tested for each sample. Two sets of 10 test specimens were tested when the sample material was suspected of being anisotropic. One set had the specimen long axes parallel to the direction of anisotropy and the other set had the specimen long axes normal to the direction of anisotropy.

The film plastic test specimens were shaped as in figure 4.1.



Tolerance ± 0.002"

Table of Metric Equivalents

in.	mm
4.0	101.60
0.750	19.05
1.061	26.95
1.000	25.40
1.118	28.40
2.0	50.80
0.002	0.051
0.500	12.70

Figure 4.1 Dimensions for the tear test specimens (ASTM, 1988a)

ASTM D 1004 (1988a) required each prepared film specimen to be tested in a power driven constant rate of grip separation type testing machine. A JJ Tensile Testing Machine (Type T30K) was found to be suitable and so was used for the tests (Plate 4.1). The gripping system used in the test was designed to minimize both slippage and uneven stress distribution on the specimen. The film plastic was held secure by tightening four alan screws on each of the grips. The grip faces were lined with 360 grade dry engineering paper (Plate 4.2).

Plate 4.1 The tensile testing machine used for the tear resistance tests

Plate 4.2 The gripping system employed for the tear resistance and tensile testing

The film specimen was placed in the grips of the testing machine. A tensile load was applied at a constant grip separation rate of 51 mm/min until the specimen was completely ruptured. The maximum tearing load was read from the recorder chart connected to the machine. This tearing load was the force to initiate tearing and could be then presented as the tear resistance (N).

4.5.1 Preparation of Apparatus

Initially, there were problems with selecting the most suitable grade engineering paper for the clamping system employed to grip the film plastics. Too finer paper tended to allow slippage whilst the coarser grades bit into the films causing small ruptures and subsequent tearing, at these points, once a load was applied. A 360 grade stearate coated dry paper was found to be the most suitable for gripping all the films, except the thicker 400μm PVC film, where 240 grade paper was required.

There were also complications in manufacturing a die, to standard specifications, with a sharp enough edge to cut the desired shape from the film plastic materials. Consequently, a template system was decided upon as a more practical means to cut the samples. A brass template was made up to conform to the dimensions presented in figure 4.1. A scalpel was used to cut around the template.

4.6 Tensile Properties

This test covered the determination of the tensile strength and the percentage elongation at break. The test was carried out according to the method outlined in the ASTM D 882 (1988b).

ASTM D 882 (1988b) required a minimum of 5 specimens to be tested for each sample. Two sets of 5 test specimens were tested where the sample material was suspected of being anisotropic. One set had the specimen long axes parallel to the direction of anisotropy and the other set had the specimen long axes normal to the direction of anisotropy.

The film plastic test specimens were rectangular in shape with dimensions 25mm × 50mm.

ASTM D 882 (1988b) Test Method A required each prepared film specimen to be tested in a power driven constant rate of grip separation type testing machine. The testing machine used was a JJ Tensile Testing Machine (Type T5000) and the gripping system described in 4.2 Initial Tear Resistance was also used in this test.

The film specimen was placed in the grips of the testing machine. A tensile load was applied at a constant grip separation rate of 500 mm/min until the specimen was completely ruptured. A load verses extension curve was plotted out on the recorder chart so the load at break, load at yield and specimen extension could be identified. This information could then be presented as the load (N), tensile strength (N/mm^2) and percentage elongation at the break point. The load was also recorded, and the tensile strength calculated, at the elastic limit.

4.6.1 Preparation of Apparatus

The testing conditions outlined in ASTM D 882 (1988b) were strictly adhered to with successful use of the available apparatus. The JJ Tensile Testing Machine (Type T5000) was able to record the load and extension for all film types except the woven PE film plastics. As the material elongation was so minimal prior to material failure, accurate extension data could not be recorded. Consequently, only the force at the break point and tensile strength is reported for the woven PE film plastics.

4.7 Impact Resistance

This test allowed the determination of the impact resistance of each of the film plastics. The test was carried out according to the method outlined in the ASTM D 1709 (1985a). Calculations were carried out according to equations presented in the ASTM D 4272 (1985b).

The film plastic test specimen dimensions, for each single determination, were 150mm × 150mm. ASTM D 1709 (1985a) required a minimum of 5 specimens from each film sample to be tested in order to obtain a reliable test result for each film material.

ASTM D 1709 (1985a) Test Method B required the prepared film plastic specimens to be subjected to the impact of a free-falling dart having a 51 mm diameter hemispherical head and dropped from a height of 1524 mm. An instrumented dart drop system was built according to the specifications illustrated in figure 4.2.

Plate 4.3 shows the dart drop system constructed and used for the impact resistance tests. The photoelectric speed trap system was encased in PVC piping to prevent contaminating light from affecting the timer (Plate 4.4).

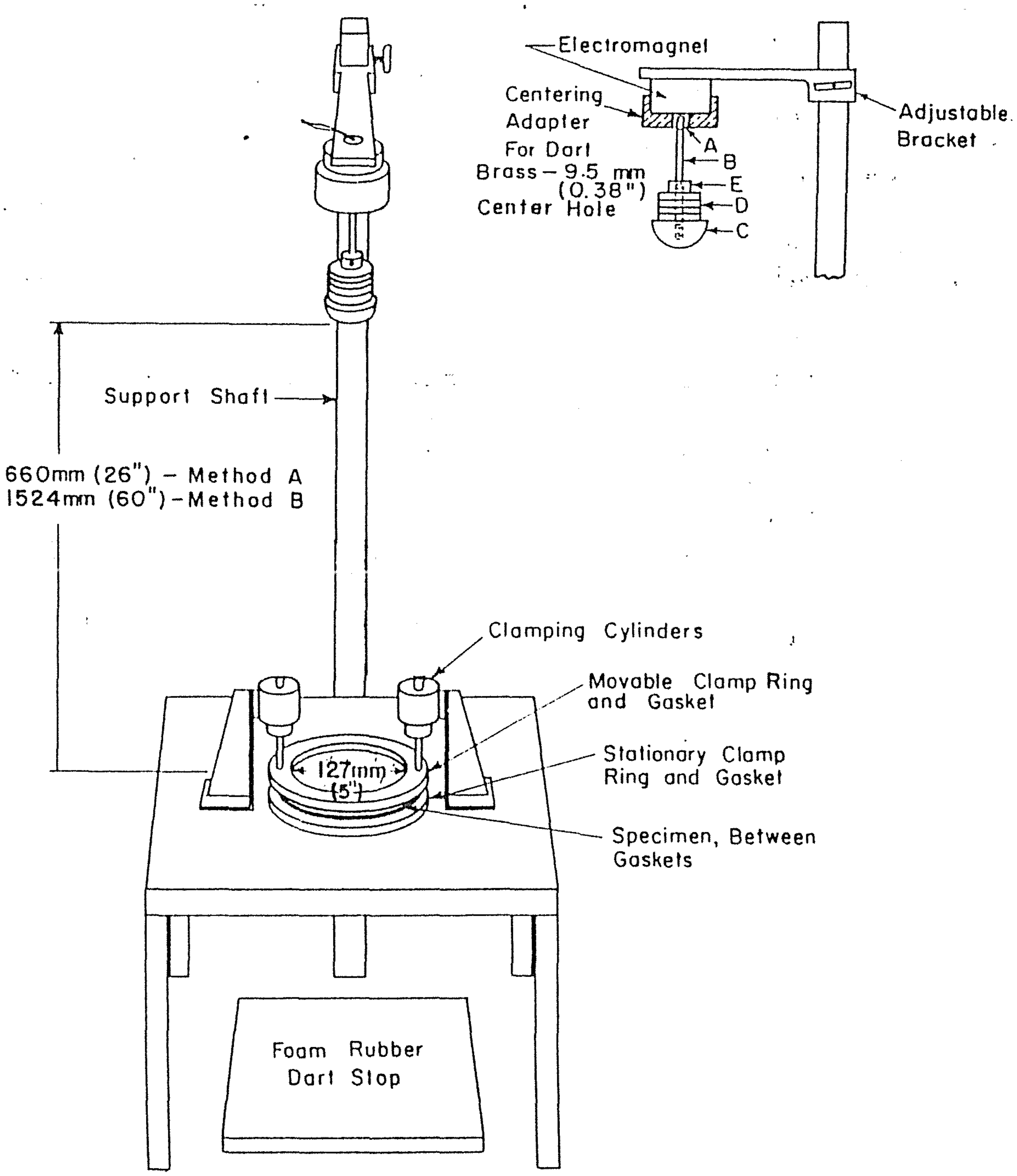


Figure 4.2 Elements of the instrumented dart drop system (ASTM, 1985a)

Plate 4.3 Dart drop system employed for the impact resistance tests

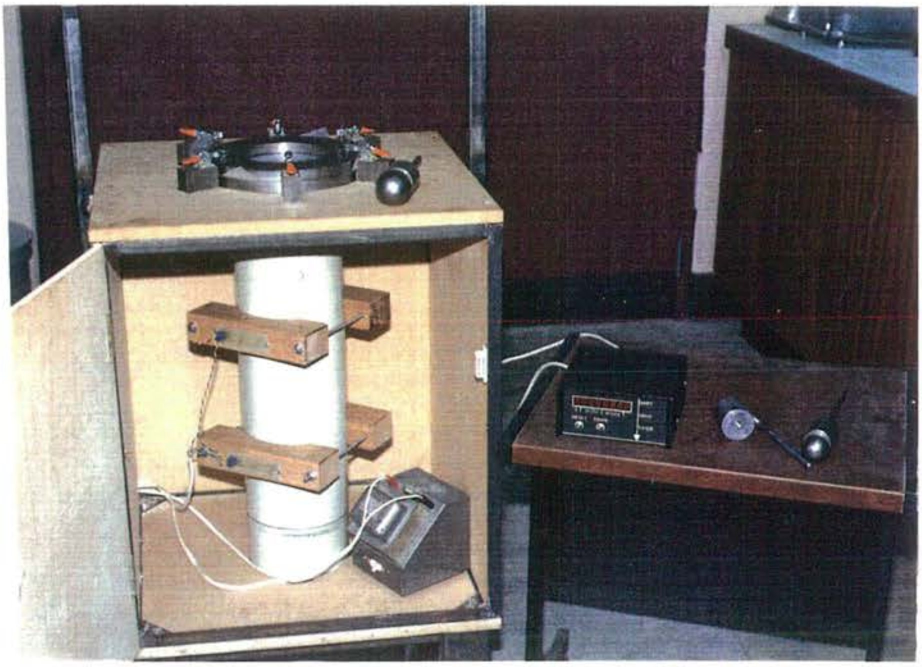


Plate 4.4 Speed trap timing system construction

Each film plastic specimen was securely held in the clamping system. The dart was released from the electromagnet by switching off the power to the electromagnetic system. The dart was then allowed to free-fall 1524 mm before it struck the film plastic sample in a direction perpendicular to the plane surface of the film. The momentum of the dart carried it through the film to the foam rubber dart stop below. The velocity of the free-falling dart that passed through the film was determined by reference to the photoelectric speed trap. The dart mass was varied according to the strength of the material being tested. The film plastics 125μm thick or less were subject to a 0.995 kg dart while those 150μm or more were subject to a 1.445 kg dart. A 2.325 kg dart was used for testing those films not ruptured by the free-fall of either of the other two darts.

ASTM D 4272 (1985b) Section 11 was referred to for calculation of the energy to rupture (J) of each test specimen. The kinetic energy corresponding to the velocity of the free-falling dart could be calculated and compared with the kinetic energy of the same dart measured without a plastic film in place. The loss in kinetic energy (i.e. the energy required to rupture) suffered by the dart that ruptured the film could then be used as an index of impact resistance.

5.5.5 Preparation of Apparatus

There was difficulty in constructing a dart drop system where the dart would free-fall with its body remaining parallel to the plane of flight, over the entire length of the drop (i.e. without rotating around the 'centre of gravity' pivot point, between the dart head and tail). The rotation problem was accentuated when the dart struck the film surface. During impact, the dart would tend to slide briefly on the film (before the film ruptured), causing it to pivot slightly and to continue to rotate as it fell through the light speed trap.

Although the same amount of energy was stored within the dart (and released from it at film impact) regardless of its orientation, the turning motion introduced a significant timing error. This was because the dart broke the 'timer on' beam (Plate 4.4) with a different point on its surface than that which broke the 'timer off' beam. In the worst cases, the dart tip would pass through the plane of the timer off beam (between the beams) and travel a considerable distance before the dart was recognised via detection of an upper part of its body.

Following many trial tests the error was found to be most successfully reduced by:

1. Increasing the number of detection beams active in both the on and off switches of the light speed trap, so that these planes were not breached without dart detection.

2. Maximising as much mass as possible within the dart head so that the centre of gravity was positioned within the dart head. The turning of the dart about its spherical head did not introduce as much a problem as the turning about the dart stem.

Prior to film sample testing, three light beams per switch were built into the speed trap system and lead metal was used to fill the spherical dart head, therefore increasing its mass.

4.8 Water Vapour Transmission

This test allowed the determination of the water vapour transmission (WVT) and water vapour permeance (WVP) of each of the film plastics. The test was carried out according to the method outlined in Section 11 of the ASTM E 96 (1990).

ASTM E 96 (1990) required a minimum of 3 specimens from each film sample to be tested in order to obtain a reliable test result for each film material.

Test dishes were filled with granulated calcium chloride desiccant to a level slightly below their brim. A circular template was used to cut the test pieces from the materials under investigation. Each test piece was placed in a dish so that the edge of the specimen projected halfway over the annular recess of the dish. A second template was placed centrally in the dish and a molten mixture of 90% microcrystalline wax and 10% plasticiser was run into the annular recess of the dish. The wax was allowed to harden prior to removal of the template. The sealing prevented the passage of vapour into and out of the specimen edges. Each specimen was attached to a dish by sealing in such a way that the dish mouth defined an area of 5 × 10^{-3} m^2 of specimen material exposed to the vapour pressure in the dish (Figure 4.3).

Each dish assembly was weighed on an analytical balance to 0.0001g. They were then placed on a rack system in desiccators containing a saturated sodium chloride solution which generated a 75% RH atmosphere. The desiccators were stored in a room having a temperature of 20°C. Each dish assembly was then weighed periodically.

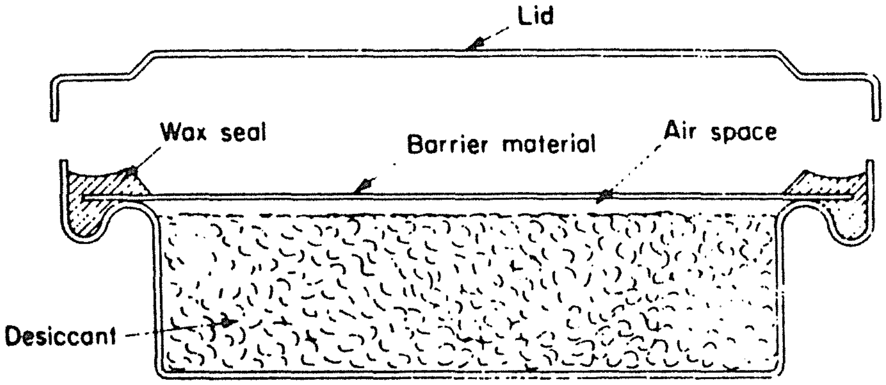


Figure 4.3 Dish assembly for WVT tests (Massey University, 1989)

The temperature sustained during the test was 20 ± 2°C and the RH was 75 ± 2% . Air was continuously circulated throughout the chamber according to the specifications outlined in ASTM E 96 (1990).

The weighing of the dish assembly allowed determination of the rate of water vapour movement through the specimen from the controlled atmosphere to the desiccant. The WVT (g/m^2.day) and the WVP (g/m^2.day.Pa) could be calculated from this data.

4.9 Standard Costings

Distributors of each of the film plastic cladding material types were approached and asked to submit the cost of each of their products to a commercial grower. The costings could then be compared on a '\$ per m^2 of film material' basis.

CHAPTER FIVE

RESULTS AND DISCUSSION

5.1 Light Transmission

This test allowed the determination of the solar, PAR, UVB, and UVC transmissivity value for each of the film plastics. The percentage haze was also determined. Tables 5.1 to 5.3 list the light transmission properties determined from those tests described in 4.3 Light Transmission.

5.1.1 Solar Radiation

The films with polyethylene (PE) as their base resin generally had the highest transmissivity (τ) values for incident solar radiation (Table 5.1). Standard PE appears to transmit the most solar radiation (τ = 91.9%) of all the films tested. Woven PE film 1 did not perform as well as the other PE based materials.

The co-extruded films, the normal ethylene vinyl acetate (EVA) type films and the reinforced EVA film performed similarly, with transmissivity values in the range of 79% to 82%. The poorest transmitters of solar radiation were the infra-red EVA (IREVA) and the PVC type films.

Table 5.1 Light Transmission Characteristics of Film Plastic Cladding Materials

Material	Solar (300nm - 850nm) Transmissivity (%)	PAR (400nm - 700nm) Transmissivity (%)
PE		
Standard	91.9	93.1
Infra-red	85.0	90.9
Woven 1.	77.9	79.5
2.	85.6	87.0
EVA		
Normal 1.*	80.6	93.4
2.	79.2	91.7
3.	80.7	93.6
4.*	80.5	92.8
Infra-red	75.8	89.3
Reinforced	79.6	92.2
PVC	74.1	90.1
Co-extruded Film		
Double Layer*	81.9	94.5
Triple Layer	80.8	91.9

* 200um thick film

5.1.2 Photosynthetically Active Radiation

Photosynthetically active radiation (PAR) transmissivity was tested within the 400nm to 700nm wavelength range rather than the 400nm to 780nm wavelength range. The latter is normally considered to include the complete band of PAR wavelengths.

The double layer co-extruded film transmitted the most PAR of all the film plastic cladding materials tested. Most of the other EVA based films performed similarly, transmitting in the range of 90% to 94% PAR (Table 5.1).

PVC film transmitted 90.1% of the PAR incident on its surface. This value is supported by findings of other researchers (refer 2.5.6 Polyvinyl Chloride).

The woven PE films 1 and 2 transmitted the least PAR with transmissivity values of 79.5% and 87.0% respectively. Of the PAR incident on the woven PE films that was not transmitted, over half was absorbed by the material. This was evident for all the film plastics that had PE as the base fabric.

Results showed that PAR transmission was hardly affected when IR absorbing additives are incorporated into the film material. Table 5.1 shows both the infra-red PE (IRPE) and IREVA films transmitted only 2% to 3% less PAR than the PE and EVA films without IR absorbers within the base fabric. This is consistent with the results of previous researchers (refer 2.5.2 Infra-red Polyethylene).

The results also showed that PAR transmission was not measurably altered by the addition of vinyl acetate (VA) to PE film resin. Such findings have been previously reported (refer 2.5.4 Ethylene Vinyl Acetate).

For all the films tested the light transmission was constant over all wavelengths within the PAR band (Appendix A figures A.1 to A.13). All the film plastics transmitted a greater amount of radiation at wavelengths over 800nm than wavelengths in the PAR band.

5.1.3 Ultra-violet Radiation

An insignificant quantity of 280nm to 320nm wavelength radiation was transmitted by the EVA type films and both the double and triple layer co-extruded films (Table 5.2). These films can be considered opaque to UVB radiation.

PVC was also opaque to UVB radiation and transmitted the least UVC radiation of all of the films tested. Furthermore, PVC performed the best as a ultra-violet (UV) radiation absorbing material, over all UV bands, of all the films tested.

It was surprising to find that the two normal EVA film materials (1 and 3) whose manufacturers do not claim contain UV stabilizers, did not perform differently to the other EVA films, the PVC and the co-extruded films which did contain UV stabilising systems. This suggests that:

1. Films with an EVA base fabric are active stabilizers of UV radiation. This is most likely due to a stabilizing affect of VA, and/or

2. The UV stabilizing systems within the EVA film plastic cladding materials may be largely inactive.

All of the film plastics having PE as their base resin performed poorly as UV radiation absorbers. These films transmited considerable UVB and UVC radiation. Such results suggest unprotected PE films have a relatively short life in the radiation environment, compared with EVA and PVC type films, because of their susceptibility to UV radiation.

Table 5.2 UV Light Transmission Characteristics of Film Plastic Cladding Materials

Material	UVB (280nm - 320nm) Transmissivity (%)	UVC (320nm - 400nm) Transmissivity (%)
PE		
Standard	83.7	89.8
Infra-red	35.4	66.8
Woven 1.	62.6	71.6
2.	73.7	81.6
EVA		
Normal 1.*	0.0	35.9
2.	0.0	34.4
3.	0.0	36.1
4.*	0.0	37.9
Infra-red	0.0	22.2
Reinforced	0.0	35.2
PVC	0.0	7.8
Co-extruded Film		
Double Layer*	0.0	40.1
Triple Layer	1.0	43.0

* 200um thick film

The manufacturers of the woven PE type films claim that the protective film coating is highly resistant to the degrading effects of UV light due to a hindering amine light stabilizer (HALS). The results clearly showed that this coating did not have an effective UV absorbing mechanism as UV transmission through the film plastics was very high. These film plastics can, however, be expected to resist the damaging effects of UV light as the HALS type additive is a quencher, rather than an absorber, of UV radiation.

5.1.4 Diffuse Radiation

Woven PE film 1 diffused incident radiation on its surface more than any of the film plastic cladding materials tested (Table 5.3). The IR films, normal EVA film 2, and the PVC film all diffused a substantial portion of the radiation incident on their surfaces. Researchers have previously reported that PVC film plastics have a greater tendency to diffuse incident radiation than PE film plastics (refer 2.5.6 Polyvinyl Chloride).

Results showed that haze properties are affected when IR absorbing additives are incorporated into the film material. Table 5.3 shows that the IRPE ,IREVA and the triple layer co-extruded films diffused significantly more incident radiation than the PE and EVA films which did not contain IR absorbers within their base resin. The light diffusion properties of the IRPE film reported here are consistent with manufacturers claims.

