Greenhouse Covering Systems

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Summary. **The diversity of coverings for the greenhouse and other plant production structures has increased dramatically during the past 4 decades. This has resulted from the availability of new types of covering materials and enhancements of previously existing materials, as well as the demands for technological improvements within the expanding controlled environment agricultural industry. The types of coverings currently available are dominated by plastics. These range from traditional glass to the recent advent of polymer plastics, such as thin films or multilayer rigid thermoset plastic panels. Available enhancements such as ultraviolet radiation (UV) degradation inhibitors, infrared radiation (IR) absorbency, and anti-condensation drip surfaces, as well as their physical and spectral properties are discussed. The selection of specific covering alternatives has implications for the greenhouse superstructure and its enclosed crop production system.**

Controlled environment plant production systems offer the possibility of providing large numbers of high-quality crops with greater predictability. Crop quality and predictability can be achieved within efficient, cost-effective structures such as. a well-designed greenhouse. The selection of the cover material (generically called glazing, a derivation from the traditional use of glass as the covering material) has a tremendous influence on the crop production capability of the greenhouse system. The glazing influences the amount and type of solar radiation at the plant canopy. This directly affects plant growth. In addition, the microclimatic factors, such as air humidity or carbon dioxide concentration, are affected indirectly by the glazing system.

For a proper discussion of greenhouse coverings, it is not only necessary to evaluate their capabilities and shortfalls, but also to consider their relationship within the overall greenhouse crop production system. There are many greenhouse configurations, both in design and dimensions. No two greenhouses are exactly alike, if one considers the overall size; dimensions of length, width, and height; number of bays; orientation; etc. The selection of a glazing and the design of the greenhouse system should not be mutually exclusive tasks. If the production of high-quality plant products within efficient, cost-effective, controlled environment systems is the ultimate goal, then the design must consider the type of crop and its associated cultural demands and the production system that will support the growth of the crop. All other greenhouse systems should support adequately these two needs. Careful thought will resolve the specific details of the greenhouse design, including a balance of the investment costs, available resources, and the potential crop-production capacity.

The crop and its biological requirements should provide the basis of the design decisions for the greenhouse system. This system contains many individual, but interrelated, components and processes. Once the biological requirements are satisfied, then the engineering concerns should be addressed in terms of the operational expectations of the proposed system. These horticultural engineering aspects of the interrelated greenhouse system have been categorized within the three general topics of automation, culture, and environment (Giacomelli, 1991; Ting and Giacomelli, 1992). Once the compatibility of the specifically selected systems within these three categories has been determined, the greenhouse superstructure can be chosen. The greenhouse structure must accommodate the production system, promote good labor and managerial working conditions, provide the desired microclimate, and minimize disturbances to its surrounding environment.

The glazing is one of the component systems for the greenhouse. The selection of a covering is crucial for attainment of an optimal controlled environment, particularly relating to the solar radiation intensity and wavelengths. No single covering material is ideal. Each will influence the plant microclimatic parameters in various ways. A glazing that is selected must help achieve the desired end product. The remaining discussion focuses on the important generalized selection criteria and the specific attributes of the various covering materials. The emphasis is on plastics as greenhouse covers.

Plastics have revolutionized the greenhouse industry in many ways. The simplified, less-costly procedure of enclosing the greenhouse structure is one of the more dramatic changes. Many new greenhouses, as well as all temporary structures, are covered with plastics. Air-inflated, double-polyethylene film greenhouses represent an estimated 80% of the new greenhouse construction within the United States (Reilly, 1992). Total greenhouse area in the United States increased by 25%, from 10,000 to 12,500 acres (4047 to 5061 ha) between 1979 and 1988 (Gray, 1992). The proportion of films and other plastic greenhouse coverings increased dramatically from 36% to more than 61% of this total area. Glass and fiberglass dropped to 16.5% and 22.3%, respectively.

Considerations for designing and selecting a covering system

Even when a material offers strength, consistency, durability, manufacturing quality control, and safety, other factors should be considered. These include the transmission of solar radiation and energy conservation, and how these interact with glazing/superstructure systems.

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Solar radiation transmission. The main purpose of a greenhouse covering is to create an internal environment that is conducive to plant growth regardless of the external environment. Energy from the sun is transmitted through the transparent greenhouse covering to the plant, where it drives the photosynthetic process. The capability of the covering to transmit light in wavelengths useful to plants, of which only a portion is visible to the eye, is therefore extremely important. The intensity of these wavelengths (400 to 700 nm) of photosynthetically active radiation (PAR) directly influences growth and development in green plants. Other nonvisible solar radiation wavebands include ultraviolet (UV), infrared (IR), and far-red (FR) wavebands.