The results indicated that the inclusion of VA into PE resins (producing EVA type materials) also affected the light diffusion properties of the film. The addition of VA slightly decreased the diffusing property of film plastics (Table 5.3). Such an effect has been previously reported by other researchers (refer 2.5.4 Ethylene Vinyl Acetate).

The standard PE film, the co-extruded films and most of the normal EVA films did not diffuse radiation to any great extent.

Table 5.3 Light Diffusion Properties of Film Plastic Cladding Materials

Material	Haze (%)
PE	
Standard	15.4
Infra-red	38.9
Woven 1.	63.7
2.	27.8
EVA	
Normal 1.*	11.5
2.	35.6
3.	12.2
4.*	12.1
Infra-red	58.6
Reinforced	28.7
PVC	57.7
Co-extruded Film	
Double layer*	11.6
Triple layer	20.8

* 200um thick film

5.1.5 Significance and Use

5.1.5.1 Product Ranking

Each of the film plastic cladding materials tested are ranked in tables 5.4 and 5.5 according to their PAR transmissivity value and susceptibility to UV degradation, respectively.

Table 5.4 Ranking of the Film Plastic Cladding Materials on the Basis of PAR Transmission

Rank	Material	Thickness (um)	Transmissivity (%)
High	Co-extruded Double layer	200	95
	EVA Normal 3	180	94
	EVA Normal 1	200	93
	PE Standard	125	93
	EVA Normal 4	200	93
	EVA Reinforced	250	92
	Co-extruded Triple layer	150	92
	EVA Normal 2	150	92
	PE Infra-red	80	91
Medium	PVC	400	90
	EVA Infra-red	150	89
	PE Woven 1	150	87
Low	PE Woven 2	200	80

Table 5.5 does not include a ranking of the woven PE type film plastics as these contain a HALS type UV stabilizer. A comparative estimate of the degrading effects of UV light on these materials can not be made solely by reference to the light transmission tests described in 4.3 Light Transmission.

Table 5.5 **Ranking of the Film Plastic Cladding Materials on the Basis of their Susceptibility to Photodegradation (a function of UVB Transmission)**

Rank	Material	Thickness (um)	Transmissivity (%)
Hardly	PVC	400	0
	EVA Infra-red	150	0
	EVA Normal 2	150	0
	EVA Reinforced	250	0
	EVA Normal 1	200	0
	EVA Normal 3	180	0
	EVA Normal 4	200	0
	Co-extruded Double layer	200	0
	Co-extruded Triple layer	150	1
Extremely	PE Infra-red	80	35
	PE Standard	125	84

5.2 Thermal Transmission

This test allowed the determination of the thermal (or IR) radiation (3μm to 25μm) transmissivity value for each of the film plastics. Table 5.6 lists the IR radiation transmission properties determined from those tests described in 4.4 Thermal Transmission. Transmission is given at two radiant source temperatures, 20°C and 80°C.

Table 5.6 **Thermal Transmissivity (%) of Film Plastic Cladding Materials**

Material	Temperature of the Radiant Source	
	20°C	80°C
PE		
Standard	71.3	69.7
Infra-red	26.0	30.3
Woven 1.	49.8	47.8
2.	46.6	45.1
EVA		
Normal 1.*	36.4	34.5
2.	56.8	53.8
3.	39.8	36.7
4.*	39.8	37.3
Infra-red	10.8	14.6
Reinforced	24.8	22.8
PVC	3.0	4.2
Co-extruded Film		
Double layer*	34.5	31.9
Triple layer	49.1	46.7

* 200um thick film

5.2.1 Polyethylene

Of all the films tested, those having PE film material as their base resin consistently performed the most poorly (Table 5.6). Standard PE transmited a high portion of incident thermal radiation over most of the wavelength band 3μm to 25μm (Appendix B, figure B.1).

IRPE film would successfully retain heat within a greenhouse structure as it transmitted very little thermal radiation (Table 5.6). The IR absorbing system incorporated into IRPE film allowed very little thermal radiation to pass through the film, particularly of wavelengths from 10μm to 25μm (Figure B.2).

Both woven PE films acted similarly, transmitting a high portion of thermal radiation over most wavelengths between 3μm and 25μm (Figures B.3 and B.4).

5.2.2 Ethylene Vinyl Acetate

Of the normal EVA film plastics tested, films 1,3 and 4 were fairly opaque to thermal radiation. Film 2 transmitted higher levels (Table 5.6). All of the normal EVA films were most opaque to the incident thermal radiation of wavelengths between 6μm and 14μm (Figures B.5, B.6, B.7 and B.8).

The EVA films were considerably more opaque to thermal radiation than the PE type films. These results are supported by previous researchers who have reported that the addition of VA polymer to PE film resin will render the film material more opaque to thermal radiation (refer 2.5.4 Ethylene Vinyl Acetate).

Normal EVA film 2 was not as opaque to thermal radiation as competitive films. This suggested that film 2 did not contain as high a levels of VA as films 1, 3 and 4, as increasing levels of VA result in increased opacity to thermal radiation (refer 2.5.4 Ethylene Vinyl Acetate).

The IREVA film plastic tested transmitted very little thermal radiation because of the IR absorbing system incorporated into the film. The films opacity was greater than that of the IRPE film tested. This is probably because of the additional benefits of VA present in the former film. The IREVA film transmitted very little thermal radiation between the wavelengths 7μm to 25μm (Figure B.9).

The reinforced EVA film was more opaque to thermal radiation than the normal EVA films. The transmission was, however, low over a similar wavelength range (Figure B.10).

5.2.3 Polyvinyl Chloride

According to the results, the PVC film plastic cladding material would retain the most radiant heat within a greenhouse clad with it, of all the cladding materials tested (Table 5.6). This is consistent with reports by previous researchers (refer 2.5.6 Polyvinyl Chloride). The PVC film tested was most opaque to thermal radiation of wavelengths between 6μm and 25μm (Figure B.11).

5.2.4 Co-extruded Films

The double layered co-extruded film tested was found to be fairly opaque to thermal radiation. The thermal radiation curve for the double layered film (Figure B.12) was very similar to those of the normal EVA films. This suggested that the base resin for both layers of this co-extruded film was EVA.

The triple layered co-extruded film tested transmitted high levels of thermal radiation (Table 5.6). This was surprising as manufacturers claim that this film had an IR absorbing system incorporated into the middle layer of the film material (refer 4.1.4 Co-extruded Films). The results suggested that the IR absorbing system incorporated into the triple layer co-extruded film would be ineffective at preventing heat loss from a greenhouse clad with this material. Thermal transmission was high over most of the wavelength band (Figure B.13).

5.2.5 Significance and Use

5.2.5.1 Radiant Heating Systems

The thermal transmission test results were used to estimate the transmissivity of the film plastics when a radiant heating system is employed in a greenhouse clad with these film materials. The transmission data showed that the transmissivity of IR type film plastics, to thermal radiation, would increase when a radiant heating system is employed.

Although the advantage of using IR type film plastics is reduced at higher blackbody temperatures, energy savings can still be expected to be high when a heating system is employed in a greenhouse clad with an IR type film, rather than a standard type film.

5.2.5.2 Product Ranking

Each of the film plastic cladding materials tested were ranked (Table 5.7) according to their heat retention properties (with reference to their thermal radiation transmissivity value).

Table 5.7 Ranking of the Film Plastic Cladding Materials on the Basis of their Heat Retention Properties

Rank	Material	Thickness (um)	Transmissivity* of IR Radiation (%)
Excellent	PVC	400	3.0
	EVA Infra-red	150	10.8
	EVA Reinforced	250	24.8
	PE Infra-red	80	26.0
Medium	Co-extruded Double layer	200	34.5
	EVA Normal 1	200	36.4
	EVA Normal 4	200	39.8
	EVA Normal 3	180	39.8
Poor	PE Woven 2	200	46.6
	Co-extruded Triple layer	150	49.1
	PE Woven 1	150	49.8
	EVA Normal 2	150	56.8
	PE Standard	125	71.3

* Radiant Source Temperature 20°C

5.3 Initial Tear Resistance

The initial tear resistance test was carried out to determine the tear resistance of the flexible plastic films at very low rates of loading. The test was designed to measure the force to initiate tearing. The specimen geometry of this method produced a stress concentration in a small area of the specimen. The maximum force, usually found near the outset of tearing, was recorded as the tear resistance (N).

Tables 5.8 to 5.11 list the performance data for each type of film as experienced under the tearing loading situation described in section 4.2, Initial Tear Resistance.

Each film was tested in two directions to establish whether the film was anisotropic. The results for both the perpendicular and parallel tests are reported in this table for every film, regardless of whether the film demonstrated anisotropic behaviour or not.

The statistical analysis used a "t test" at the 5% level. Each value in tables 5.8 to 5.11 represents the mean of 10 observations.

5.3.1 Polyethylene

Standard PE appeared to be anisotropic and had a much lower tear resistance (Table 5.8) than the PVC film tested, the woven films and the reinforced EVA film.

The EVA films had similar tear resistance values to the PE film. The resistance per unit thickness (N/mm) values, however, indicated that the PE film was a stronger material and would be more resistant to tearing than the EVA film if the compared film thicknesses were the same. This suggested that the addition of VA copolymers tended to weaken PE film. Such findings have been previously reported, and it is generally accepted that the incorporation of high levels of any additives into PE resins will result in a slightly weaker film.

Table 5.8 Mean Initial Tear Resistances (n=10) of Polyethylene Based Film Plastic Cladding Materials and Corresponding Standard Errors ( )

Material	Thickness (um)	Tear Resistance (N)		Resistance per mm.	
		A*	B~	A*	B~
Standard	125	10.9 (0.15)	11.7 (0.16)	87.1 (1.18)	93.9 (1.26)
Infra-red	80	5.3 (0.09)	5.9 (0.16)	66.7 (1.06)	73.8 (2.01)
Woven 1.	150	47.9 (1.35)	39.2 (2.47)	319.6 (8.98)	261.3 (16.5)
2.	200	44.2 (1.05)	44.1 (2.31)	221.1 (5.23)	220.7 (11.5)

* Perpendicular ~ Parallel

EVA films can be expected to be mechanically stronger than PE films up to a certain VA content because of the EVA copolymer cross linking (Figure 5.1). With cross linking there is a chain tangling effect which results in increased strength. With too higher levels of VA, however, the cross linking tends to force the long PE chains far apart, weakening the film structure.

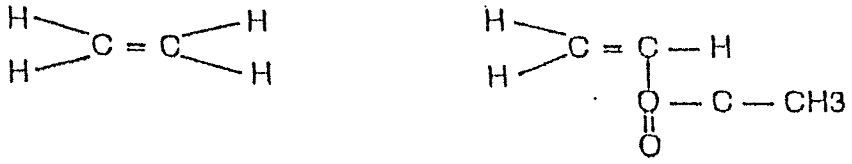


Figure 5.1 Co-polymers formed from ethylene (left) and VA (right).

The IRPE film had the lowest tear resistance of all the films tested. It was also the thinnest film to be tested, so this result was not surprising. This type of film is extensively used as an inner lining where a double cladding system is employed, or as a thermal screen material. Obviously, such functions do not require the film to be mechanically strong as the film is not exposed to the outside environment. Rather, the film can be expected to have excellent heat retention properties. The additives used to enhance the thermal retention properties can be expected to weaken the PE base material. This assumption is supported by the comparatively low resistance per unit thickness (N/mm) value observed for the IRPE film tested.

The woven PE films had a greater resistance to tearing than any of the other films tested. The two woven PE films tested had dissimilar woven structures and were of differing thickness. The two films, however, had similar tear resistances that were not significantly different. They could, therefore, be expected to act similarly when exposed to a tear loading situation.

5.3.2 Ethylene Vinyl Acetate

Within their group, the normal EVA films had a significant range of tear resistance values (Table 5.9). There were significant differences from film to film, even when the film thickness was similar. This suggested that the manufacturing process may, to an extent, determine the inherent mechanical properties of EVA type films. It also suggested that each of the film types tested may have had differing levels of VA added to the PE resin. It is conclusively accepted that the level of VA polymer incorporated into the PE resin largely determines film strength (refer 2.5.4 Ethylene Vinyl Acetate).

Of the normal EVA films tested, film 1 and film 4 shared the lowest tear resistance. The tear resistance of film 3 was significantly greater and film 2 had a comparatively higher tear resistance than all the other normal EVA films even when the competing materials were of greater thickness. Consequently, film 2 had the greatest resistance per unit thickness (N/mm) and, therefore, could be considered the strongest EVA material tested under a tear loading.

Two of the normal EVA type films were tested at varying thicknesses. Results showed that a significant increase in product tear resistance could be expected with films manufactured to greater thicknesses.

Of the four normal EVA films tested, only film 1 of 200μm thickness and film 2 showed significant anisotropic properties.

The normal EVA films had similar tear resistances to the standard PE film. This was probably largely due to the greater thickness of the 150μm, 180μm, and 200μm EVA films making up for the lost strength resulting from the addition of VA (refer 5.3.1 Polyethylene).

The IREVA film tested was significantly stronger than all the normal EVA films tested under a tear type loading. The IREVA film had a similar, although significantly greater, tear resistance to the normal EVA film 2. Both films were available from the same manufacturer. Although the IREVA film was made more opaque to thermal radiation by enriching the resin with mineral fillers (refer 2.5.2 Infra-red Polyethylene), the similarity in tear resistance was not surprising. Both the IREVA film and the normal EVA film 2 were anisotropic.

The IREVA film had a significantly higher tear resistance than both the IRPE film tested and the triple layer copolymer film, which had an IR absorbing central layer. Therefore, of the IR absorbing films, which were primarily manufactured for their excellent heat retention properties, the EVA type offered the better tear resistance.

Table 5.9 Mean Initial Tear Resistances (n=10) of Ethylene Vinyl Acetate Based Film Plastic Cladding Materials and Corresponding Standard Errors ( )

Material	Thickness (um)	Tear Resistance (N)		Resistance per mm.	
		A*	B~	A*	B~
Normal 1.	150	8.0 (0.19)	8.1 (0.31)	53.3 (1.29)	53.7 (2.09)
	200	9.7 (0.12)	10.7 (0.30)	48.6 (0.61)	53.6 (1.51)
2.	150	12.7 (0.23)	11.5 (0.32)	84.7 (1.57)	76.5 (2.11)
3.	180	10.3 (0.09)	10.3 (0.12)	57.1 (0.51)	57.1 (0.67)
4.	125	7.6 (0.22)	7.7 (0.15)	61.1 (1.75)	61.2 (1.16)
	150	8.2 (0.21)	8.1 (0.21)	54.4 (1.40)	53.6 (1.36)
	200	10.8 (0.20)	10.9 (0.22)	54.0 (0.98)	54.3 (1.08)
Infra-red	150	13.9 (0.10)	12.1 (0.16)	92.9 (0.70)	80.4 (1.08)
Reinforced	250	21.1 (2.06)	22.4 (2.57)	84.2 (8.25)	89.6 (10.27)

* Perpendicular ~ Parallel

The EVA film reinforced with woven polyester mesh had a relatively high tear resistance. Although the actual EVA film tore similarly to normal EVA films, the polyester strands offered greater resistance to tearing and only broke once the reported tear resistance load had been reached. Under tear load situations the reinforced EVA was only bettered by the woven PE films.

5.3.3 Polyvinyl Chloride

The polyvinyl chloride (PVC) film offered a relatively high tear resistance compared with all the alternative films, excepting the woven PE and the reinforced EVA films (Table 5.10). This was probably due to the PVC being of greater thickness (400μm) than the other films tested. This conclusion was supported by the relatively low resistance per unit thickness (N/mm) value that the PVC film had compared with all the other films tested. The PVC film was anisotropic.

The PVC film offered a greater tear resistance than the IR films and can also be expected to effectively retain heat within a greenhouse (refer 2.5.6 Polyvinyl Chloride).

Table 5.10 Mean Initial Tear Resistances (n=10) of the Polyvinyl Chloride Based Film Plastic Cladding Material and Corresponding Standard Errors ( )

Material	Thickness (um)	Tear Resistance (N)		Resistance per mm.	
		A*	B~	A*	B~
PVC	400	16.0 (0.30)	14.7 (0.22)	40.1 (0.74)	36.7 (0.55)

* Perpendicular ~ Parallel

5.3.4 Co-extruded Films

The thinner (125um) double layer co-extruded film was particularly weak when it was subject to the tear loading (Table 5.11). This film had the second lowest tear resistance of all the films tested. At the 200um thickness, however, this type of film was competitive with all the normal EVA films (except film 2) as the double layer film had a significantly greater tear resistance. The double layer co-extruded film had the same tear resistance as the standard PE film and the normal EVA film 4 (200μm).

Table 5.11 Mean Initial Tear Resistances (n=10) of Co-extruded Film Plastic Cladding Materials and Corresponding Standard Errors ( )

Material	Thickness (um)	Tear Resistance (N) A*	Tear Resistance (N) B~	Resistance per mm. A*	Resistance per mm. B~
Double Layer	125	6.0 (0.11)	5.9 (0.12)	48.1 (0.87)	47.0 (0.98)
	200	11.7 (0.21)	10.8 (0.20)	58.4 (1.03)	53.9 (1.01)
Triple Layer	150	11.3 (0.14)	9.9 (0.20)	75.5 (0.95)	66.5 (1.34)

* Perpendicular ~ Parallel

The triple layer co-extruded film could be ranked as the next strongest, under the double layer co-extruded film, when subject to a tearing load. It was surprising that this film performs so well compared to the PE and EVA types, as it had considerably more additives in the base resin. The manufacturer of this film claimed that the film's competitive strength is due to the co-extruded structure which "can be likened to lamination".

The co-extruded films appeared to be anisotropic, although the thinner (125μm) double layer film did not behave anisotropically.

5.3.5 Significance and Use

5.3.5.1 Anisotropy

The film plastic materials were tested in two directions for the determination of the tearing resistance so that any anisotropic behaviour could be identified. The anisotropic character of film plastics was most likely determined by the cross bonding nature of the film structure. With the EVA group of films the cross bonding of the VA polymer is most significant in determining the film's strength.

Some of the EVA films tested exhibited anisotropic properties while others did not. Furthermore, the anisotropic property that was evident in the thicker version of the normal EVA film 1 was not evident in the thinner. This inconsistency was also apparent with the double layer co-extruded type film.

These inconsistencies strongly suggest that the manufacturing process largely determines the mechanical properties of the film and, more exactly, the tendency of the film to be anisotropic in its behaviour. In the case of a thinner film plastic material being anisotropic when a thicker form of the same film product is not, the extrusion process may effect the mechanical properties more particularly when the extruder gap is smaller (i.e. when the film is extruded into thinner sheets). The extruder gap restricts the spread of the cross bonding in the direction perpendicular to the plane of the material and, subsequently, effects the natural form of the material.

Although trends of anisotropic behaviour were clearly evident in some of the films it was difficult to be conclusive with others when relying solely on these results. This was because of the inconsistencies discussed above, the insufficient number of samples tested for each type of film, and because the test design focused more on the tear resistance property rather than the anisotropic behaviour. The latter restriction was particularly relevant as the accuracy of the force measuring device, required to distinguish very slight anisotropic behaviour, was great compared with that required to measure tear loadings.

In practice film plastic cladding materials are subject to tearing and tensile forces from all directions. The importance of determining whether a film material is anisotropic or not, for most affective installation, is thus reduced. However, the anisotropic testing obtained a minimum strength value for each of the film plastics. Such a value is useful as a selection criterion.

5.3.5.2 Loading Rate

It is important to note that, with the ASTM D 1004 (1988a) test used to identify the tear resistance of the various film plastics, the samples were subjected to a very low rate of loading. In addition, the loading was applied at a constant rate. In practice, a greenhouse cladding material is likely to be subjected to wind and structural loads which tend to act erratically at very high rates. Therefore, the tear testing procedure used to test the greenhouse cladding materials was not totally representative of what happens in practice. The procedure did not determine the force to initiate tearing of films subject to the conditions determined by their practical use, but rather the force to initiate tearing generated by experimental procedure.

Although the experimentally determined forces to initiate tearing may have differed from those observed in practice, the tear resistance of each of the film plastics could be expected to be relative. Consequently, the ranking of the film plastics on the basis of their tear resistance was both possible and legitimate.

5.3.5.3 Specimen Shape

The shape of the specimen promotes tear failure at the v-notch point. The tensile pull of the load is slightly off centre. This will have a minor effect on the measured force to initiate tearing.

5.3.5.4 Specimen Thickness

The resistance to tear of plastic film, while partly dependant on thickness, had no simple correlation with specimen thickness (ASTM, 1988a). Hence, tearing forces measured in newtons cannot be normalised over a wide range of specimen thickness without producing misleading data as to the actual tearing resistance of the material. Resistance to tear may be expressed in force per unit thickness (N/mm), but it should be realised that comparison between films of dissimilar thickness may not be valid. In addition, growers are not so much interested in the performance of a film on a per unit thickness basis, but are interested in the performance of a film of specified thickness. For these reasons emphasis should be placed on the force to initiate tearing, or tearing resistance (N), rather than the resistance per unit thickness (N/mm). The latter is reported, but is of least concern.

5.3.5.5 Product Ranking

The film plastic cladding materials were ranked (Table 5.12) according to their relative tear resistances (N).

Table 5.12 Ranking of the Film Plastic Cladding Materials on the Basis of Tear Resistance

Rank	Material	Thickness (um)	Tear Resistance (N) A*	Tear Resistance (N) B~	Anisotropy
High	PE Woven 2	200	44	44	-
	PE Woven 1	150	48	39	Yes
	EVA Reinforced	250	21	22	-
Medium	PVC	400	16	15	Yes
	EVA Infra-red	150	14	12	Yes
	EVA Normal 2	150	13	12	Yes
	PE Standard	125	11	12	Yes
	Co-extruded Double layer	200	12	11	Yes
	EVA Normal 4	200	11	11	-
	Co-extruded Triple layer	150	11	10	Yes
	EVA Normal 1	200	10	11	Yes
Low	EVA Normal 3	180	10	10	-
	EVA Normal 4	150	8	8	-
	EVA Normal 1	150	8	8	-
	EVA Normal 4	125	8	8	-
	Co-extruded Double layer	125	6	6	-
	PE Infra-red	80	5	6	Yes

* Perpendicular ~ Parallel

5.4 Tensile Properties

The tensile tests were carried out to determine the strength the film plastic cladding materials have in a tensile loading situation. Tables 5.13 to 5.20 list the performance data for each type of film as experienced under the tensile loading situation described in section 4.3, Tensile Properties.

Each film was tested in two directions to establish whether the film was anisotropic. The results for both the perpendicular and parallel tests are reported in these tables for every film, regardless of whether the film demonstrated anisotropic behaviour or not.

The statistical analysis used a "t test" at the 5% level. Each value in tables 5.13 to 5.20 represents the mean of 5 observations.

The results showed that the maximum tensile strength and the tensile strength at break were identical for all the film plastics tested except the reinforced EVA type film. Subsequently, the tensile strength is reported as the tensile strength at break in tables 5.13, 5.15, 5.17 and 5.19, but as the tensile strength at the elastic limit for the reinforced EVA film in table 5.16.

5.4.1 Polyethylene

When standard PE was subject to the tensile loading described in 4.3 Tensile Properties it typically reacted as illustrated in figure 5.2. Following load initiation there was a yield point after minor film extension. After this, the strength of the material decreased slightly and then gradually increased to a break point at a loading well above that initialising the film yield.

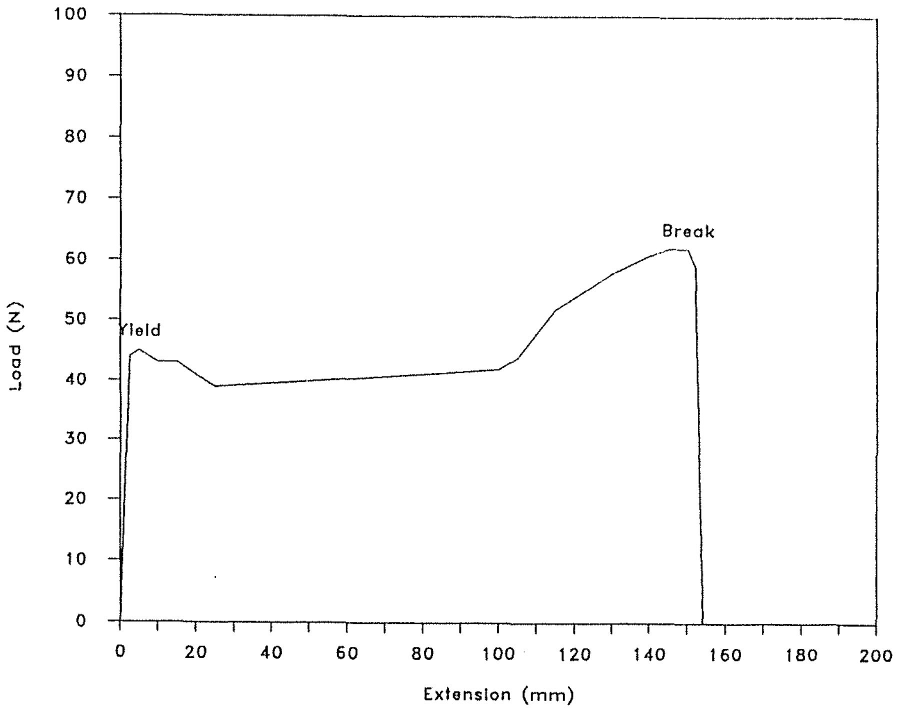


Figure 5.2 Typical load/extension diagram for standard PE type film plastic cladding material

The tensile load sustained at break by the standard PE (Table 5.13) was comparable to all the EVA films. The load was not significantly different to the load sustained by the normal EVA films 1 and 4 (200μm), 2 (150μm) or to the IREVA. The normal EVA film 3 was the only EVA film having a significantly higher break point load than the standard PE. All the other normal EVA films, of lesser thickness, were not as strong as the standard PE film at break point in the tensile loading situation.

Table 5.13 **Mean Tensile Property Values (n=5) at Break of Polyethylene Based Film Plastic Cladding Materials and Corresponding Standard Errors ( )**

Material	Thickness (um)	Load (N)		Tensile strength (N/mm^2)		Elongation (%)	
		A*	B~	A*	B~	A*	B~
Standard	125	65.9 (3.49)	59.0 (1.52)	21.1 (1.12)	18.9 (0.49)	313 (20)	291 (12)
Infra-red	80	24.9 (0.89)	26.0 (0.45)	12.5 (0.45)	13.0 (0.22)	141 (11)	126 (6)
Woven 1.	150	401 (6.1)	466 (15.3)	106 (1.6)	124 (4.1)		
2.	200	396 (10.8)	523 (33.2)	79.2 (2.15)	105 (6.6)		

* Perpendicular ~ Parallel

The standard PE film can be considered far weaker than the EVA film reinforced with woven polyester mesh, in a tensile loading situation. The reinforced EVA film had, by definition, a break point load that was not significantly different than the load sustained by standard PE. The reinforced EVA film had, however, a substantially higher yielding load than its own break point load, than the break point load of the standard PE, and yield point load of the standard PE.

The tensile load sustained at break by the standard PE was significantly lower than that sustained by the PVC film.

Although standard PE does not have a break point load that was significantly different than that of the triple layer co-extruded film, it was significantly lower than the break point load of the thicker, double layer co-extruded film.

The IRPE film reached a yield point and a break point when it was subjected to a tensile loading (Figure 5.3). The loads at break point and yield, for the IRPE film, were significantly lower than those measured for all the other films tested.

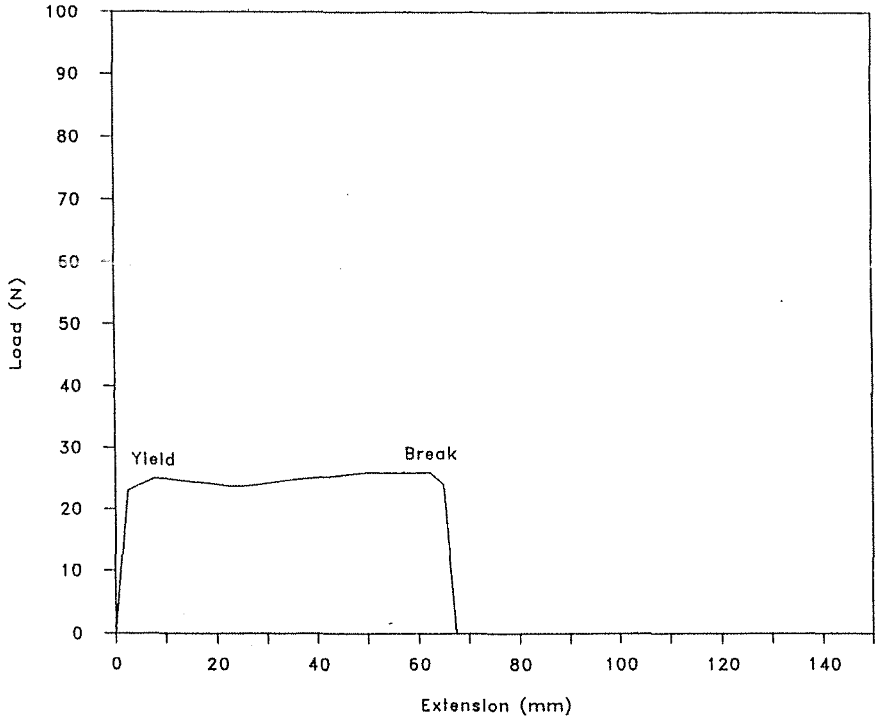


Figure 5.3 Typical load/extension diagram for the IRPE type film plastic cladding material

The two woven PE films behaved similarly. Of all the film plastic materials tested under the tensile loading situation, the woven PE films performed the best. They were considerably stronger than all the other films tested.

5.4.1.1 Elastic Properties

Standard PE sustained a comparatively higher load at the elastic limit than the IRPE film (Table 5.14) and all the other film plastics tested, except the reinforced and IREVA films, the normal EVA film 2 and the PVC film.

Table 5.14 Mean Tensile Property Values (n=5) at the Elastic Limit of the Polyethylene Based Film Plastic Cladding Material and Corresponding Standard Errors ( )

Material	Thickness (um)	Load (N)		Tensile strength (N/mm^2)		Elongation (%)	
		A*	B~	A*	B~	A*	B~
Standard	125	45.8 (0.81)	44.6 (0.18)	14.7 (0.27)	14.3 (0.04)	10.0 (0)	10.0 (0)
Infra-red	80	23.9 (0.18)	23.2 (0.36)	12.0 (0.09)	11.6 (0.18)	11.0 (0)	10.0 (0)

* Perpendicular ~ Parallel

IRPE performed similarly to the remaining EVA type films and better than those of 150um (or lesser) thickness. The almost clear IRPE film material tended to become cloudy at the elastic limit point and became more cloudy as increased tensile force was applied (Plate 5.1). The gripped edges of the sample viewed in plate 5.1 were transparent whilst the mid-sample area, that was subjected to a high level of tensile stress, was clouded over.

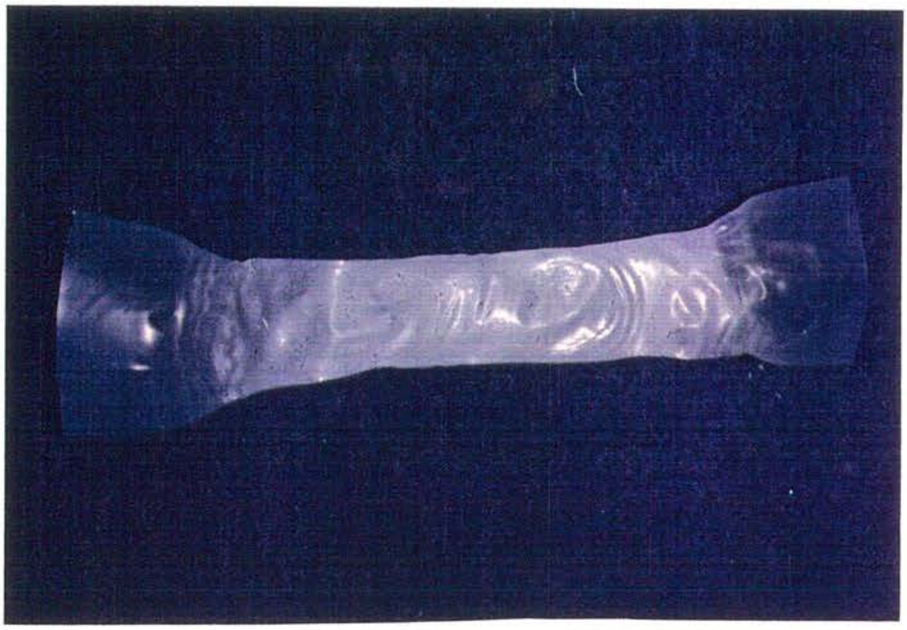


Plate 5.1 Infra-red polyethylene film sample after breach of the materials elastic limit

Such a reaction to tensile stress, following a breach of the elastic limit, was also evident for the other films containing an IR absorbing system (i.e. IREVA and the triple layered co-extruded film). Molecular compounds, probably those associated with the IR absorbing system, were obviously physically disrupted by the tensile forces. This disruption resulted in an undesirable clouding of the film plastic material.

Since the clarity (transparency) of the film containing an IR absorbing system was impaired, the solar transmission of the film plastic could be expected to have dropped significantly. This is particularly important when considering the affect that large tensile forces, causing the film plastic materials to stretch, could have on the PAR transmissivity of the cladding material. Such film plastics, rather than require tensioning, may require replacement following a breach of the elastic limit.

The elongation at the elastic limit for both standard and IRPE was around 10% (Table 5.10). Although not substantial, this was similar to the elongation of most films tested.

The elastic limit for the woven PE film plastics was unable to be identified (refer 4.6.1 Preparation of Apparatus).

5.4.2 Ethylene Vinyl Acetate

Films 1 (200μm), 3 and 4 (200μm) had break point loadings that were not significantly different from each other. These film plastics were the strongest of the all normal EVA films, of varying thickness, tested (Table 5.15).

Of the normal EVA films 1, 3 and 4, none had a yield point when subjected to a tensile loading, regardless of their thickness. Instead, the normal EVA films tended to act as illustrated in figure 5.4. The lack of real yield point for these EVA type films was not surprising. Researchers have reported a distinct decrease in yield strength following increases in the levels of VA incorporated into PE resins (refer 2.5.4 Ethylene Vinyl Acetate).

The normal EVA film 2 had a point of yielding when it was subject to a tensile loading (Figure 5.5). This suggested that normal EVA film 2 contained less VA than the other normal EVA films tested. Film 2 was the stronger of the 150μm grade normal EVA films and was as strong as the 200μm films, 1 and 4 (Table 5.15).

The IREVA film behaved similarly to the normal EVA film 2 under the tensile loading situation. The similar behaviour was not surprising as they were produced by the same manufacturer and contained similar levels of VA. Their respective yield point and break point loadings were not significantly different.

Table 5.15 Mean Tensile Property Values (n=5) at Break of Ethylene Vinyl Acetate Based Film Plastic Cladding Materials and Corresponding Standard Errors ( )

Material	Thickness (um)	Load (N)		Tensile strength (N/mm^2)		Elongation (%)	
		A*	B~	A*	B~	A*	B~
Normal 1.	150	57.0 (2.15)	50.7 (1.61)	15.2 (0.58)	13.5 (0.45)	269 (6)	231 (7)
	200	72.1 (5.10)	63.3 (6.71)	14.4 (1.03)	12.7 (1.34)	255 (12)	254 (20)
2.	150	66.5 (1.79)	64.6 (1.79)	17.7 (0.45)	17.2 (0.45)	252 (6)	245 (10)
3.	180	80.4 (1.74)	74.2 (4.96)	17.9 (0.40)	16.5 (1.12)	344 (13)	148 (10)
4.	125	38.2 (1.61)	45.8 (0.76)	12.2 (0.54)	14.7 (0.22)	193 (10)	248 (7)
	150	38.0 (0.63)	34.3 (0.67)	10.1 (0.18)	9.2 (0.18)	157 (1)	166 (1)
	200	72.0 (4.87)	66.0 (2.10)	14.4 (0.98)	13.2 (0.40)	285 (19)	263 (10)
Infra-red	150	56.9 (2.77)	63.5 (0.85)	15.2 (0.76)	16.9 (0.22)	228 (12)	172 (3)
Reinforced	250	66.2 (0.18)	61.8 (0.18)	10.6 (0.31)	9.9 (0.31)	206 (3)	206 (3)

* Perpendicular ~ Parallel

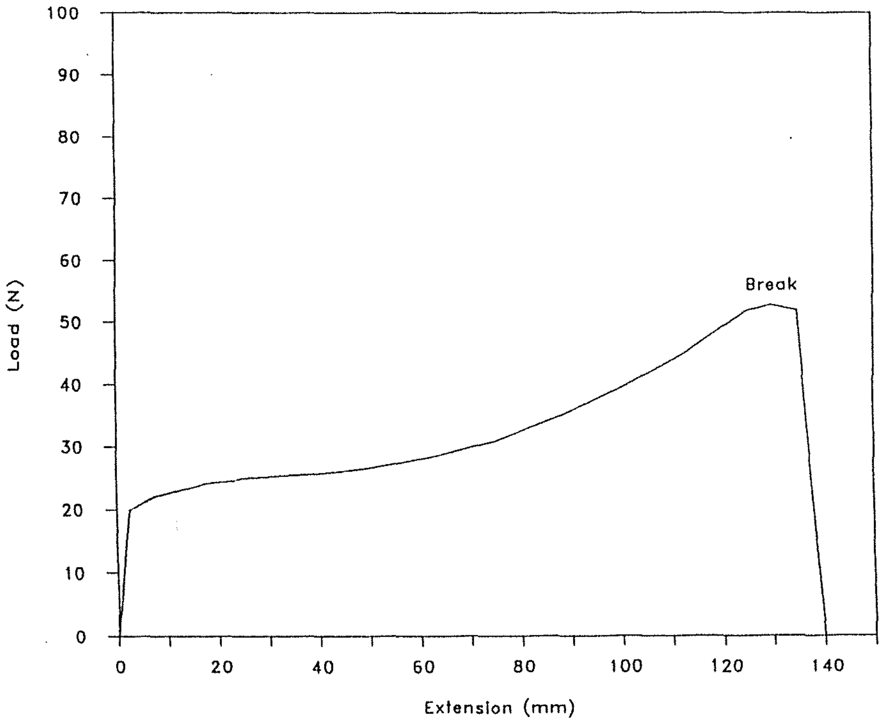


Figure 5.4 Typical load/extension diagram for the normal EVA type film plastic cladding materials (curve data from the normal EVA film 1, 150μm test)

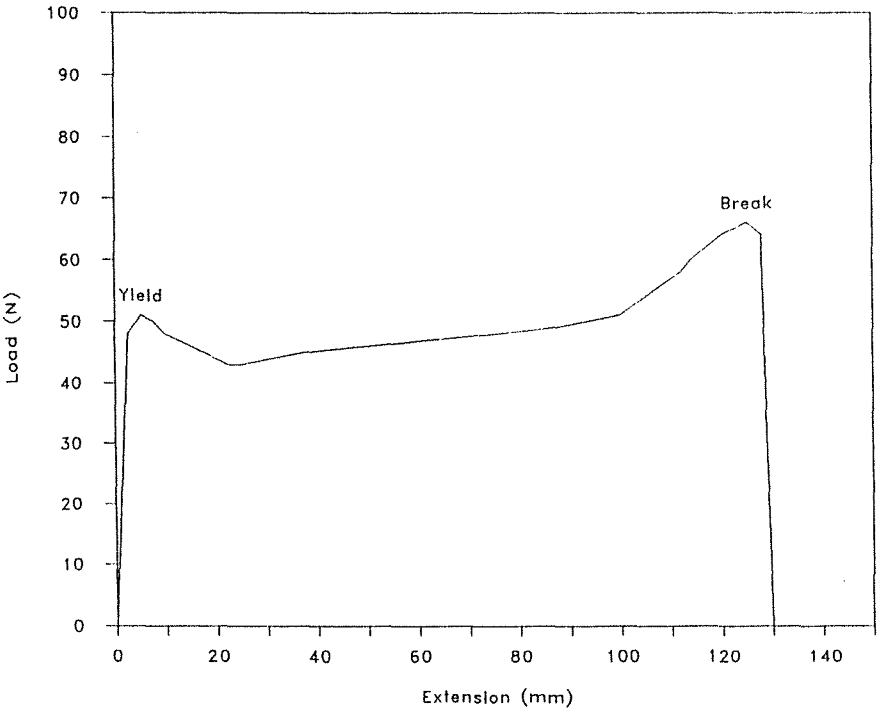


Figure 5.5 Typical load/extension diagram for the normal EVA film 2 type film plastic cladding material

The EVA film reinforced with woven polyester strands behaved differently from all the other films tested. As illustrated in figure 5.6, the reinforced EVA had three points of peak loading leading to the final point of film rupture. Shortly after extension occured, reinforced EVA offered the maximum resistance to tensile loading (defined in figure 5.6 as the yield point). At the yield point, the first of the polyester strands was broken as the tensile force acted in a direction parallel to the length of the strands. As extension continued the remaining strands were subjected to an increasing tensile loading until they broke at the point defined in figure 5.6 as 'A'. From this point on, the polyester strands offered negligible resistance to the loading and were dragged through the EVA film. The actual film was then subjected to the tensile loading and was extended until a yield point, then a break point, was reached. Rupture occured at the film break point.

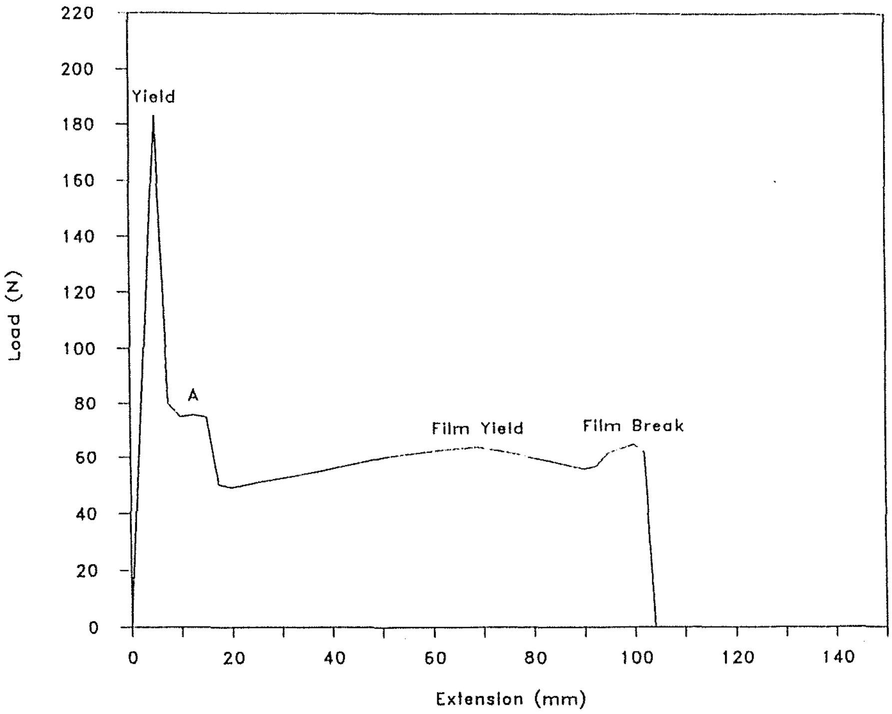


Figure 5.6 Typical load/extension diagram for the reinforced EVA type film plastic cladding material

The high tensile strength of the woven polyester strands maked reinforced EVA film significantly stronger than the standard PE and IRPE films, all the other EVA films, and the PVC film tested.