Solar radiation can be the most limiting, uncontrollable environmental factor in plant growth, particularly at latitudes >25° from the equator. For example, the available radiation in December is about one-third of that available in June at latitudes near 40°N. This is primarily because of the low sun angle and the short day length. The atmosphere acts as a filter to reduce the absolute amount of solar energy that can pass. It also changes the proportion of the PAR waveband compared to the other wavebands by selectively filtering more of the UV region of the total solar energy spectrum (Table 1). Above the atmosphere, only 38.2% of the solar radiation is within the PAR waveband. The proportion of PAR increases to 42.9% of the total energy reaching the ground, and is dependent on the atmospheric conditions (clouds, moisture, pollution) (Ting and Giacomelli, 1987a).

Solar energy can be transmitted, reflected, or absorbed by the atmosphere and the greenhouse covering. The transmitted portion is needed for plant growth, but only a fraction (1% to 5%) is used by the plant. The remainder is absorbed and re-emitted as thermal radiation (heat), thereby warming the greenhouse air. This "greenhouse effect" is the welcome result of radiation transmission into a closed space, although subsequent cooling of the air may be required to maintain desirable plant growth temperatures. The heat transfer capability of the covering system therefore becomes a very important secondary factor to consider when designing the greenhouse. This is discussed later.

Table 1. ***Percentage of energy distribution of solar radiation above the atmosphere and at the Earth's suface.***

Waveband	Above atmosphere[z]	Earth's surface[y]
UV (390–400 nm)	8.6	6.4
PAR (400–700 nm)	38.2	42.9
FR (700–850 nm)	16.5	15.2
IR (850–2800 nm)	33.9	34.2
Thermal (>2800 nm)	2.7	1.3

[z] *Duffie and Beckman (1980).*
[y] *Thimijan and Heins (1983).*

Radiation received directly from the sun, without prior reflection, is called direct or beam radiation. Diffuse radiation results from the scattering of direct radiation within the atmosphere (or by the cover) and can be received by the plant from all directions. The greenhouse cover transmits both direct and diffuse radiation, but, because of its physical properties, the cover may alter the proportions of each. The diffuse component will increase while the direct component is reduced. This is particularly true for many of the plastic films.

Transmittance (τ) is a physical property of the covering material. It is defined as the ratio of the measured radiation intensity beneath the covering material (I) to that measured simultaneously above (I_o), in the same waveband. The waveband may be the visible PAR or the nonvisible UV(290-400 nm), FR (700-850 nm), or IR (850-2800 nm) wavebands.

$$\text{Transmittance: } \tau = I/I_o$$

Transmittance generally is measured as the total radiation, which is the sum of the direct and diffuse components. This is important because the type ofgreenhouse cover and the greenhouse structure directly affect the absolute amount and the proportion of direct and diffuse radiation that becomes available to the plant canopy beneath.

It is difficult to determine the true transmittance of a greenhouse covering system. The most accurate procedure may require actual measurement of the specific greenhouse during operation. Even this could be misleading if not carefully determined by repetitive measurements throughout a season. Furthermore, the effect of weathering or aging of the covering system continually changes this value.

The reported transmittance values for a glazing typically are obtained from laboratory studies. Measurements performed on the controlled conditions of the laboratory bench will provide the maximum transmissivity for the material. The larger the value, the more desirable, but it must always be <100%. In most cases, this value will be representative of new, clean material, receiving beam radiation that is directed squarely at its surface. This procedure cannot determine the transmittance of similar cover material once installed within a greenhouse, as the circumstances are significantly different. Unfortunately, these are the values regularly provided for the comparison ofprospective cover materials.

In order to maximize solar radiation for the plant, covering materials with the best direct visible radiation transmittance properties traditionally have been used. This may not be the best strategy considering that diffuse radiation is much more predominant on the light-limiting, cloudy periods of the year. It would be more beneficial to determine the total amount of energy (direct and diffuse) transmitted through the glazing for a specific time period (day, season, or year). This could be calculated from the product of the hourly transmittance (τ), measured at the plant canopy, and the solar radiation above the cover (I_o) for each hour.

$$\text{Total Hourly Energy} = \tau_{\text{hour}} * I_o$$

Adding these hourly values for the whole day would represent the total energy available for the plants for that day. To estimate the plant growth potential, a factor for the ability of the plant to use the energy for growth and development should be included. Plant photosynthetic efficiency (η) is dependent on the environmental conditions (radiation intensity, carbon dioxide concentration, etc.). Thus, each hourly energy value could be modified by the plant's efficiency.

$$\text{Total Hourly Energy} = \tau_{\text{hour}} * I_o * \eta$$

This procedure would provide comparisons of greenhouse covering systems based on the potential for plant growth and development, and not solely on the radiation transmission capabilities of the cover material.