5.4.2.1 Elastic Properties

Normal EVA film 1 and the IREVA film had the greatest load at the elastic limit of all the normal EVA type films (Table 5.16) and had a greater load than both the double and triple layer co-extruded films. The remaining EVA films sustained a load of between 20 N and 29 N depending, largely, on film thickness.

Table 5.16 Mean Tensile Property Values (n=5) at the Elastic Limit of the Ethylene Vinyl Acetate Based Film Plastic Cladding Materials and Corresponding Standard Errors ( )

Material		Thickness (um)	Load (N)		Tensile strength (N/mm^2)		Elongation (%)	
			A*	B~	A*	B~	A*	B~
Normal	1.	150	20.0 (0)	20.0 (0)	5.3 (0)	5.3 (0)	10.0 (0)	10.0 (0)
		200	26.0 (0)	26.0 (0)	5.2 (0)	5.2 (0)	10.0 (0)	10.0 (0)
	2.	150	51.3 (0.63)	50.7 (0.94)	13.7 (0.18)	13.5 (0.27)	5.5 (1)	9.0 (1)
	3.	180	29.0 (0)	29.0 (0)	6.4 (0)	6.4 (0)	10.0 (0)	10.0 (0)
	4.	125	20.0 (0)	20.0 (0)	6.4 (0)	6.4 (0)	10.0 (0)	10.0 (0)
		150	20.0 (0)	20.0 (0)	10.7 (0)	10.7 (0)	6.0 (0)	6.0 (0)
		200	29.0 (0)	29.0 (0)	5.8 (0)	5.8 (0)	10.0 (0)	10.0 (0)
Infra-red		150	48.0 (0)	48.9 (0.76)	12.8 (0)	14.7 (0.14)	7.5 (0)	8.0 (0)
Reinforced		250	183 (3.1)	182 (1.7)	29.3 (0.49)	29.3 (0.27)	9.0 (1)	12.5 (0)

* Perpendicular ~ Parallel

IREVA film became cloudy following an increase in the tensile force breaching the elastic limit (refer 5.4.1.1 Elastic Properties).

Reinforced EVA sustained the greatest tensile load at the elastic limit of all those films tested (elastic limit readings were not taken for the woven PE type films).

For most of the film plastics having EVA as their base resin, the elongation at the elastic limit was 10% or less. The only exception was reinforced EVA which had an elongation of up to 13% in at least one direction.

5.4.3 Polyvinyl Chloride

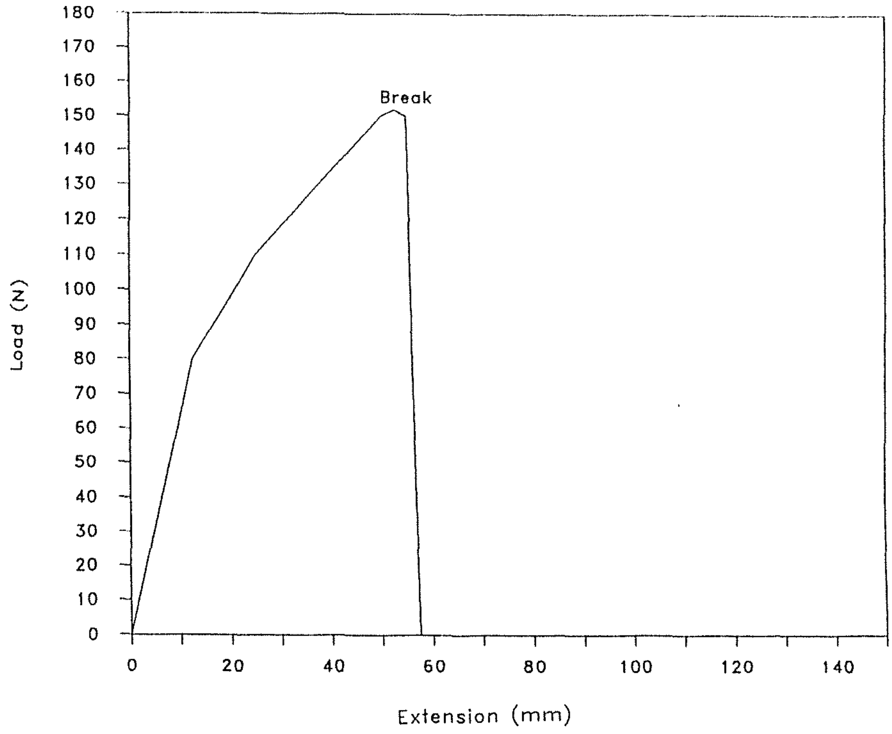


Figure 5.7 Typical load/extension diagram for the PVC type film plastic cladding material

The typical behaviour of PVC film under a tensile load is illustrated in figure 5.7. PVC does not yield when subjected to a tensile load.

PVC sustained a significantly higher load before rupturing (Table 5.17) than standard PE and IRPE, than all the EVA films excepting the reinforced EVA film, and a higher load than all the co-extruded films.

Table 5.17 Mean Tensile Property Values (n=5) at Break of the Polyvinyl Chloride Film Plastic Cladding Material and Corresponding Standard Errors ( )

Material	Thickness (um)	Load (N)		Tensile strength (N/mm^2)		Elongation (%)	
		A*	B~	A*	B~	A*	B~
PVC	400	156.4 (3.40)	148.2 (7.07)	15.6 (0.36)	14.8 (0.72)	106 (5)	133 (10)

* Perpendicular ~ Parallel

5.4.3.1 Elastic Properties

PVC film demonstrated convincing anisotropic behaviour at the elastic limit. PVC film sustained the next greatest tensile load at the elastic limit (Table 5.18) after reinforced EVA type film.

Table 5.18 Mean Tensile Property Values (n=5) at the Elastic Limit of the Polyvinyl Chloride Film Plastic Cladding Material and Corresponding Standard Errors ( )

Material	Thickness (um)	Load (N)		Tensile strength (N/mm^2)		Elongation (%)	
		A*	B~	A*	B~	A*	B~
PVC	400	55.0 (0)	40.0 (0)	5.5 (0)	4.0 (0)	16.0 (0)	12.0 (0)

* Perpendicular ~ Parallel

PVC film had the greatest elongation at the elastic limit of all the films tested. This suggested that PVC film will return to its original length more readily than the other films following elongation of up to 16% in at least one direction.

5.4.4 Co-extruded Films

The double layer co-extruded film did not yield when subjected to the tensile load. At a thickness of 200μm it offered more resistance prior to rupture (Table 5.19) than all the EVA films tested, except normal EVA film 3 and the reinforced EVA film. The double layer co-extruded film offered more resistance than both standard PE and IRPE , and the triple layered co-extruded film. The triple layered co-extruded film acted similarly to standard PE, having both a yield point load and break point load of similar magnitude.

Table 5.19 Mean Tensile Property Values (n=5) at Break of Co-extruded Film Plastic Cladding Materials and Corresponding Standard Errors ( )

Material	Thickness (um)	Load (N)		Tensile strength (N/mm^2)		Elongation (%)	
		A*	B~	A*	B~	A*	B~
Double layer	125	30.9 (1.43)	36.4 (1.48)	9.9 (0.45)	11.7 (0.45)	198 (6)	187 (4)
	200	79.2 (0.94)	75.9 (2.95)	15.8 (0.18)	15.2 (0.58)	290 (5)	296 (23)
Triple layer	150	63.1 (1.21)	53.4 (0.45)	16.8 (0.31)	14.2 (0.13)	200 (3)	240 (3)

* Perpendicular ~ Parallel

5.4.4.1 Elastic Properties

Table 5.20 shows the tensile properties of the co-extruded film plastics at their elastic limit. The 200μm double layer and 150μm triple layer co-extruded films were anisotropic and stronger at the elastic limit than many of the EVA based films in at least one direction.

Table 5.20 Mean Tensile Property Values (n=5) at the Elastic Limit of the Co-extruded Film Plastic Cladding Materials and Corresponding Standard Errors ( )

Material	Thickness (um)	Load (N)		Tensile strength (N/mm^2)		Elongation (%)	
		A*	B~	A*	B~	A*	B~
Double layer	125	16.0 (0)	16.0 (0)	5.1 (0)	5.1 (0)	12.0 (0)	6.0 (0)
	200	34.0 (0)	32.0 (0)	6.8 (0)	6.4 (0)	14.0 (0)	8.0 (0)
Triple layer	150	40.0 (0)	39.0 (0.27)	10.7 (0)	10.4 (0.09)	10.0 (0)	7.5 (0)

* Perpendicular ~ Parallel

The triple layered co-extruded film became cloudy following an increase in the tensile force breaching the elastic limit (refer 5.4.1.1 Elastic Properties).

All the co-extruded films had an elongation competitive with the other film plastics tested in at least one direction. The double layer co-extruded film performed particularly well, elongating up to 14% in at least one direction. The amount of elongation was dependant on film thickness.

5.4.5 Significance and Use

5.4.5.1 Anisotropy

The film plastic materials were tested in two directions for the determination of the tensile properties so that any anisotropic behaviour could be identified.

Although trends of anisotropic behaviour were clearly evident in some of the films it was difficult to be conclusive with others when relying solely on these results. This was because of the insufficient number of samples tested for each type of film, and because the test design focused more on the tensile loading determination rather than on the anisotropic behaviour.

Section 5.3.6.1 Anisotropy discussed the anisotropic behaviour of some of the film plastic cladding materials tested.

In practice, film plastic cladding materials are subject to tensile forces from all directions. The determination of anisotropic behaviour is relatively unimportant (refer 5.3.6.1 Anisotropy).

5.4.5.2 Loading Rate

As with those samples tested to identify the tear resistance of the various film plastics, the samples subject to the tensile loading outlined in 3.6 Tensile Properties experienced a constant, low rate of loading. Since, in practice, a greenhouse cladding material is not usually subject to such controlled loadings (refer 5.3 Tearing Resistance) the tensile properties of the greenhouse cladding materials determined by this testing procedure could be most effectively applied in the process of ranking the films.

5.4.5.3 Specimen Shape

The rectangular shape of the specimens used in the tensile test tended to cause a stress concentration and subsequently, promote tear failure at the grips. Although in most tensile testing procedures this is undesirable, for our tests this was considered acceptable because, in practice, film failure usually occurs at the fixing points. It may be useful to carry out a similar tensile test using the most popular film plastic cladding fixing systems as test grips.

5.4.5.4 Specimen Thickness

The results showed that the thickness of a film plastic material largely determined the magnitude of the load it could resist before film yield or failure. Therefore, a ranking of the films tested based on their load (N) values rather than on their tensile strength (N/mm^2) values is probably of most interest to growers. This is because the latter would report the relative strength of the polymer used in the films on a per mm thickness basis, rather than the relative strength of each film at the thickness commercially available to the grower.

The film plastic cladding materials were ranked according to the former system (Tables 5.21 and 5.22).

5.4.5.5 Yield Point

Ultimately, the yielding and subsequent deformation of film plastics is not as important to the grower as rupture failure. If the film is stretched the crop is still protected from the outside environment. If it is ruptured, however, damage to the crop will result.

5.4.5.6 Elastic Limit

ASTM D 882 (1988b) required that only materials whose stress-strain curves exhibited a point of zero slope could be considered as having a yield point. Consequently, only a few films had a point of yield. On the other hand, all the films tested had an elastic limit occurring prior to the yield point being reached once the tensile load was applied. The elastic limit and yield point of some films were identical.

In practice, once the film plastic cladding material has passed the elastic limit it will not return to its original physical condition. It will tend to sag and will require tensioning. Continual film tensioning will cause the film to become thinner as each succeeding elastic limit is breached. This may result in the film becoming less resistant to tear or impact failure. Furthermore, breaching the elastic limit may not only result in film sag but film fatigue as the film tends to flap in the wind. Therefore, the conditions bringing a film plastic to a point of yield is not so much important as the conditions resulting in a breach of the elastic limit. For this reason, the tensile properties relating to the elastic limit were reported, in this study, rather than those relating to the yield point.

5.4.5.7 Product Ranking

The film plastic cladding materials were ranked according to their load at the break point and load at the elastic limit (Tables 5.21 and 5.22, respectively).

Table 5.21 Ranking of the Film Plastic Cladding Materials on the Basis of Maximum Tensile Load

Rank	Material	Thickness (um)	Tensile Load (N)		Anisotropy
			A*	B~	
High	PE Woven 2	200	523	396	Yes
	PE Woven 1	150	401	466	Yes
	EVA Reinforced	250	183	182	-
	PVC	400	156	148	-
Medium	Co-extruded Double layer	200	79	76	-
	EVA Normal 3	180	80	74	-
	EVA Normal 4	200	72	66	-
	EVA Normal 1	200	72	63	-
	EVA Normal 2	150	67	65	-
	PE Standard	125	66	59	-
	EVA Infra-red	150	57	64	-
	Co-extruded Triple layer	150	63	53	Yes
	EVA Normal 1	150	57	51	-
Low	EVA Normal 4	125	38	46	Yes
	EVA Normal 4	150	38	34	Yes
	Co-extruded Double layer	125	31	36	Yes
	PE Infra-red	80	25	26	Yes

* Perpendicular ~ Parallel

Table 5.22 Ranking of the Film Plastic Cladding Materials on the Basis of the Load at the Elastic Limit

Rank	Material	Thickness (um)	Tensile Load (N)		Anisotropy
			A*	B~	
High	EVA Reinforced	250	183	183	-
Medium	PVC	400	55	40	Yes
	EVA Normal 2	150	51	51	-
	EVA Infra-red	150	48	49	-
	PE Standard	125	46	45	-
	Co-extruded Triple layer	150	40	39	Yes
	Co-extruded Double layer	200	34	32	Yes
	EVA Normal 4	200	29	29	-
	EVA Normal 3	180	29	29	-
	EVA Normal 1	200	26	26	-
	PE Infra-red	80	24	23	Yes
Low	EVA Normal 1	150	20	20	-
	EVA Normal 4	150	20	20	-
	EVA Normal 4	125	20	20	-
	Co-extruded Double layer	125	16	16	-

* Perpendicular ~ Parallel

5.5 Impact Resistance

Impact tests were carried out to determine the resistance the film plastic cladding materials had in the impact loading situation. Tables 5.23 to 5.26 list the performance data for each type of film as experienced under the impact loading situation described in section 4.4 Impact Resistance.

The statistical analysis involved a "t test" at the 5% level. Each value in tables 5.23 to 5.26 represents the mean of 5 observations.

5.5.1 Polyethylene

The standard PE and the IRPE films had the least resistance to impact loadings of all the films tested (Table 5.23).

Table 5.23 Mean Impact Resistances (n=5) of Polyethylene Based Film Plastic Cladding Materials and Corresponding Standard Errors ( )

Material		Thickness (um)	Energy to Rupture (J)
Standard		125	8.4 (0.17)
Infra-red		80	3.8 (0.15)
Woven	1.	150	>39.9 (0.42)
	2.	200	>39.9 (0.42)

This was probably largely due to their relatively small thickness (125μm). The impact energy tended to be absorbed largely within the impact zone. This zone area was circular and defined by the spherical shape of the dart head in contact with the film at impact. The film ruptured (or, more specifically, tore) around the radius of the impact zone.

The woven PE films, however, were very resistant to the impact loading. Even when using the 2.325 kg dart of greatest mass neither of these films were ruptured. The woven structure of this type of fabric appeared to distribute the impact energy quite readily to the gripping system rather than absorb the energy itself. The reported impact energy for the woven PE films in table 5.23 represents the greatest energy the films could be subjected to with the testing system. The films successfully withstood the loading of the dart without rupture. The films could obviously resist an impact energy greater than that reported in table 5.23.

5.5.2 **Ethylene Vinyl Acetate**

Of the normal EVA type films tested, film 2 performed the most poorly while films 1 and 3 performed the best (Table 5.24). Previous researchers have reported a significant improvement in impact strength with PE films containing increased levels of VA (refer 2.5.4 Ethylene Vinyl Acetate). The test results reported in tables 5.23 and 5.24 support this observation. Furthermore, the test results suggest normal EVA film 2 did not contain as high a levels of VA as the other normal EVA type films (refer 5.4.2 Ethylene Vinyl Acetate).

The mode of failure for the normal EVA films was the same as that described for the PE films (refer 5.5.1 Polyethylene). Film thickness appeared to influence impact strength. Normal EVA films 1 and 4 resisted the greatest impact loading when at greatest thickness (Table 5.24).

Table 5.24 Mean Impact Resistances (n=5) of Ethylene Vinyl Acetate Based Film Plastic Cladding Materials and Corresponding Standard Errors ( )

Material	Thickness (um)	Energy to Rupture (J)
Normal 1.	150	21.9 (0.32)
	200	19.5 (0.24)
2.	150	10.7 (0.14)
3.	180	21.4 (0.21)
4.	125	14.9 (0.17)
	150	17.8 (0.33)
	200	18.9 (0.43)
Infra-red	150	9.1 (0.26)
Reinforced	250	14.5 (0.57)

The IREVA film acted similarly to the normal EVA film 2 which was produced by the same manufacturer. However, statistical analysis revealed that the latter film had a significantly, although not substantially, greater impact resistance than the former.

The woven polyester strands incorporated into the reinforced EVA film did not appear to improve the impact resistance of EVA type film plastics (Table 5.24). This was because much of the energy tied up in the impact load was due to the velocity of the impacting mass. For a film material to resist the impact load it must reduce the velocity of the impacting mass before destructive elongation (rupture) of the film material takes place. The elasticity of the polyester strands was low (Figure 5.6). Therefore, the strands were incapable of absorbing a large impact energy over their small elastic range. Therefore, the strands tended to snap readily when subjected to the high energy load (rapidly moving object).

5.5.3 Polyvinyl Chloride

The PVC film was highly resistant to the impact loading compared to other film plastic materials tested. The reported impact energy for the PVC film represented the greatest energy the film could be subject to with the testing system. Even with using the 2.325 kg dart of greatest mass the PVC film could not be ruptured.

Table 5.25 Mean Impact Resistance (n=5) of the Polyvinyl Chloride Film Plastic Cladding Material and Corresponding Standard Error ( )

Material	Thickness (um)	Energy to Rupture (J)
PVC	400	>39.9 (0.42)

The elastic nature of this type of film (Figure 5.17) appeared to aid distribution of the impact energy throughout the film mass rather than promote absorption of the energy within the impact zone. The energy in the impacting mass was distributed and then absorbed causing the film to behave elastically (i.e. the film first elongated then returned to its original form).

5.5.4 Co-extruded Films

The double layer co-extruded film plastic performed considerably better than the triple layer when subjected to an impact load (Table 5.26).

Table 5.26 Mean Impact Resistances (n=5) of Co-extruded Film Plastic Cladding Materials and Corresponding Standard Errors ( )

Material	Thickness (um)	Energy to Rupture (J)
Double Layer	125	13.8 (0.26)
	200	22.6 (0.21)
Triple Layer	150	8.5 (0.15)

Both types of co-extruded film absorbed energy and ruptured in the same way as the PE type films (refer 5.5.1 Polyethylene). The 200μm double layer co-extruded film was most resistant to impact loading.

5.5.5 Significance and Use

5.5.5.1 Dart Shape

The convex surface of the dart head, in contact with the film surface, tended to cause tearing and rupture of the film material. In practice, greenhouse cladding materials would be subject to the impact of sharper objects than this type of dart, resulting in puncture failure of a film rather than tearing failure.

5.5.5.2 Specimen Size

The size of the specimen could be expected to influence the amount of energy that it could absorb prior to any damage. With a higher film volume (i.e. larger sample surface area) subjected to impacting forces, more energy could be distributed and absorbed within the film mass.

In practice, a large surface area of film is subject to impacting loads.

This type of test, however, could be successfully used to rank, according to an impact resistance (J), each film relative to competing products.

5.5.5.3 Product Ranking

Each of the film plastic cladding materials tested were ranked according to their impact resistance and are listed in table 5.27.

Table 5.27 **Ranking of the Film Plastic Cladding Materials on the Basis of their Impact Resistance**

Rank	Material	Thickness (um)	Energy to Rupture (J)
High	PE Woven 1	150	>40
	PE Woven 2	200	>40
	PVC	400	>40
Medium	Co-extruded Double layer	200	22
	EVA Normal 1	200	22
	EVA Normal 3	180	21
	EVA Normal 1	150	20
	EVA Normal 4	200	19
	EVA Normal 4	150	18
	EVA Normal 4	125	15
	EVA Reinforced	250	15
	Co-extruded Double Layer	125	14
	EVA Normal 2	150	11
Low	EVA Infra-red	150	9
	Co-extruded Triple layer	150	9
	PE Standard	125	8
	PE Infra-red	80	4

5.6 Water Vapour Transmission

This test covered the determination of the water vapour transmission properties of film plastic cladding materials available in New Zealand. The passage of water through these materials is of importance to the grower as the energy associated with water vapour has an affect on the thermal environment within the greenhouse (refer 2.4.4 Water Vapour Permeability). From the test results the water vapour transmission (WVT) and the water vapour permeance (WVP) values were calculated.

Tables 5.28 and 5.29 list the performance data for each type of film as experienced under the test conditions described in 4.4, Water Vapour Transmission. Each value in tables 5.28 and 5.29 represents the mean of three observations.

5.6.1 Polyethylene

Water vapour passed through standard PE film at a low rate compared to most of the other film plastic materials tested (Table 5.28). The remaining PE based film plastics transmitted water vapour at a similar rate to standard PE.