The value of the hourly radiation transmission (and, ultimately, the total energy) is dependent on numerous physical and time-dependent factors. The following is a list of major factors that together modify the actual radiation transmitted.

- day of year and hour of day
- latitude
- local weather conditions
- predominance of direct or diffuse solar radiation
- spectral quality or waveband of the radiation
- cover material properties (at installation and as affected in time by weathering, air pollutants, moisture condensation, and dust and dirt accumulation).

In general, radiation transmission also is influenced by the physical structure of the greenhouse. The factors include:

- angle and shape of the roof
- the number and width of spans (distance from gutter to gutter if multispan or ground to ground if single-span)
- height of end walls
- length to width ratio of the structure
- compass orientation.

These factors and their interrelationships make accurate determination of the transmittance of a greenhouse covering system difficult. Laboratory determinations provide a relative maximum potential transmittance of the covering material alone, but provide little information about the covering system transmittance after installation, and nothing of the potential amount of radiation transmission within a greenhouse.

Two alternative methods for making determinations of light transmission are by computer simulation and actual measurement. Computer simulation requires the development of a mathematical model. The model contains a highly detailed description of the physical situation that is represented by equations. This procedure is time-consuming; however, once completed, it can effectively provide a relative theoretical comparison among various alternative designs (Critten, 1987a, 1987b).

Actual measurement of the radiation available within operational greenhouses is also time-consuming. It can only provide information specific to the greenhouse structure and covering material measured. However, such measurements also can give insight to more general situations.

Table 2. *Average daily percent transmission of PAR (400–700 nm) measured just inside the roof and near the plant canopy for four covering material/greenhouse structure combinations.*[z]

Sensor location	Type of covering material			
	Single glass	Acrylic	Double glass	Double PE
At roof	60	58	58	67
At plant canopy	56	55	56	45

[z] *Ting and Giacomelli (1987a); Giacomelli et al. (1988).*

Table 2 contains values for the average daily PAR transmission for four cover/structure combinations (Ting and Giacomelli, 1987b; Giacomelli et al., 1988). Data were calculated from average hourly measurements obtained within greenhouse bays at two sensor locations: 1) 0.5 m (1.6 ft) below the covering material (at roof), which represents transmission of the covering material alone, and 2) 1.8 m (5.9 ft) above the ground (at plant canopy), which represents the influence of the greenhouse structure and the covering material on transmission.

The single-glass (4.8 mm, 0.19 inch), double-glass (38 mm, 1.5-inch spacing), and the acrylic structured panel (16 mm, 0.62 inch) coverings were measured within a commercial cut-flower (rose) greenhouse range. The double-polyethylene greenhouse was a commercially available structure, used for research purposes on the Rutgers Univ. campus. The double-polyethylene greenhouse contained additional component systems located below the cover but above the plant canopy, which the other greenhouses did not contain.

The values in Table 2 include the combined effects of widely varied solar angles and weather conditions during one winter season. These data indicate that the amount of solar energy transmitted to the plant canopy was influenced by the superstructure, as well as other components of the crop production system that may be located overhead. These could include heating pipes or tubes, energy screen, watering system, etc. These results indicated that factors other than the type of cover material could significantly affect the percentage of available solar radiation that was transmitted to the plant canopy during the light-limiting period of the year. This was especially evident within the double-polyethylene-covered research greenhouse.

Energy conservation

The greenhouse also must provide protection from variable weather conditions such as winds, hail, snow, and excessive heat or cold. The heat-retaining properties of the covering system during the long nights and cloud-covered days of the cold season are particularly important. Comparisons of energy conserving capabilities ofgreenhouse covering systems in combination with movable nighttime insulation systems have been documented extensively. A summary can be found in NRAES-3 (Roberts et al., 1989).

The thermal environment of the greenhouse is based on the relative input and outflow of energy. The energy sources are daily solar radiation and/or supplemental heating devices. These sources must balance with the energy losses to maintain the desired conditions.