Table 5.28 Mean Water Vapour Transmission Values (n=3) of the Polyethylene Based Film Plastic Cladding Materials and Corresponding Standard Errors ( )

Material	Thickness (um)	WVT (g/m^2.day)	WVP ($10^{-3} g/m^2$.day.Pa)
Standard	125	0.41 (0.05)	0.24 (0.03)
Infra-red	80	1.14 (0.09)	0.65 (0.05)
Woven 1.	150	0.57 (0.04)	0.33 (0.02)
2.	200	0.39 (0.06)	0.22 (0.03)

Table 5.29 Mean Water Vapour Transmission Values (n=3) of the Film Plastic Cladding Materials and Corresponding Standard Errors ( )

EVA			
Normal 1.	150	6.01 (0.18)	3.43 (0.10)
	200	5.28 (0.34)	3.01 (0.20)
2.	150	0.60 (0.02)	0.35 (0.01)
3.	180	2.18 (0.09)	1.25 (0.05)
4.	125	4.87 (0.06)	2.78 (0.03)
	150	5.35 (0.04)	3.05 (0.02)
	200	3.24 (0.05)	1.85 (0.03)
Infra-red	150	0.55 (0.04)	0.31 (0.02)
Reinforced	250	2.50 (0.29)	1.43 (0.17)
PVC	400	3.41 (0.20)	1.94 (0.11)
Co-extruded Film			
Double Layer	125	7.19 (0.14)	4.10 (0.18)
	200	3.69 (0.10)	2.11 (0.16)
Triple Layer	150	0.94 (0.13)	0.54 (0.18)

5.6.2 Ethylene Vinyl Acetate

The test results showed that the addition of VA to PE resin rendered EVA film plastics more permeable to water vapour (Table 5.29). Such an observation has been previously reported by other researchers (2.5.4 Ethylene Vinyl Acetate). It is postulated that the increase in permeance was due to the VA cross linking forcing the long PE chains apart. Such action resulted in an increase in film pore size, allowing rapid water vapour flow.

Of the EVA films tested, normal EVA film 2 and the IREVA film transmitted water vapour at the slowest rate. This low permeance to water vapour was not surprising as the films were produced similarly, with only 4% VA, by the same manufacturer. The permeance values for these two films were not significantly different.

Where normal EVA films were tested at varying film thicknesses, the thinner films tended to have greater permeance to water vapour (Table 5.29).

5.6.3 Polyvinyl Chloride

PVC film had a relatively low permeance to water vapour compared with most other films tested.

5.6.4 Co-extruded Films

The double layer co-extruded film of 125μm thickness had the highest permeance value of all the films tested. The thicker 200μm film had a substantially lower permeance value.

The triple layer co-extruded film had a low permeance to water vapour compared with most of the other films tested.

5.6.2 Significance and Use

Each film was tested in only one position so that the passage of water was monitored in one direction. The film positioning was such that the higher humidity conditions in the test were imposed on that side of the film which would be subjected to high humidity conditions in practice.

Water vapour loss or gain to the greenhouse interior modifies the thermal condition of the environment. Furthermore, changes in humidity can be expected to affect the incidence of condensation formation and may change crop irrigation requirements and promote the development and spread of crop diseases (refer 2.2.7 Double Cladding). The importance of water vapour transmission through film plastic cladding materials, however, is questionable. The amount of water vapour passing through the cladding system is insignificant compared with that amount introduced to, or purged from, the greenhouse interior via ventilation infiltration.

5.7 Standard Costings

The standard cost for each of the film plastic cladding materials, which underwent testing in this study, are presented in table 5.30. The values listed here represent the estimated cost to commercial growers, as at October 1989, as reported by film distributors.

Table 5.30 Costings of Film Plastic Cladding Materials

Material	Cost ($\$/m^2$)
PE	
Standard	1.50
Infra-red	0.75
Woven 1.	2.16
2.	2.71
EVA	
Normal 1.*	2.43
2.	2.75
3.	2.03
4.*	1.79
Infra-red	2.85
Reinforced	4.42
PVC	7.50
Co-extruded Film	
Double layer*	1.75
Triple layer	2.20

* 200um thick film

CHAPTER SIX

APPLICATIONS

The results of each of the optical, thermal and mechanical tests have been used to evaluate and compare the competing products. By combining the results of all the significant tests, an overall property definition for each of the film plastic cladding materials can be generated. Furthermore, a products performance under specified environmental conditions and restraints (i.e. under scenario conditions) can be evaluated and compared to the performance of products subject to those same conditions.

The following scenario conditions are commonly faced by commercial growers:

1. Conditions where an 'all-round' cladding is required, offering high light levels, good heat retention properties and a fair degree of mechanical strength.

2. Conditions where high PAR levels are required for optimal yields.

3. Conditions where PAR levels are not critical.

4. Conditions where the physical durability of the cladding material is important.

5. Where a double cladding system is to be employed.

6.1 Procedure

The optical, thermal retention and mechanical strength properties and the standard cost values of each of the film plastics tested, were linearly scaled. Consequently, each material was designated four values, ranging between 0 and 100. Three values represented the performance of the material optically, thermally and mechanically, respectively. The remaining value represented the relative cost of the material. The weighting of each of the four scaled values could then be changed according to the demands of the relevant scenario.

The values were used to compare the overall functional performance of each of the film plastic cladding materials. The best performers were identified as having the highest total weighted average.

6.1.1 Optical Properties

Of all the light entering the greenhouse space, photosynthetically active radiation (PAR) is the most important for plant growth (refer 2.2.1.2 Photosynthetically Active Radiation). For this reason the PAR transmissivity (PT) of each of the film plastic cladding materials was linearly scaled.

The PAR transmissivities were scaled according to the following equation:

$$PT_s = \frac{(PT - PT_w)}{(PT_b - PT_w)} \times 100 \qquad (6.1)$$

where PT_s = linearly scaled PAR transmission value

PT = PAR transmissivity

PT_w = PAR transmissivity of the worst performing material

PT_b = PAR transmissivity of the best performing material

The linearly scaled PAR transmission values (PT_s) are listed in table 6.1.

6.1.2 Thermal Properties

The thermal transmissivity (TT) of each of the film plastic cladding materials was linearly scaled. The transmissivities were scaled according to the following equation:

$$TT_s = \frac{(TT_w - TT)}{(TT_w - TT_b)} \times 100 \qquad (6.2)$$

where TT_s = linearly scaled thermal transmission value

TT = thermal transmissivity

TT_w = thermal transmissivity of the worst performing material

TT_b = thermal transmissivity of the best performing material

The linearly scaled thermal transmission values (TT_s) are listed in table 6.1.

6.1.3 Mechanical Properties

The three most important mechanical properties of film plastics are the tear resistance, the maximum tensile strength and the impact resistance (refer 2.4.2 Mechanical Damage). By combining the individual linearly scaled values from the results of the tear resistance, tensile strength and impact resistance tests, a combined mechanical strength property for each film material can be obtained.

The combined scaled mechanical strength (MS_s) of each of the film plastic cladding materials was calculated by scaling each of the test results, then averaging over the three tests, according to the following equation:

$$MS_s = \frac{TR_s + TS_s + IR_s}{3} \tag{6.3}$$

where MS_s = combined scaled mechanical strength

TR_s = linearly scaled tear resistance value

TS_s = linearly scaled tensile strength value

IR_s = linearly scaled impact resistance value

The linearly scaled combined mechanical strength (MS_s) values are listed in table 6.1.

6.1.4 Standard Costings

The standard cost per m^2 of each of the film plastic cladding materials was linearly scaled. The standard costs were scaled according to the following equation:

$$C_s = \frac{(C_e - C)}{(C_e - C_i)} \times 100 \qquad (6.4)$$

where C_s = linearly scaled standard cost value

C = standard cost

C_e = standard cost of the most expensive material

C_i = standard cost of the most inexpensive material

The linearly scaled standard cost values (C_s) are listed in table 6.1.

Table 6.1 Linearly Scaled Values (PTs, TTs MSs and Cs) from the Results of the PAR Transmission, Thermal Transmission and Combined Mechanical Strength Tests and From the Costings of Each of the Materials

Material	Thickness (um)	PAR Transmission (PT_s)	Thermal Transmission (TT_s)	Mechanical Strength (MS_s)	Standard Cost (C_s)
PE					
Standard	125	87	0	8	89
Infra-red	80	73	66	1	100
Woven 1.	150	0	31	98	79
2.	200	47	36	100	71
EVA					
Normal 1.	150	89	51	17	84
	200	89	51	22	75
2.	150	78	21	12	70
3.	180	91	46	22	81
4.	125	86	46	11	91
	150	86	46	12	91
	200	86	46	19	84
Infra-red	150	62	89	10	68
Reinforced	250	81	68	33	45
PVC	400	67	100	52	0
Co-extruded Film					
Double Layer	125	100	54	7	92
	200	100	54	24	85
Triple Layer	150	80	32	8	79

6.2 Analysis

6.2.1 Scenario One - An 'All Round' Cladding Material is Required

A film plastic cladding material which will allow high PAR levels into the greenhouse, is mechanically strong and which will retain radiant energy within the greenhouse, is often sought by growers.

The 'all round' best performing film plastic cladding materials were identified by:

1. Equally weighting the PAR transmission (PT_s), thermal transmission (TT_s), the overall mechanical strength (MS_s) and the standard cost (C_s) values.
2. Averaging the weighted PT_s, TT_s, MS_s and C_s values.

The best 'all round' film plastic cladding materials are listed, in descending order, in table 6.2.

Table 6.2 **Best Overall Film Plastic Cladding Materials**

Material	Total Weighted Average#	Susceptibility to Photodegradation	Cost
Co-extruded Double Layer 200um	66	Low	Low
PE Woven 2	61	Assumed Low~	Medium
Co-extruded Double Layer 125um	63	Low	Low
EVA Reinforced	60	Low	High
EVA Normal 1 150u	60	Low	Low

~ Refer 5.1.3 Ultra-violet Radiation
\# $(PT_s + TT_s + MS_s + C_s)/4$

Both the 200μm and the 125μm thick co-extruded double layer materials performed the best as 'all round' films (Table 6.2). The co-extruded film transmitted very high levels of PAR and could be expected to retain much radiant heat within a greenhouse clad with it. The films were relatively low in cost compared with the standard cost of competing products.

The performance of the woven PE film was largely influenced by its excellent mechanical strength. This film would not transmit as much PAR into a greenhouse as would be desired in most cultivating situations. The woven PE film 2 was, however, inexpensive and could be expected to last a long period of time without degrading under the affects of the high ultra-violet (UV) radiation levels experienced in New Zealand.

The normal EVA films 1 (150μm) and 3 had excellent PAR transmission are were not expensive. Both films will not degrade readily following long term exposure to UV radiation.

Unfortunately, PVC and reinforced EVA film plastic cladding materials are very expensive (Table 5.30). The cost of the cladding material is a very important selection criterion for commercial growers.

6.2.2 Scenario Two - Conditions Requiring High PAR Transmission

The yield of most commercial greenhouse crops grown in New Zealand (especially tomato, cucumber and carnation crops) is limited by the intensity and duration of PAR incident on the canopy (Mastalerz, 1977; Rost *et al.*, 1979). Furthermore, higher light intensities will enhance the effect of carbon dioxide enrichment of the greenhouse atmosphere, resulting in increased crop yields and improved produce quality (Enoch and Hurd, 1977; Slack and Hand, 1985). Therefore, high light (particularly PAR) transmission is essential in many situations.

The film plastic cladding materials most suitable for obtaining high PAR levels within the greenhouse were identified by:

1. Double weighting the PAR transmission (PT_s) and keeping the weighting of the thermal transmission (TT_s) and the overall mechanical strength (MS_s) values as in scenario one.

2. Averaging the weighted PT_s, TT_s and MS_s values.

The best film plastic cladding materials for this scenario are listed, in descending order, in table 6.3.

Table 6.3 Best Performing Film Plastic Cladding Materials When High PAR Levels are Required

Material	Total Weighted Average#	Susceptibility to Photodegradation	Cost
PVC	72	Low	High
Co-extruded Double Layer*	70	Low	Low
EVA Reinforced	66	Low	High
Co-extruded Double Layer~	65	Low	Low
EVA Normal 1*	63	Low	Low

* 200um thick film

~ 125um thick film

\# $(2.PT_s + TT_s + MS_s)/4$

The PVC film and the reinforced EVA film performed very well in this scenario. This is because of the films comparitively high mechanical strength and heat retention properties. The PVC film plastic did not, however, transmit as much PAR as most competitive products and it had a high cost.

The double layer co-extruded film performed very well at both the 125μm and 200μm thickness, largely because of its very high PAR transmission capabilities. These film plastics were also relatively inexpensive. The thinner 125μm double layer co-extruded film has limited mechanical strength.

The normal EVA type film plastic cladding material of 200μm thickness also performed well as it had high PAR transmission capabilities.

6.2.3 Scenario Three - Conditions Where PAR Transmission is Not Critical

Such a scenario is indicative of a greenhouse nursery situation or when the greenhouse is shaded for a large portion of the daylight hours (e.g. as in conservatories). The film plastic cladding materials most suitable for employment in such situations were identified by:

1. Not including the weighting of the PAR transmission (PT_s) but equal weighting the thermal transmission (TT_s) and the overall mechanical strength (MS_s) values.

2. Averaging the weighted TT_s and MS_s values.

The best film plastic cladding materials for this scenario are listed, in descending order, in table 6.4.

Table 6.4 Best Performing Film Plastic Cladding Materials Where PAR Transmission is not Critical

Material	Total Weighted Average#	Susceptibility to Photodegradation	Cost
PVC	76	Low	High
PE Woven 2	68	Assumed Low~	Medium
PE Woven 1	65	Assumed Low~	Medium
EVA Reinforced	52	Low	High
EVA Infra-red	50	Low	Low

~ Refer 5.1.3 Ultra-violet Radiation
* 200um thick film
\# $(TT_s + MS_s)/2$

The PVC film plastic cladding material performed well in the situation described as scenario three. The excellent heat retention properties of PVC are most beneficial in a nursery situation, as the greenhouse environment generally needs to be stabilized at a warm temperature for optimal plant development. Furthermore, a heating system is often employed to maintain a warm environment at night and a PVC film plastic cladding material will keep heating costs to a minimum.

The woven PE film plastics were probably the most suitable for a nursery situation. These materials have excellent mechanical strength and their UV quenching additives should maintain their weathering performance. They were most limited by their poor heat retention properties. The woven films could, however, be considered preferable to PVC as their cost was much less.

The reinforced EVA would be suitable in this situation, with respect to both heat retention and mechanical strength requirements.

The infra-red EVA (IREVA) film plastic cladding material was not primarily manufactured as a single skin film. It did, however, exhibit excellent heat retention and fair mechanical strength properties, which make the film material suitable for cladding a greenhouse where PAR transmission is not critical. The moderate cost of the IREVA film makes it competitive with PVC, although not with the woven film plastics.

6.2.4 Scenario Four - Conditions Where Excellent Mechanical Strength is Required

High mechanical strength is imperative in situations where a film plastic cladding material is subject to harsh environmental conditions (i.e. where the incidence of hail and extreme precipitation or wind loads is high). The film plastic cladding materials most suitable for employment in such situations were identified by:

1. Double weighting the overall mechanical strength (MS_s) and keeping the weighting of the PAR transmission (PT_s) and thermal transmission (TT_s) values as in scenario one.

2. Averaging the weighted PT_s, TT_s and MS_s values.

The best film plastic cladding materials for this scenario are listed, in descending order, in table 6.5.

Table 6.5 Best Performing Film Plastic Cladding Materials When High Strength is Required

Material	Total Weighted Average#	Susceptibility to Photodegradation	Cost
PE Woven 2	71	Assumed Low~	Medium
PVC	68	Low	High
PE Woven 1	57	Assumed Low~	Medium
EVA Reinforced	54	Low	High
Co-extruded Double Layer*	51	Low	Low
EVA Normal 1*	46	Low	Low

~ Refer 5.1.3 Ultra-violet Radiation
* 200um thick film # $(PT_s + TT_s + 2.MS_s)/4$

The woven film plastics, the PVC and the reinforced EVA film plastics all performed well where the mechanical strength of the film plastic cladding material was critical. The high cost of the PVC film material and the low PAR transmissivity of the woven materials should, nonetheless, be considered as an important criteria for cladding material selection.

The low cost double layer co-extruded and the normal EVA film 1 materials also performed well. In very extreme environmental conditions these film materials should be regarded as unsuitable because of their medium mechanical strength.

6.2.5 Scenario Five - Where a Double Cladding System is to be Employed

In a double cladding system, the outer film layer is subject to the weathering environment and so it must be mechanically strong. The inner film layer generally functions as a barrier to thermal radiation, so radiant energy is retained within the greenhouse. A portion of incident light is reflected at each film air interface (refer 2.2.2.1 Reflection). Therefore, both film layers must transmit high levels of PAR as a high proportion of incident PAR can be expected to be reflected by a double layer cladding system.

The most common film combinations used for double cladding were evaluated. In New Zealand these combinations generally comprise of two film plastic materials which are made available by the same distributor. Other combinations of film materials, not evaluated here, may also be competitive.

The film plastic cladding materials most suitable for employment as an outer cladding layer were identified by:

1. Weighting the PAR transmission (PT_s) and combined mechanical strength (MS_s) values equally and disregarding the thermal transmission (TT_s) value (Table 6.1).

2. Averaging the weighted PT_s and MS_s values.

The film plastic cladding materials most suitable for employment as an inner cladding layer were identified by:

1. Weighting the PAR transmission (PT_s) and thermal transmission (TT_s) values equally and disregarding the combined mechanical strength (MS_s) value (Table 6.1).

2. Averaging the weighted PT_s and TT_s values.

The best film plastic cladding materials for utilizing in a double cladding system are listed, in descending order, in table 6.6.

Table 6.6 Best Performing Combinations of Film Plastic Materials Commonly Used for Double Cladding

Material		Layer	Total Weighted Average*	Combined Average
Co-extruded Double Layer	200um	Outer	62	
	125um	Inner	77	70
EVA Normal 1	200um	Outer	56	
	150um	Inner	70	63
EVA Normal 1	200um	Outer	56	
PE Infra-red		Inner	70	63
EVA Normal 2		Outer	45	
EVA Infra-red		Inner	76	60
EVA Normal 4	200um	Outer	53	
	150um	Inner	66	59

* Outer layer = $(PT_s + MS_s)/2$ Inner layer = $(PT_s + TT_s)/2$

The combination of 125μm and 200μm double layer co-extruded film plastic materials appeared to be most promising for a double cladding system. The suitability of this combination was accentuated by the very high PAR transmissivity of the double layer co-extruded film material. Furthermore , both films contained UV absorbers and were comparatively inexpensive.

The combinations involving the 200μm normal EVA film 1 as the film material for the outer layer also performed well as a double cladding system. The infra-red PE (IRPE) film plastic cladding material was specifically manufactured as an inner lining for use with the normal EVA film 1 in a double cladding system. Hence, the

IRPE film was manufactured as a low strength 80um film with excellent radiant heat retention properties (Table 5.6). The 150μm normal EVA film plastic cladding material may be preferred as an inner layer where high PAR transmission of the double cladding system is required.

The IREVA film plastic cladding material also had excellent radiant heat retention properties (Table 5.6) and was primarily manufactured as an inner lining for use with the normal EVA film 2 in a double cladding system. The mechanical strength, specifically the comparatively low impact strength (Table 5.24), of the normal EVA film plastic was limiting in this double cladding combination.

6.3 Significance and Use

Potentially there are many ways of scaling and weighting the property values and ranking the film plastic cladding materials. The resultant weighted averages reported in tables 6.2 to 6.6 are comparative. It should be realised that, although some of the values are low, this does not necessarily mean the product is a poor performer in the given scenario situation. Rather, it is not as suitable as competitive products.

Furthermore, the evaluation of the performance of each of the film plastic cladding materials under the various scenario restraints is arbitrary.

6.3.1 Scaling

The linear scaling system used in the evaluation resulted in the best performing product having a scaled property value of 100, and the worst performing product having a scaled property value of zero. This may be considered hypercritical as a product having a significant property value, however small, is designated a powerless value in the scenario analysis.

Upon investigation, it was found that no other elementary scaling system scaled the optical, thermal and mechanical properties in such a way as to make them comparable and equally weighted for averaging.

6.3.2 Weighting

The process of weighting was entirely arbitrary. The magnitude of the weighting components were, however, largely influenced by practical and realistic reasoning.

For example, the weighting of PAR transmissivity, in most situations, should be comparatively high. This is because the crop yield is limited by the amount of PAR incident on the plants. The level of PAR transmitted into the greenhouse is determined by the cladding material.

Upon weighting the scaled heat retention property (TT_s) of the internal layer of a double cladding system, the overall heat retention effect of double cladding should be considered. This is because it more than outweighs the benefits gained from installing an IR, rather than a normal, film plastic as the inner film layer.

The scaled combined mechanical strength (MS_s) value could be calculated differently in situations where a particular mechanical property (i.e. tear resistance, tensile strength or impact resistance) is of more importance than another.

CHAPTER SEVEN

SUMMARY AND CONCLUSIONS

Many greenhouse designers and growers in New Zealand are confused with the multitude of commercially available film plastic cladding materials and their range of quality and cost. Furthermore, the quality of any product is dependant on its optical performance, radiant heat retention properties and mechanical strength. Therefore, questions frequently arise as to which is the best product, or which should be used in a specific situation.

The principle objectives of this study were to measure and evaluate the optical, thermal and mechanical properties of film plastic cladding materials available in New Zealand. The film plastics were to be compared and ranked according to their performance as established from testing.

Laboratory experiments were carried out on film plastic samples volunteered by distributors. The experiments included light transmission, thermal radiation transmission and various mechanical strength tests.

Based on the experiments and their analysis, the following conclusions were drawn:

1. The film plastics allowing the highest transmission of photosynthetically active radiation (PAR) included the standard polyethylene (PE) and infra-red PE (IRPE) films, the normal ethylene vinyl acetate (EVA) films, the reinforced EVA film and the co-extruded films. The PAR transmissivity values of all the film plastics tested are listed in table 5.1.

2. PAR transmission was hardly affected (i.e. a change of less than 3%) by the addition of vinyl acetate (VA) to PE resin, or the addition of infra-red (IR) absorbers or ultra-violet (UV) stabilizers to standard PE or EVA resins.

3. The film plastics most prone to the affects of UV radiation (photodegradation) were standard PE and IRPE films. The effect of UV radiation on woven PE film plastics was not estimated.

4. The inclusion of VA and/or IR absorbers into standard PE or EVA resins affected the light diffusion properties of the resulting film materials.

5. The film plastic cladding materials which were most opaque to thermal (IR) radiation were polyvinyl chloride (PVC) film, the IR films and the reinforced EVA film. The thermal transmissivity values of all the film plastics tested are listed in table 5.6.

6. The inclusion of an IR absorbing system into the standard PE or EVA resin substantially improved the radiant heat retention properties of the resulting film material. However, the heat retention properties of the triple layer co-extruded film plastic tested were poor.

7. The woven PE films, the reinforced EVA and the PVC films consistently performed the best in all the mechanical strength tests. The tear resistance, tensile strength and impact resistance properties, of each of the film plastics tested, are listed in tables 5.8 to 5.11, 5.13 to 5.20 and 5.23 to 5.26, respectively.

8. The thickness of the film plastics largely contributed to the tear resistance, tensile strength and impact resistance of the materials.

9. The addition of high levels of VA (i.e. levels significantly greater than 4%) to PE resin impaired the tear resistance and tensile strength properties of the resulting material. The greater thickness of these EVA film plastics compensated for this 'weakening' affect (refer Conclusion 8).

10. The addition of IR absorbers and/or UV stabilizers hardly affected the mechanical properties of the film plastics. However, it was recognised that the addition of UV stabilizers would largely prevent the mechanical weakening of the film plastics during long periods of weathering.

11. The transparency of film plastics containing IR absorbers was reduced when they were mechanically stressed. It was postulated that the physical bonding of the film polymers was disrupted during the extreme mechanical loading. The stress resulted in a clouding of the film material.

12. The co-extruded film plastics did not 'out perform' the PE and EVA films with respect to mechanical strength. However, it was recognised that such film plastics are manufactured to improve PAR transmission into the greenhouse and to retain heat, rather than to be mechanically superior.

13. The addition of VA to PE resin increased the water vapour permeance of the resulting film material. The water vapour transmission and water vapour permeance values, for each of the film plastics tested, are listed in table 5.28.

14. The PVC film and the reinforced EVA film plastics performed exceptionally well for most application scenarios. However, their high cost may limit their selection in some situations.

15. Of the less expensive film plastics, the double layer co-extruded film and the normal EVA film 1 performed well for most application scenarios, especially where good PAR transmission and heat retention properties were important.

16. The woven PE film plastics were most suitable for cladding where PAR transmission into the greenhouse was not critical (e.g. nursery situations) and where excellent mechanical strength was required.

17. The most promising double cladding combinations were those utilizing the varying thicknesses of the double layer co-extruded film or the normal EVA film 1. The IR films, IRPE and IREVA, were best utilized as the inner lining for the double cladding system.

CHAPTER EIGHT

LIMITATIONS OF THIS STUDY AND RECOMMENDATIONS FOR FURTHER RESEARCH

While conducting this study it was recognised that the evaluation of the film plastic cladding materials was limited by the nature of laboratory scale tests. In particular, the controlled testing of mechanical properties meant that the film plastics were subject to tear, tensile and impact loadings which were not strictly characteristic of those experienced in practice. Although the tests allowed the film plastics to be appropriately ranked, the limitations of each product's individual performance, as found in practice, may not have been accurately estimated.

Each of the products were obtained directly from the distributor and stored prior to testing. Consequently, the test results were for new film plastic materials rather than for those having experienced some period of aging or weathering. The process of aging and weathering could be expected to affect the optical, thermal and mechanical properties of the materials. Furthermore, the effectiveness of ultra-violet (UV) stabilizing mechanisms is most successfully proven following long term film exposure to UV radiation.

The evaluation of the film plastics, as functional claddings in varying situations, is somewhat limited by the approach to scaling of the respective properties and the arbitrary process of weighting each property. A more reliable evaluation and ranking system could be developed using an appropriate mathematical model of a fully functional greenhouse.

In view of the above limitations, the following topics warrant research to develop further understanding of the performance of film plastic cladding materials:

1. The mechanical properties of the film plastics need to be studied under conditions which simulate, more closely, the loading conditions occurring in practice. This could be achieved through development of standard laboratory procedure and/or development of standard apparatus.

2. Long range weathering tests need to be carried out. The optical, thermal and mechanical properties of the film plastics should be re-evaluated following a period of no less than one years exposure to the natural environment. Further evaluation following considerably longer periods (up to five years) of exposure would also be useful.

3. Independent research into the performance of UV stabilizing systems, in particular UV quenching systems. Comparison of optical, thermal and mechanical properties of film plastics, with and without UV stabilizing packages, and re-evaluation of these differences following long term weathering, would render the most important information.

4. The incorporation of the optical and thermal properties of each of the film plastics, as variables, into a steady state mathematical model which predicts the thermodynamic state of the greenhouse environment. This would serve to qualify the suitability of each of the film plastics for any specific application. This would also help quantify the performance of each of the film plastics under the unique radiation environment experienced in New Zealand.

REFERENCES

Agpac Plastics Limited. 1989. Developments in Greenhouse Technology Film. *New Zealand Horticulture* 6 (12): 17.

Allen, P.G. 1975. Heat Conservation in Film Plastic Structures. *Commercial Grower* 4145: 1131, 1161.

American Society for Testing and Materials. 1977. "D 1003 Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics." Philadelphia.

American Society for Testing and Materials. 1981. "D 618 Conditioning Plastics and Electrical Insulating Materials for Testing." Philadelphia.

American Society for Testing and Materials. 1984. "D 638M Standard Test Method for Tensile Properties of Plastics (Metric)." Philadelphia.

American Society for Testing and Materials. 1985a. "D 1709 Standard Test Method for Impact Resistance of Polyethylene Film by the Free-falling Dart Method." Philadelphia.

American Society for Testing and Materials. 1985b. "D 4272 Standard Test Method for Impact Resistance of Plastic Film by Instrumented Dart Drop." Philadelphia.

American Society for Testing and Materials. 1987. "E 171 Standard Atmospheres for Conditioning and Testing Materials." Philadelphia.

American Society for Testing and Materials. 1988a. "D 1004 Standard Test Method for Initial Tear Resistance of Plastic Film and Sheeting." Philadelphia.

American Society for Testing and Materials. 1988b. "D 882 Standard Test Method for Tensile Properties of Thin Plastic Sheeting." Philadelphia.

American Society for Testing and Materials. 1990. "E 96 Standard Test Method for Water Vapour Transmission of Materials." Philadelphia.

Bailey, B.J. Unpublished report. "Infra-red and Optical Properties of Some Plastic Materials Used in Greenhouses." Departmental Note No. DN/G/616/2105, N.I.A.E., Bedford.

Balls, R. 1986. Glasshouses and Translucent Plastic Structures. In "Horticultural Engineering Technology - Fixed Equipment and Buildings." MacMillan Education Ltd., London.

Barahona, F.J. and J.M.G. Vasquez. 1985. Influence of Pesticides on the Degradation of Polyethylene Film Greenhouse Cladding on the Andalusian Coast. *Plasticulture* 65: 3 - 10.

Bowman, G.E. 1972. Influence of Greenhouse Covering, Propagation Bench Design and Pot Type on Environmental Temperature. *Agric. Met.* 10: 211.

Breuer, D.R. 1985. "Energy in New Zealand Greenhouses." New Zealand Energy Research and Development Committee. Report No. 120.

Bruns, G.W. 1985. Experiences on Damages to Roofing - Materials and Greenhouse Construction. *Acta Hort.* 170: 127 - 131.

Brydson, J.A. 1982. Additives for Plastics. In "Plastics Materials." Butterworth Scientific, London.

Coulson, K.L. 1975. "Solar and Terrestrial Radiation." Academic Press Inc., New York.

Dartiguepeyrou, R. 1986. EVA for Cladding Plastic Structures. What to Choose? *Plasticulture* 70: 19 - 26.

Duffie, J.A. and W.A. Beckman. 1980. Radiation Transmission Through Covers and Absorption by Collectors. In "Solar Engineering of Thermal Processes." John Wiley and Sons, New York.

Duncan, G.A. and J.N. Walker. 1975. Selection of Greenhouse Covering Materials. *Trans. A.S.A.E.* 18: 703 - 706.

Enoch, H. and R. Hurd. 1977. Effect of Light Intensity, Carbon Dioxide Concentration, and Leaf Temperature on Gas Exchange of Spray Carnation Plants. *J. Experimental Bot.* 28 (102): 84 - 95.

Fuller, R.J. and P.I. Cooper. 1983. Solar Transmittance of Australian Greenhouse Cladding Materials. *Agric. Eng. Aust.* 12 (1): 25 - 33.

Garzoli, K.V. 1985. Property Requirements of a Greenhouse Covering Material for Clear Sky Conditions. *Acta Hort.* 170: 59 - 67.

Gemmel, A. 1986. A New Grade of Polyester Film Aids Greenhouse Development. *Plasticulture* 69: 2 - 8.

Godbey, L.C., T.E. Bond and H.F. Zornig. 1979. Transmission of Solar and Long-Wavelength Energy by Materials Used as Covers for Solar Collectors and Greenhouses. *Trans. A.S.A.E.* 22: 1137 - 1144.

Goldsberry, K.L. 1984. Temperature, Solar Radiation and Sulphur Cause Yellowing of Plastic Greenhouse Glazings. *Res. Bull.* 406: 2 - 4.

Grafiadellis, M. 1985. A Study of Greenhouse Covering Plastic Sheets. *Acta Hort.* 170: 133 - 142.

Halleux, D. de, J. Nijskens, J. Deltour, S. Coutisse and A. Nisen. 1985. The Effect of Condensation on the Heat Transfers of Greenhouse Covering: Glass or Polyethylene. *Plasticulture* 66: 19 - 25.

Hare, J.G., B. Norton and S.D. Probert. 1984. Design of 'Greenhouses': Thermal Aspects. *App. Energy* 18: 49 - 82.

Holman, J.P. 1986. Introduction. In "Heat Transfer (6th Ed.)." McGraw-Hill Book Company, Singapore.

Horiguchi, I. and T. Hirano. 1988. Effects of the Properties of Plastic Film on Fog Formation in Greenhouses. *J. Agric. Met.* 43 (4): 295 - 303.

Horiguchi, I., H. Sugaya and H. Tani. 1982. The Measurement of Longwave Radiation Properties Upon Plastic Films Used in Greenhouses. *J. Agric. Met.* 38 (1): 9 - 14.

Hurd, R.G. 1983. Energy Saving Techniques in Greenhouses and Their Effects on the Tomato Crop. *Sci. Hort.* 34: 94 - 101.

Incropera, F.P. and D.P. DeWitt. 1985. "Fundamentals of Heat and Mass Transfer (2nd Ed.)." John Wiley and Sons, New York.

Landgren, B. 1985. Aging Tests With Covering Materials for Greenhouses. *Acta Hort.* 170: 119 - 131.

M.A.F. 1976. "Plastic Greenhouses." Publication 40. Ministry of Agriculture and Food, Ontario.

M.A.F. 1981. "Greenhouses." Publication 40. Ministry of Agriculture and Food, Ontario.

Massey University. 1989. "Food Packaging Technology Laboratory Manual." Department of Packaging Technology, Massey University, New Zealand.

Mastalerz, J. 1977. "The Greenhouse Environment." John Wiley and Sons, New York.

McLean, C.D. 1982. Polyethylene Greenhouses - Trends and Extended Lifetimes. *Aust. Hort.* 80 (1): 15 - 19.

McNaughton, K.G., A.K.H. Jackson and I.J. Warrington. 1981. "Greenhouse Covering Materials - Optical and Thermal Properties of Some Materials Available in New Zealand." Technical Report No. 9. Plant Physiology Division, D.S.I.R., New Zealand.

Mermier, M. and A. Baille. 1988. The Optical Properties of Plastics Materials for Greenhouses and Screens. *Plasticulture* 73: 11 - 24.

Mitchell B. J. Personal communication. D.S.I.R. Industrial Development Division. Christchurch, New Zealand.

Mognani, G. 1987. Performance of Different Plastics Films in Double-clad Greenhouse: Four Years Research. *Plasticulture* 73: 9 - 22.

Monteith, J.L. and M.H. Unsworth. 1990. "Principles of Environmental Physics (2nd Ed.)." Edward Arnold, London.

Nijskens, J., J. Deltour, S. Coutisse and A. Nisen. 1984. Heat Transfer Through Covering Materials of Greenhouses. *Agric. For. Met.* 33: 193 - 214.

Nijskens, J., J. Deltour, S. Coutisse and A. Nisen. 1988. Radiometric and Thermal Properties of the New Plastic Films for Greenhouse Covering. In "International Symposium on Engineering and Economic Aspects of Energy Saving in Protected Cultivation." September 4th - 8th. Cambridge.

Nijskens, J., D. de Halleux, J. Deltour, S. Coutisse and A. Nisen. 1985. Condensation Effect on Heat Transfer Through Greenhouse Claddings: Glass and Polyethylene. *Acta Hort.* 174: 135 - 138.

O,Flaherty, T. 1977. Double-clad Polythene Greenhouses for Energy Saving. *Farm and Food Research* 8 (1): 17 - 18.

O.A.R.D.C. 1979. Modification Methods. In "Conserving Energy in Ohio Greenhouses." Ohio Agricultural Research and Development Centre, Ohio.

Orliac, F. 1981. Snow, Wind and Greenhouses. *Plasticulture* 51: 35 - 42.

Pacini, L. 1985. Plastics Specified for Improvement of Protected Crops: the Italian Standard Mark. *Plasticulture* 65: 11- 16.

Raviv, M., Y. Allingham. 1983. Modification Characteristics of Polyethylene Films. *Plasticulture* 59: 3 - 12.

Roberts, W., J.C. Simpkins and D. Mears. 1985. Performance of IR Polyethylene Film Over Two Years Trial. *Acta Hort.* 170: 81 - 90.

Robertson, G.L. Unpublished report. "Evaluating the Permeability of Thermoplastic Polymers." Department of Packaging Technology, Massey University.

Rost, T.L., M.G. Barbour, R.M. Thornton, T.E. Weir and C.R. Stocking. 1979. Photosynthesis. In "Botany. A Brief Introduction to Plant Biology." John Wiley and Sons, New York.

Salisbury, F.B. and C.W. Ross. 1978. Special Topics. In "Plant Physiology (2nd Ed.)." Wadsworth Publishing Company, California.

Scott, G. (editor) 1980. Loss of UV Stabilizers from Polyolefins During Photo-oxidation. In "Developments in Polymer Stabilization - 3." Allied Science Publishers Ltd., London.

Sherry, W.J. and K.L. Goldsberry. 1978. Night Heat Requirements of Plastic Covered Greenhouses. *Colo. Flow. Grow. Ass. Bull.* 334: 1 - 3.

Slack, G. and D. Hand. 1985. The Effect of Winter and Summer CO_2 Enrichment on the Growth and Fruit Yield of Glasshouse Cucumber. J. Hort. Sc. 60 (4): 507 - 516.

Son, P. 1990. UV Stabilizers. *Modern Plastics Encyclopedia* 66 (11): 209 - 211.

Spice, H.R. 1974. The Use of Plastics for Protected Environments. *Outlook on Agric.* 8: 63 - 69.

Stepek, J. and H. Daoust. 1983. Ultraviolet Protecting Agents. In "Additives for Plastics." Springer-Verlag, New York.

Sturrock, J.W. 1981. Energy Conservation in the Greenhouse Industry. *N.Z. Commer. Grow.* 36 (7): 21 - 25.

Tesi, R., C. Dehennau and D. Marlarme. 1986. Properties of New PVC Rigid Sheets for Greenhouses. *Plasticulture* 71: 37 - 46.

Thekaekara, M.P. 1971. Solar Magnetic Radiation. In "NASA Space Vehicle Design Criteria (Environment)." NASA SP-8005, National Aeronautics and Space Administration, Washington D.C.

Ting, K.C. and G.A. Giacomelli. 1987a. Solar Photosynthetically Active Radiation Transmission Through Greenhouse Glazings. *Energy in Agric.* 6: 121 - 132.

Ting, K.C. and G.A. Giacomelli. 1987b. Availability of Solar Photosynthetically Active Radiation. *Trans. A.S.A.E.* 30 (5): 1453 - 1457.

Tzeklev, G., B. Samra and J.D. Solarkov. 1984. A Study on Multi-Wall Covering of Greenhouses in Bulgaria. *Plasticulture* 62: 11 - 18.

Vanzin. D.A. 1990. Antifogging agents. *Modern Plastics Encyclopedia* 66 (11): 161.

Waaijenburg, D. 1985. Research on Greenhouse Cladding Materials. *Acta Hort*. 170: 103 - 109.

Weimann, G. 1989. The Characteristics of Light Transmissivity, Heat Consumption and Condensation Processes in Different Film Greenhouses. *Acta Hort*. 245: 133 - 140.

Wells, C. 1989. "Greentech 89." Agricultural Engineering Department, Massey University.

White, R.A.J. 1978. Some Comparisons Between Plastic and Glass Greenhouses. *Int. Pla. Prop. Soc. Comb. Proc*. 28: 273 - 279.