Greenhouse energy balance

Solar Energy + Supplemental Heat = Energy Losses

Energy is lost from the greenhouse by a combination of convection, radiation, andinfiltration through the surface covering of the greenhouse.

Energy Losses = Convection + Radiation + Infiltration

Convective heat losses generally are similar for all single, thin-layer materials, while most double-layer coverings are nearly alike. Convective heat losses depend on the insulating value of the cover material. The insulation value is increased significantly when a second layer is added. For example, when double layers ofplastic film are separated by a small air space, the result is an approximate 30% reduction in energy transfer compared to a single glass layer (Roberts and Mears, 1969).

Radiative heat losses are related directly to the physical properties of the cover material. These include the emissivity and the transmissivity (in the infrared and thermal wavebands) of the covering material. The emissivity is a material property that defines its ability to emit radiation energy that it has absorbed. Energy absorbed by the cover from inside the greenhouse and emitted to the outdoor environment provides a heat loss from the greenhouse environment. The larger the emissivity the greater the rate of radiation heat loss. The transmissivity is a material property that determines its ability to transmit radiation energy. In this case, it is not the visible radiation that is of concern, but infrared and thermal radiation. This energy is transmitted directly by the cover from inside the greenhouse and it creates a heat loss from the greenhouse environment. The larger the transmissivity for infrared or thermal radiation, the greater the rate of radiation heat loss.

The net radiation of the greenhouse is important for evaluation of the greenhouse energy situation. Net radiation is the difference between the energy received and energy lost by radiation. During the day, the sun, which generally provides a large amount of radiation, assures a net gain of energy because the losses are much smaller. This net gain of energy causes a subsequent greenhouse air temperature rise. However, at night, the warm masses within the greenhouse (earthen floor, concrete paths, metal benches, plants, etc.) produce significant radiation losses to the colder outdoor environment. The net energy loss is caused by transmission of infrared and thermal radiation through the cover, as well as emission of radiation from the cover to the cold sky. The amount of this radiation energy loss depends not only on the properties of the cover, but also on the temperature of the cover and the atmospheric conditions (water vapor, carbon dioxide, and ozone content).

Because of the potential radiation heat loss, it is important to consider the transmittance properties of the cover material in the infrared and thermal wavelengths, which includes those <850 nm. Laboratory tests have documented these transmittance properties for most glazing materials (Ametek, 1984; Godbey et al., 1979; Robins and Spillman, 1980). However, as just previously described for PAR transmission, these values should only be a relative indicator among the various materials and not a true measure during greenhouse operation. Simpkins et al. (1984) studied the net radiation and convective energy losses from single-bay, polyethylene-covered greenhouse structures. They confirmed that a combination of night sky conditions (cloud cover, atmospheric humidity) and the location of adjacent, heated structures (other greenhouses or buildings) directly affected the net radiation losses. The proximity of other structures also affected energy transfer by altering wind-induced infiltration and convective heat losses.

Infiltration energy losses are related to the openings within the structure and covering material, as well as on the outside wind speed and direction. The amount, size, and location of the openings affect infiltration. These may include the required access doors, heater intake/exhaust openings, and fan/ventilator openings. They also include the undesirable cracks and joints within the structure and covering system. Infiltration attributed directly to the covering system is highly dependent on whether the covering material is a continuous film, such as a sheet of polyethylene, or whether modular in design, such as glass or rigidly structured panels. The latter case has many edges that provide access for gas and moisture exchange. Infiltration rates may vary from as little as 0.5 volumetric air changes per hour (VAC/h) for continuous-sheet, film-covered structures to 0.75 to 1.5 VAC/h with newer glass panel glazings (Aldrich and Bartok, 1989).

Condensation of water vapor from the warm moist air onto the cool surface of the covering material represents an indirect method for heat loss from the greenhouse. The change of water vapor to liquid results in a release of energy called latent heat. As condensation occurs on the cover this latent heat energy can be lost from the greenhouse by convective heat transfer through the cover. This condensation, however, will help to reduce radiation heat losses, as water reduces the transmission of infrared radiation. However, as the surfaces become covered, droplets of water are formed and may fall to the crop below. This is an undesirable situation as excessive moisture can damage the crop by overwatering, and encourage the spread of disease. Efforts to incorporate inhibitors to droplet formation, particularly on plastic coverings, have somewhat reduced this problem.

Interaction and integration of glazing/superstructure

The selection of a particular covering material also will determine particular requirements for the greenhouse structure. These will include the required weight to support, the maximum spacing between glazing support bars and attachments, the size and strength of the supports, the maximum distance from the gutter to the ridge, -the type of attachments, etc.