APPENDICES

Appendix A Solar Radiation Transmission Curves

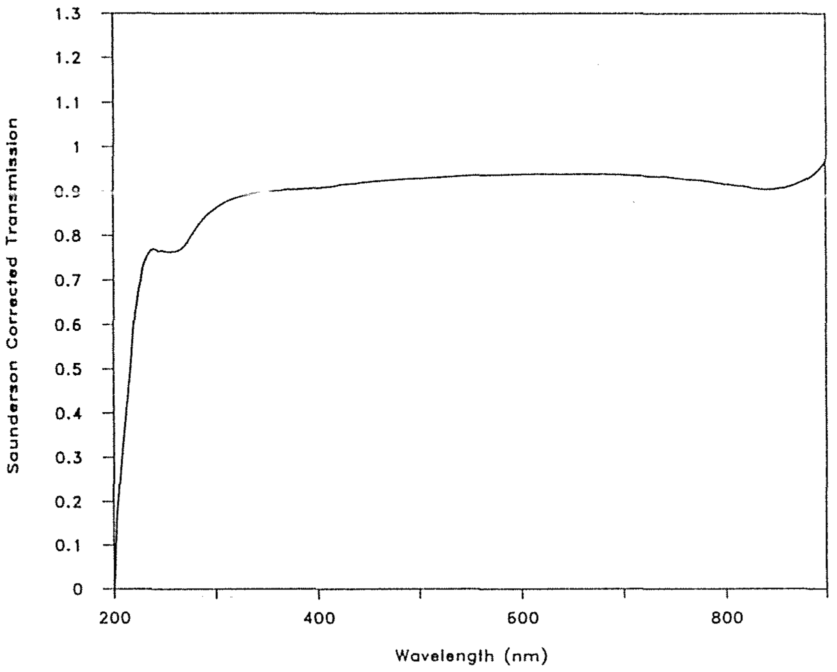


Figure A1 Standard polyethylene film plastic cladding material

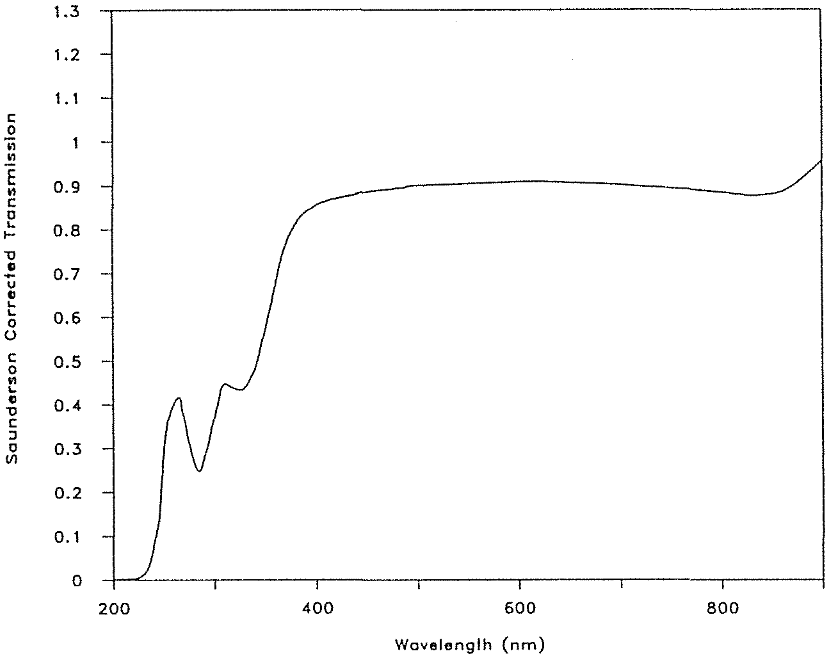


Figure A2 Polyethylene infra-red film plastic cladding material

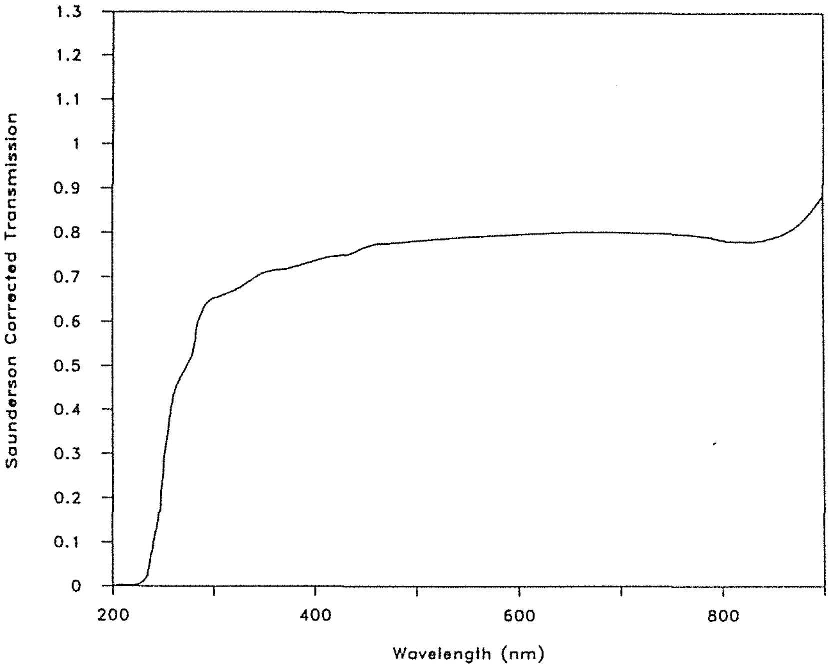


Figure A3 Polyethylene woven 1 film plastic cladding material

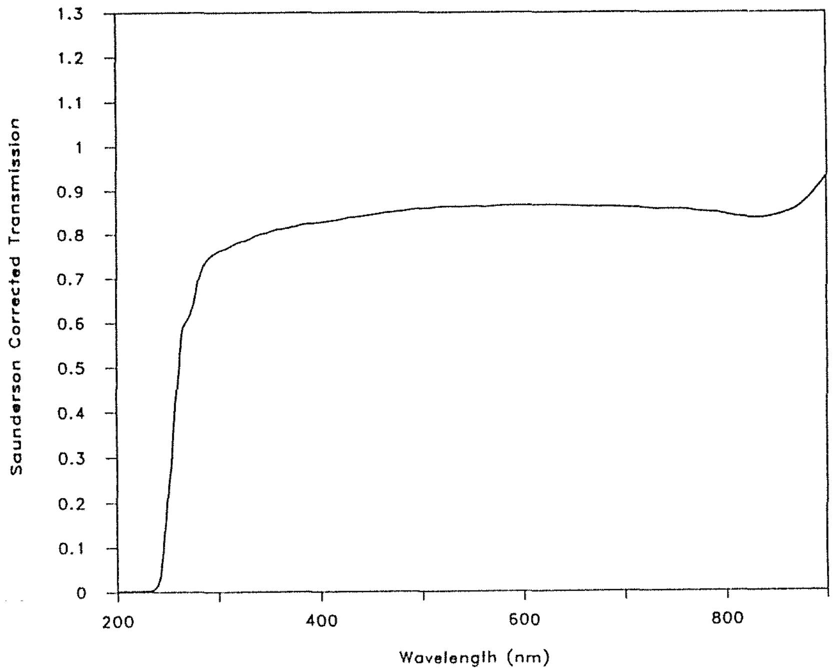


Figure A4 Polyethylene woven 2 film plastic cladding material

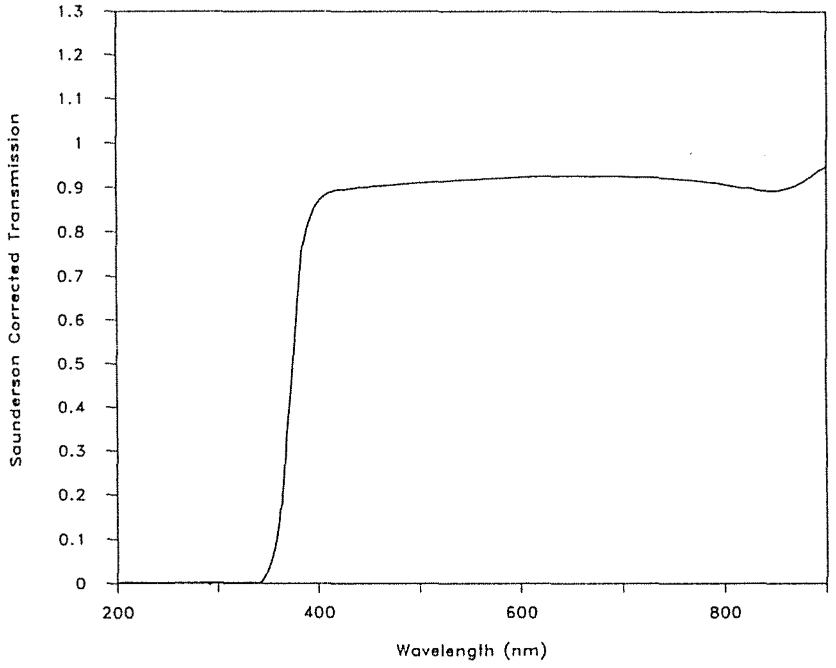


Figure A5 EVA normal 1 film plastic cladding material

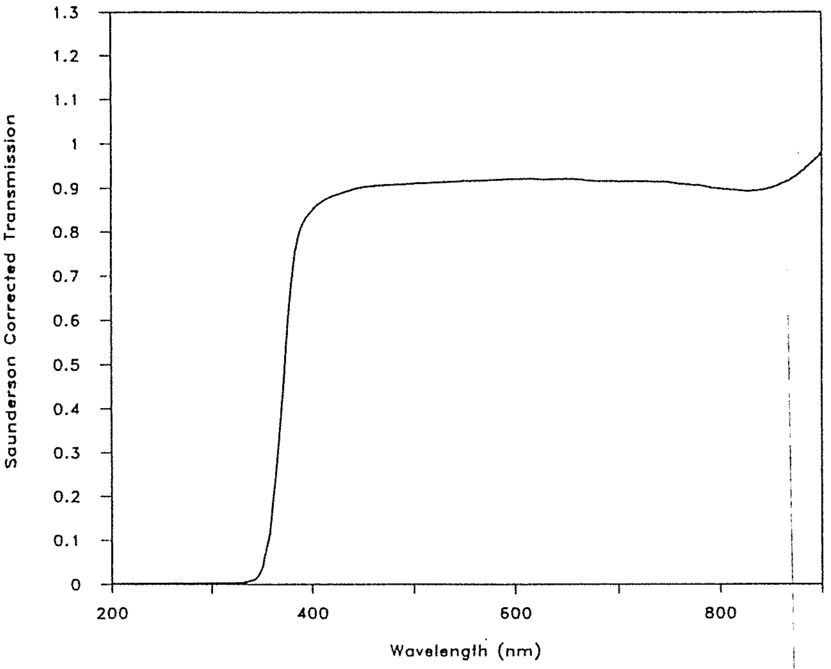


Figure A6 EVA normal 2 film plastic cladding material

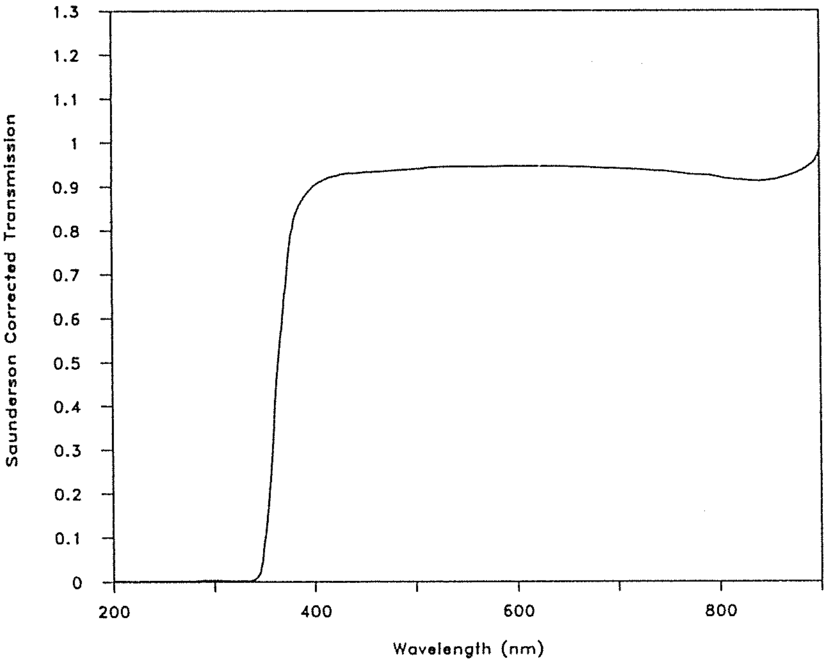


Figure A7 EVA normal 3 film plastic cladding material

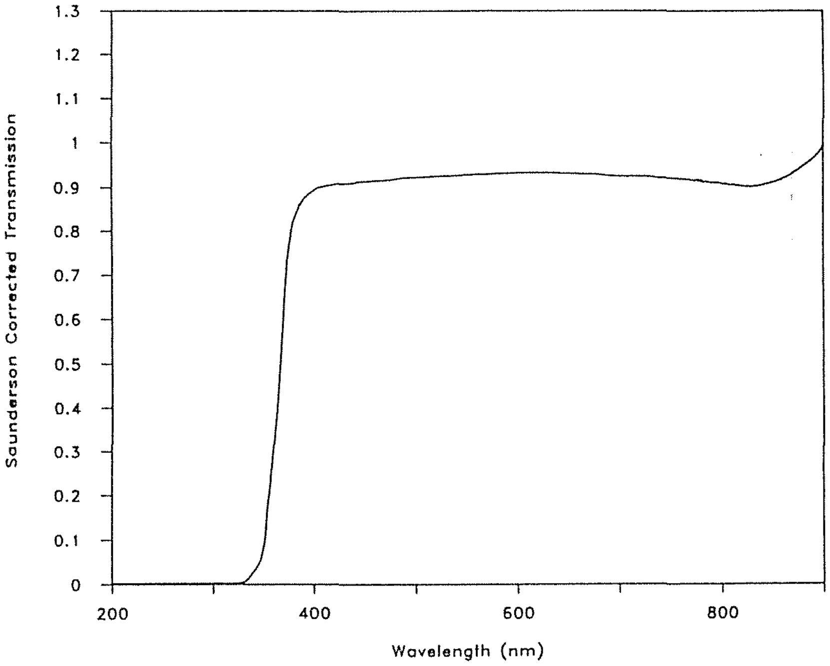


Figure A8 EVA normal 4 film plastic cladding material

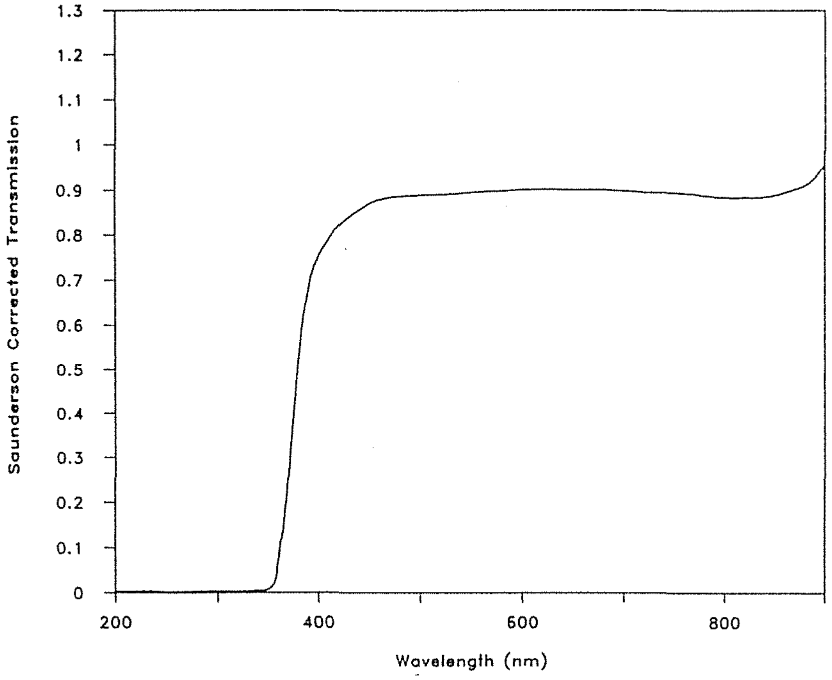


Figure A9 EVA infra-red film plastic cladding material

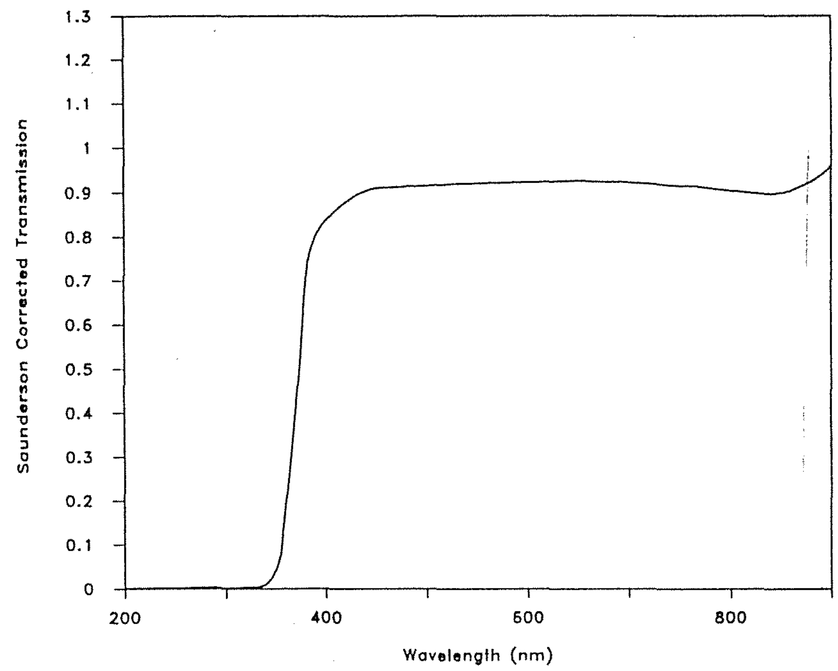


Figure A10 EVA reinforced film plastic cladding material

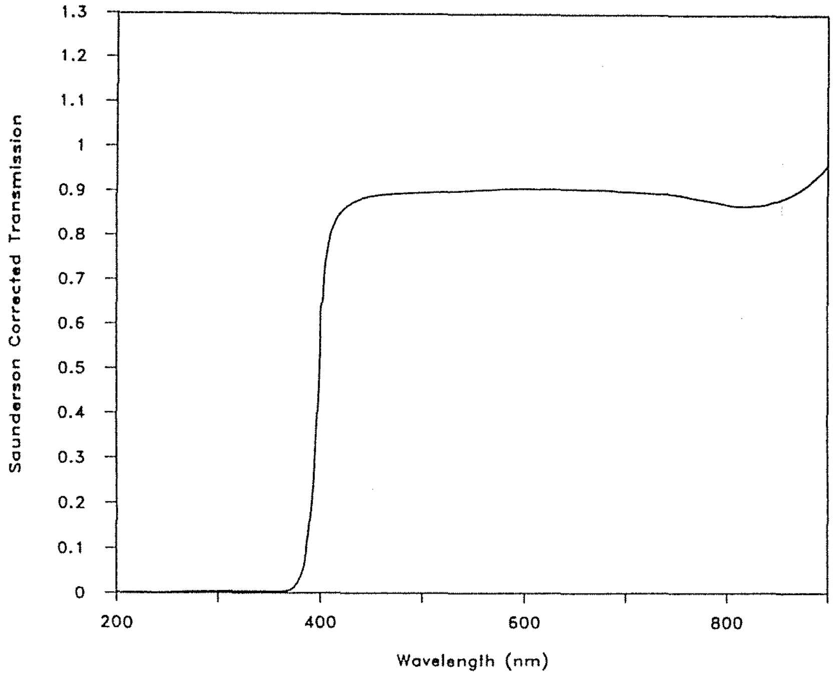


Figure A11 Polyvinyl chloride film plastic cladding material

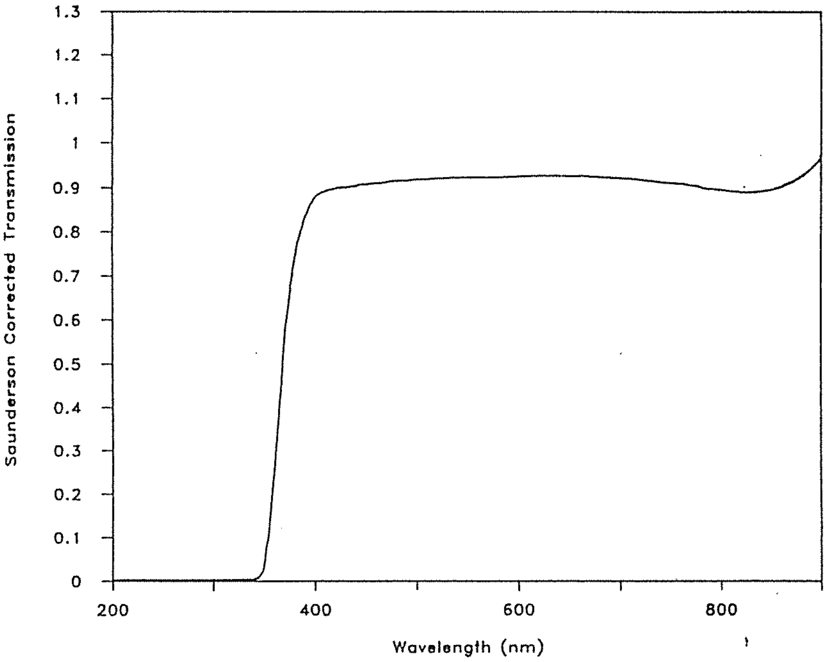


Figure A12 Co-extruded double layer film plastic cladding material

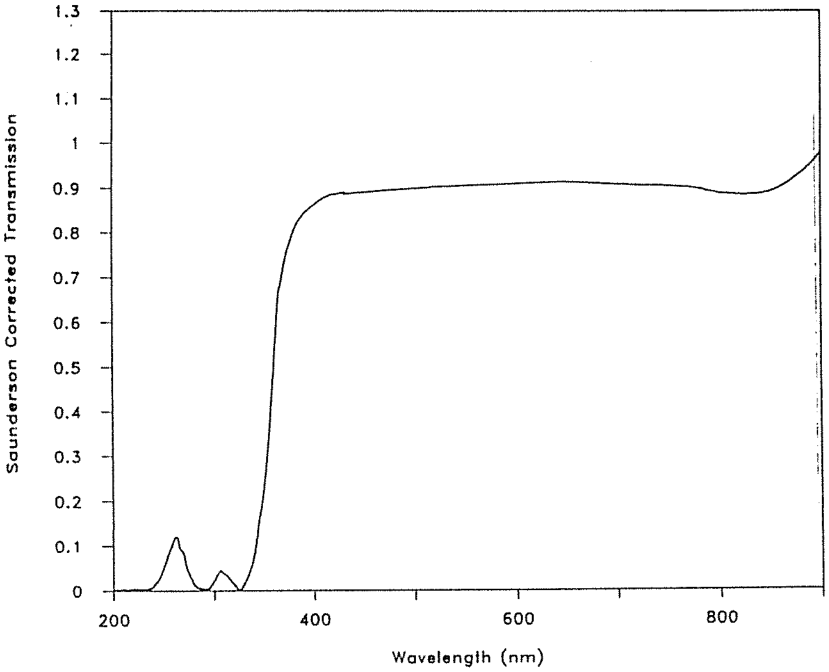


Figure A13 Co-extruded triple layer film plastic cladding material