The selection of a particular glazing to gain a desirable physical property may come at the expense of another property. An example is the comparison of glass or rigidly structured panels to polyethylene film glazings. Total daily PAR transmission to the plant canopy with a greenhouse covered with either panels or film may be relatively equal. However, the translucent film generally provides more diffuse radiation, while transmission from the panels yields a greater proportion of direct radiation. The film provides more uniform light intensity at the canopy height throughout the greenhouse because of this diffusing property, and a reduction of distinct shadows resulting from fewer glazing support bars. The greater number and size (length and width dimensions) of the glazing support bars are generally required for glazings that are heavy, less flexible, and have a small unit size and low bending strength. Thus a relatively heavy covering of narrow width, such as glass, would require a greater proportion of supports than a lightweight film or structured panel glazing.

Finally, the unit size of the glazing material will also influence infiltration energy losses. A smaller unit width provides a greater proportion of edges that must be kept sealed to prevent infiltration.

Alternative glazing considerations

There are three general types of coverings typically used for greenhouses: Glass, plastic films, and rigid plastic panels. About 30 years ago, there was primarily only one-glass. Buclon (1966) reported that 1000 acres (403 ha) of plastic and 5000 acres (2016 ha) ofglass-covered greenhouses in the United States in 1959 had expanded by 1964 to 4000 acres (1612 ha) of plastic and 6250 acres (2520 ha) of glass. Modern plastics have become the only alternative to traditional glass for covering the greenhouse. Plastic glazings include rigidly structured plastic panels, such as fiberglass-reinforced polyester (FRP), acrylic (polymethylmethacrylate, PMMA), polycarbonate (PC), and polyvinyl chloride (PVC) panels. Thin film coverings include low-density polyethylene (LDPE), polyvinylchloride (PVC), and ethylene vinyl acetate copolymer (EVA). These materials have been used in single, double, and even triple layers to cover the greenhouse.

Glass and plastic. Glass is quite inert, in contrast to plastic, and can provide effective use for many decades. Most plastic coverings are affected by weathering. Glass is non-combustible, resistant to *W* radiation and air pollutant degradation, and it maintains initial radiation transmission. The most predominant drawback of glass may be its vulnerability to catastrophic losses caused by hail. Glass may be tempered to greatly increase its strength and size. Traditionally small in size, new glass panes are now available with dimensions up to 2 × 3.65 m (6.6 × 12 ft). Cleaning the glass to maintain maximum radiation transmission and sealing the edges for reducing energy losses are all the maintenance that is required regularly.

Modern glass products for greenhouse glazing have improved radiation transmittance properties. One improvement has been the manufacture of glass with a lower iron oxide content (0.03%) as compared to traditional float glass (0.1%), thus increasing PAR transmission. Another product has a minute pattern impregnated on each surface of the glass during the manufacturing process. This effectively increases the radiation diffusing capability or translucency of the glass and improves uniformity of solar radiation distribution to the crop. Another product is available with a metal oxide surface coating layer, which provides a lower material emissivity, reducing heat transfer by radiation.

Ultraviolet radiation promotes photochemical degradation processes in all plastics and is generally the major cause for their replacement. Temperature extremes and their duration can also weaken the film. This can become a problem where the film makes contact with the greenhouse structure. Air pollutants also reduce the usable life of plastic coverings. These may be from sources external to the greenhouse that are attracted to the outer plastic layers and reduce radiation transmission. They also may come from internal sources, such as chemicals used for pest control, which can cause premature failure of the plastic.

Polyethylene film greenhouses have been developed so that they are reliable, and usually have a lower initial cost than most other greenhouse glazing systems. Low air infiltration rates resulting from the continuous film cover have improved energy savings, but contribute to high greenhouse air humidity conditions. Moisture condensation, especially on flattened arch-shaped roofs, promotes dripping on the crop below. Fan ventilation generally is required for cooling. It traditionally has been difficult to install ridge-vent openings; thus, effective natural ventilation has not been available, especially for large, gutter-connected units. Naturally ventilated polyethylene film covered structures have become available only recently.

Selection of the type of covering material to use on new construction or on renovation requires many practical considerations. The flexible and forming properties of the film simplify the covering process compared to rigid plastics or glass. The attachment procedures for plastic film range from the simplicity of wooden nailer strips to the reusable aluminum extrusion interlocking strips. The need for replacing the film every 2 or 3 years requires that the recovering process be rapid and easy. A means of recycling or disposing of spent film also must be considered. Glass or rigidly structured plastic panels require the more elaborate aluminum extrusions for their attachment to the greenhouse structure. These must be designed for the longer life of these covering materials.