Appendix B Thermal Radiation Transmission Curves

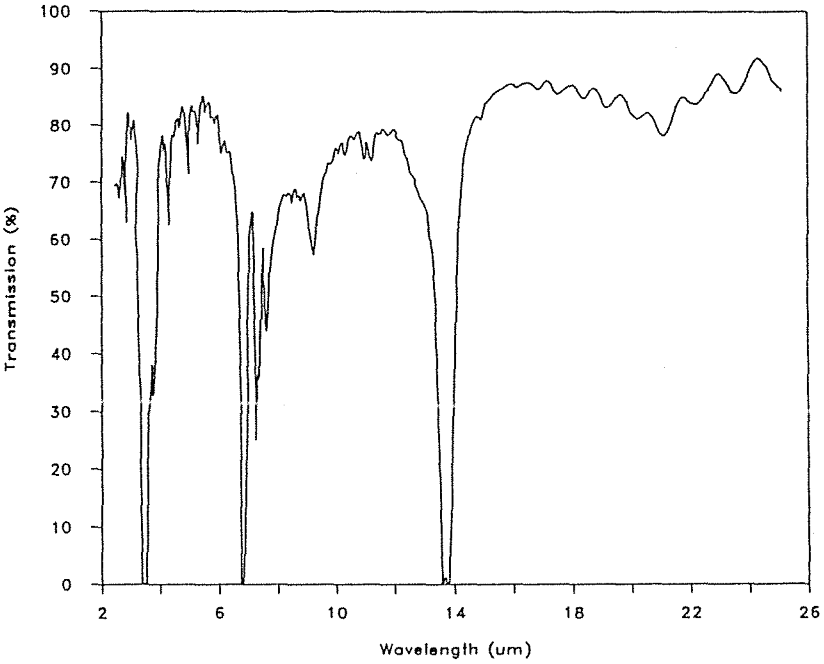


Figure B1 Standard polyethylene film plastic cladding material

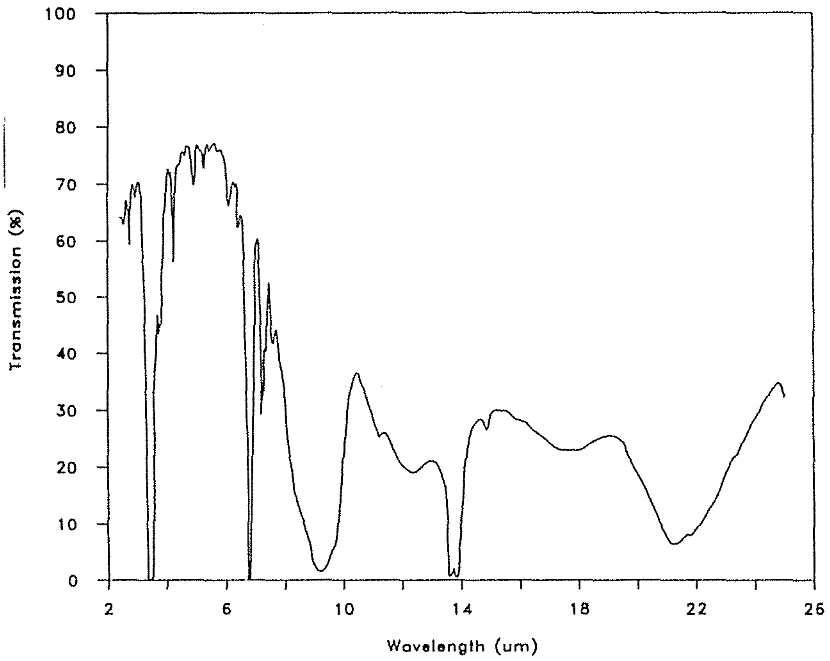


Figure B2 Polyethylene infra-red film plastic cladding material

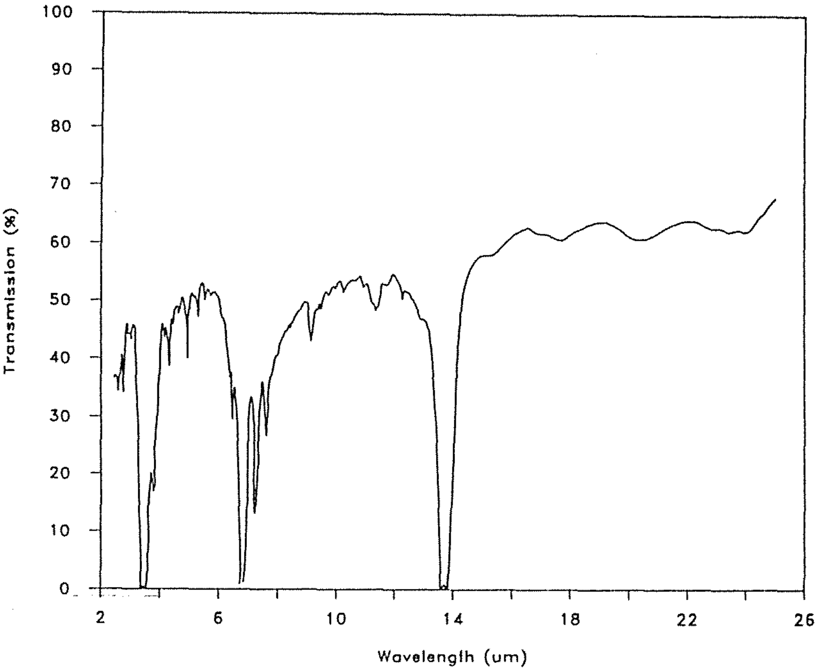


Figure B3 Polyethylene woven 1 film plastic cladding material

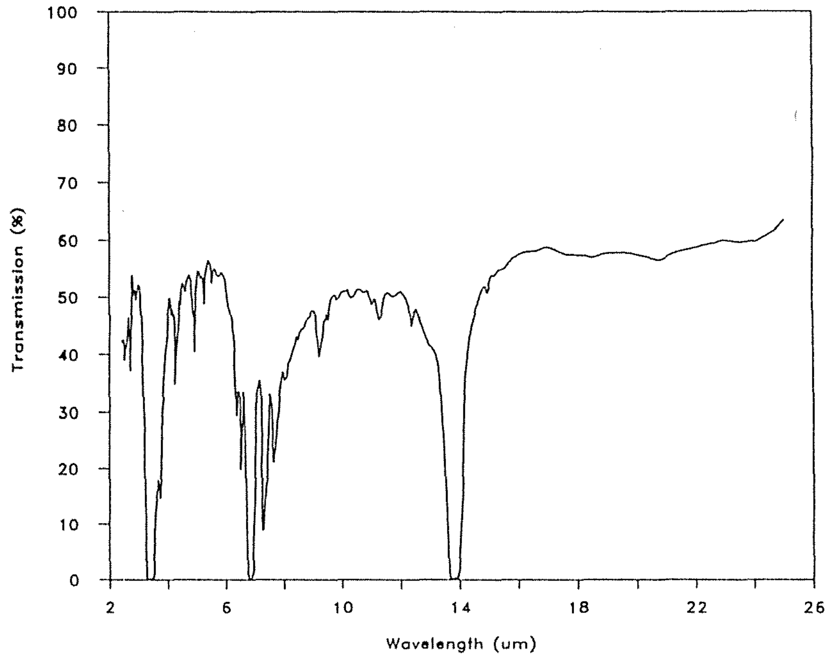


Figure B4 Polyethylene woven 2 film plastic cladding material

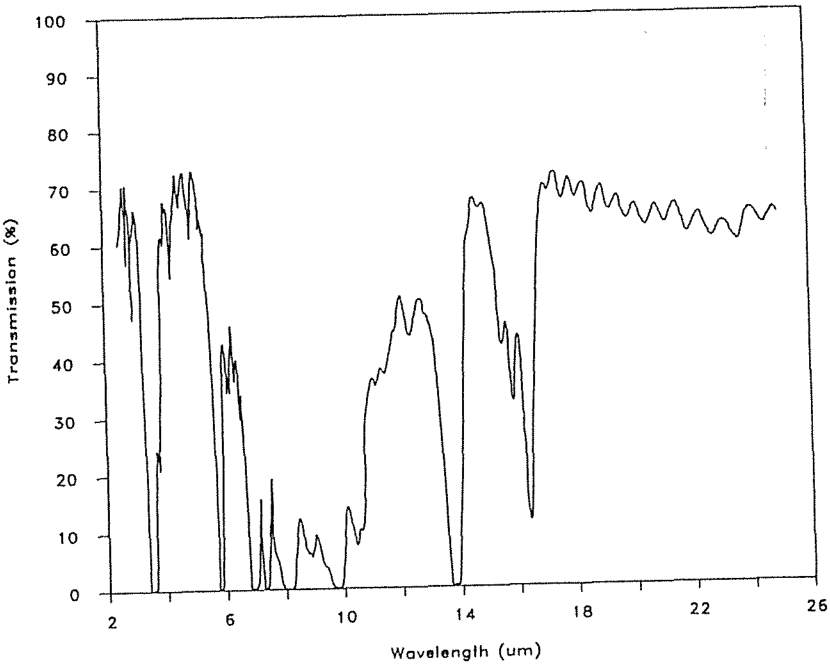


Figure B5 EVA normal 1 film plastic cladding material

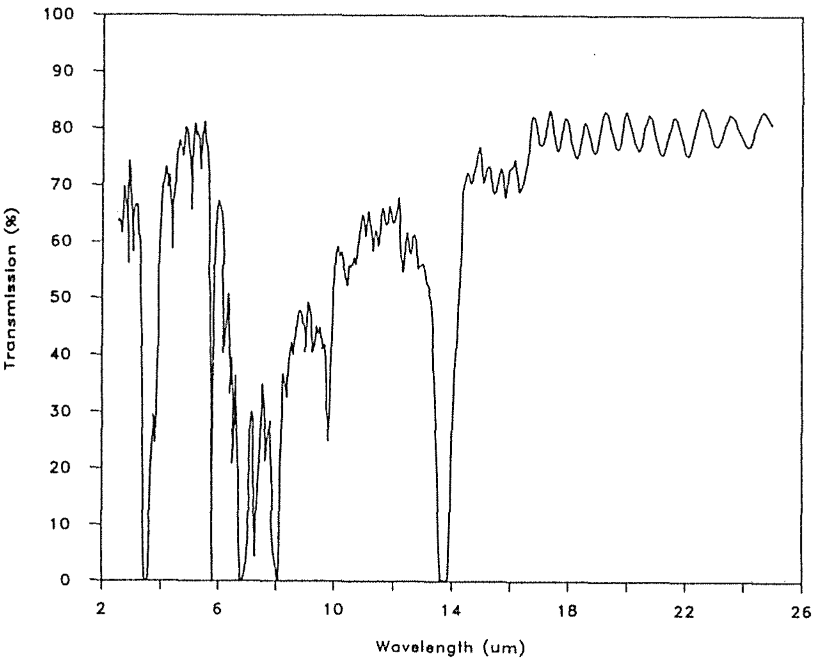


Figure B6 EVA normal 2 film plastic cladding material

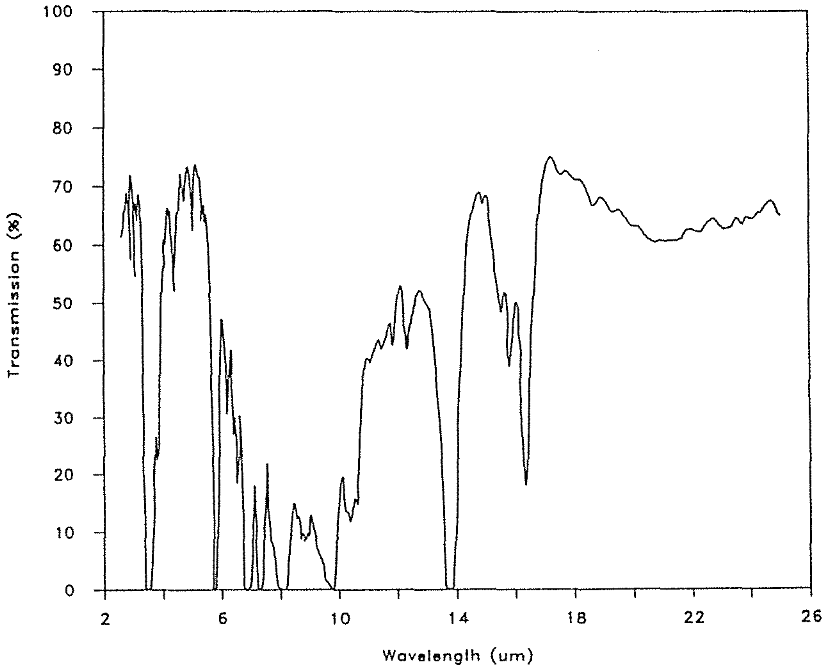


Figure B7 EVA normal 3 film plastic cladding material

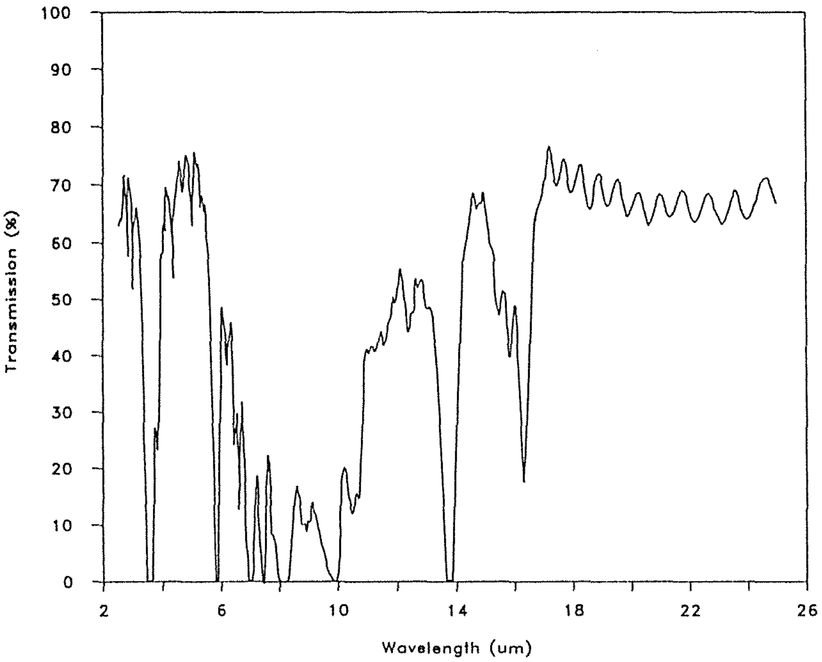


Figure B8 EVA normal 4 film plastic cladding material

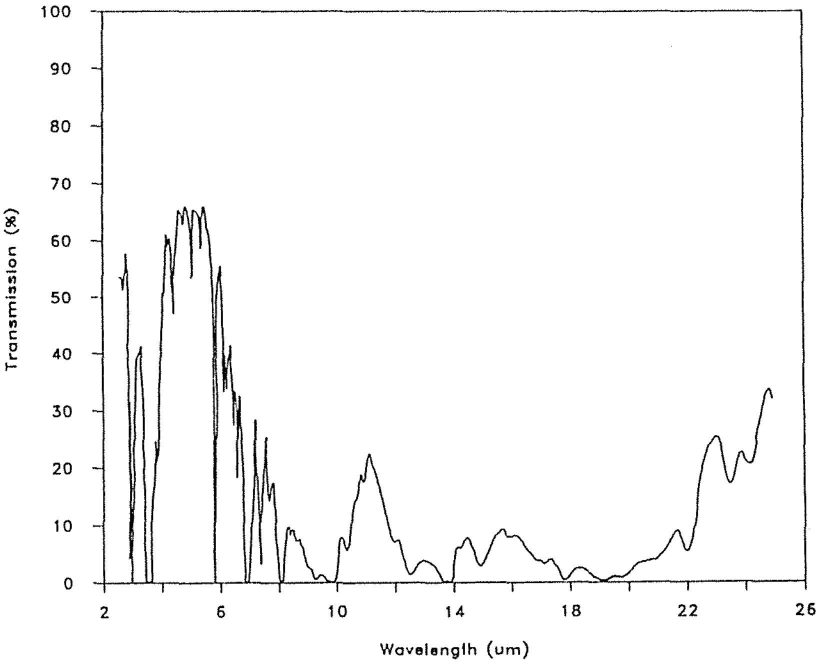


Figure B9 EVA infra-red film plastic cladding material

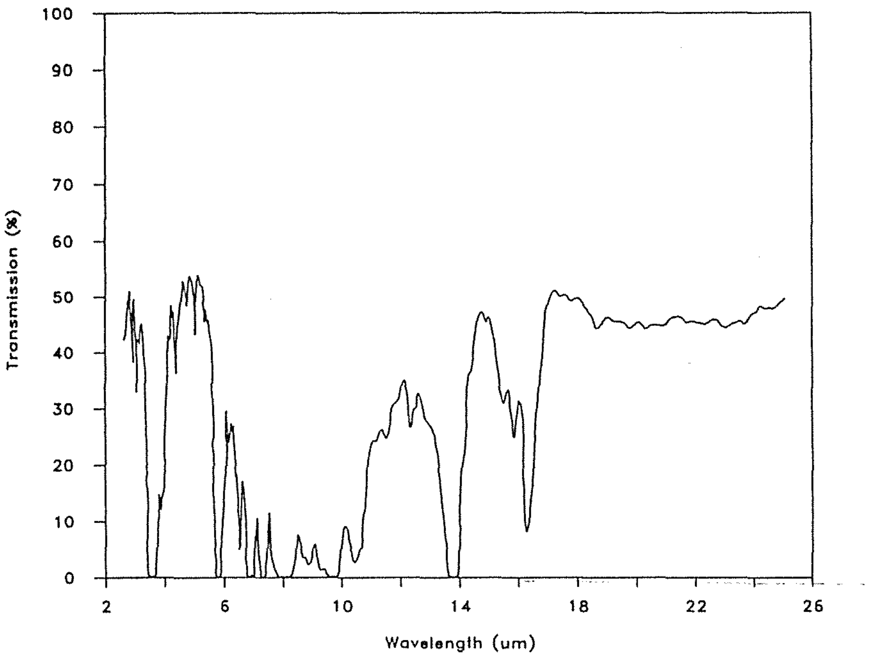


Figure B10 EVA reinforced film plastic cladding material

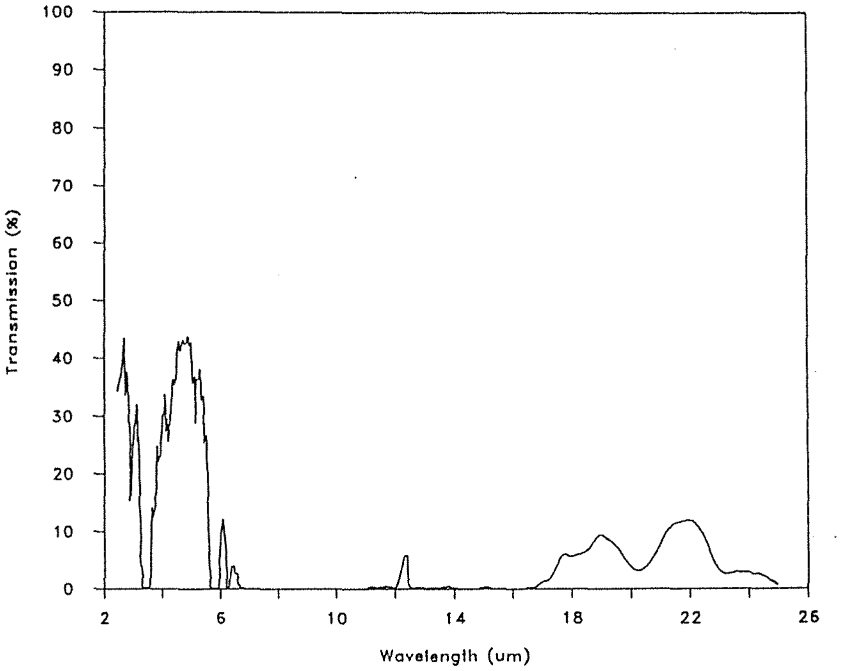


Figure B11 Polyvinyl chloride film plastic cladding material

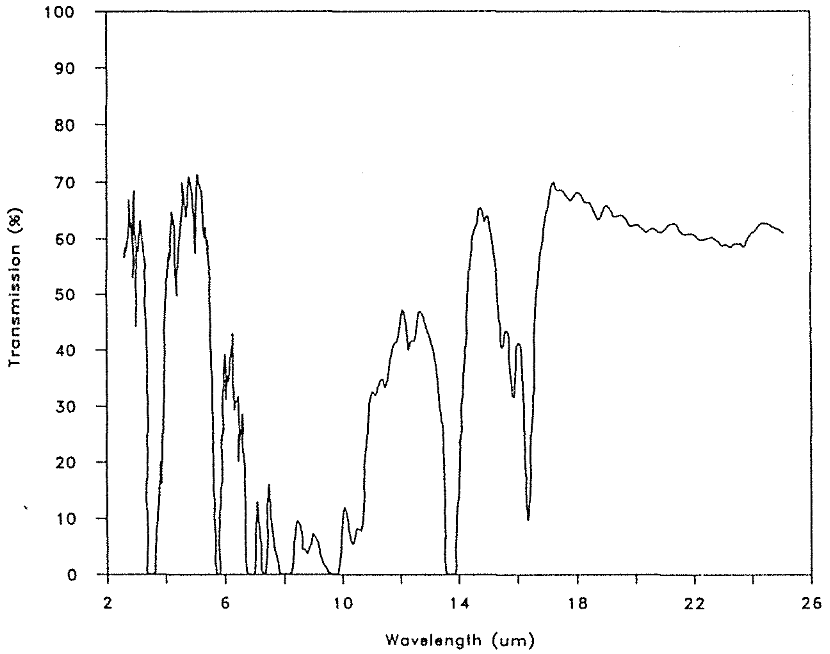


Figure B12 Co-extruded double layer film plastic cladding material

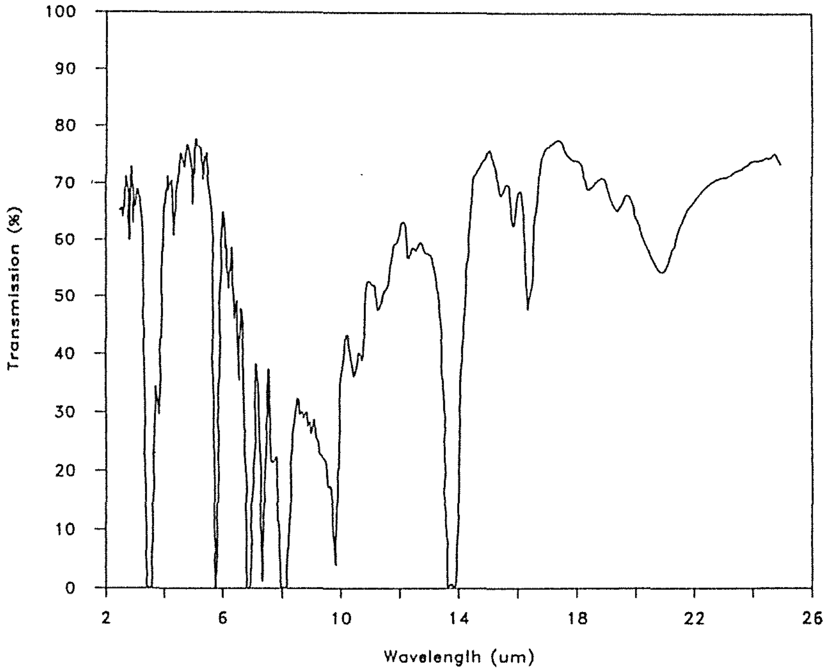


Figure B13 Co-extruded triple layer film plastic cladding material