Ridge and furrow or gutter-connected structures designed for a double-polyethylene covering should use a continuous tube ofplastic film, as an alternative to applying two individual sheets. Both glazing layers are applied simultaneously as the tube is unrolled, greatly simplifying the task. The distance between adjacent gutters should be <20 to 21 ft (<6.4 m) on an arch-shaped roof greenhouse. This assures that a 25-ft (7.6-m) tube, currently the largest manufactured, will span the arch between the gutters. The lock-down devices at the roof gutters must be easy to operate, reusable, and free from maintenance. Covering gutter-connected greenhouses with double film layers from a tube has been accomplished at rates as much as 1 acre/day (0.4 ha/day) with eight workers.

Rigidly structured plastic panels made of acrylic, polycarbonate, PVC, and FRP are initially more expensive as a cover than polyethylene film, but they require less maintenance and provide a longer useful life. They can be used on new construction and on glasshouse renovations. Reglazing systems for acrylic and polycarbonate panels use fewer, stronger support elements that are spaced wider apart. This has effectively reduced the amount of structural shading typically associated with glass. The strength of these wider panels (compared to glass) comes from their double-walled cross section depths, which range up to 16 mm (0.63 inch).

The greenhouse design with rigidly structured plastic panels must consider carefully the climates where heavy snowfall is likely. The insulated double-walled panels reduce the rate of snow melt, thereby allowing for large amounts of snow to accumulate. This is unlike double-layer polyethylene glazing, where the layers collapse together when loaded with snow, thereby increasing the melting rate.

Rigid panel structures are excellent choices for garden centers, sales areas, and general public access locations because of their durability and low maintenance. Acrylic or polycarbonate panels designed with a color tint for reducing radiation transmission are practical for retail sales areas. They can reduce significantly the direct solar radiation (as much as 50%) and thus the amount of cooling required to maintain a comfortable inside air temperature. Acrylic, polycarbonate, FRP, or PVC panels have become popular alternatives for the sidewalls and ends of large greenhouses with double-layered polyethylene roofs.

Plastic Films-PE, PVC, and EVA

Polyethylene film is the most common greenhouse covering film in the United States and, at present, there is a great selection ofhigh-quality greenhouse film from which to choose. Early films were dependable for a maximum of one growing season (Blom and Ingratta, 1985). However, by the mid-1960s, the quality and longevity of PE film had improved. Clark, in 1965, described the development of a 2-year film by the Plastics Division of Ethyl Corp. About the same time, the Monsanto Company began marketing “602,” a film that could last two growing seasons, and it came to be the predominate greenhouse film for many years.

At present, all greenhouse-grade polyethylene film has a minimum useful life of 24 months in most areas of the United States. However, 3- and 4-year films are now available. These films, normally a co-polymer of PE and ethyl vinyl acetate, are manufactured with the addition of 1% to 5% vinyl acetate. This formulation has improved significantly the physical properties of PE, including its resistance to cracking in cold temperatures and its tearing strength (particularly where folded).

Degradation of the physical properties of PE by W radiation remains the primary cause for its limited life. The addition of inhibitors during manufacture are necessary to slow the degradation process. Ahindered amine light stabilizer (HALS) is one type of inhibitor that has been used to protect clear films. Alternative UV degradation inhibitors for PE films include a group of nickel-based additives.

Pesticides also can reduce the expected life of PE films. Their influence is dependent on the chemical structure of the pesticide, the application frequency and concentration, and the chemical composition of the film (LDPE or EVA) (Henniger and Pedrazzetti, 1990).

Total transmittance (direct plus diffuse) of new polyethylene film in the PAR waveband, measured in the laboratory, is 90% for a single layer and 80% for two layers. As with most films, a portion of the transmitted radiation is diffused because of the translucent nature of the film. For example, the diffuse component of the total solar energy measured beneath the film on the greenhouse was 29% and 40% for single and double layers of polyethylene respectively (Godbey et al., 1979).

Table 3. ***Effects of weathering on average daily percent transmission of PAR (400–700 nm) and 300–1100-nm wavebands (measured at the roof) for a double polyethylene film- (UV-stabilized, non-IR barrier) covered greenhouse.***[z]

	Transmission	
Waveband	New	After 48 months
400–700 nm	0.73	0.68
300–1100nm	0.75	0.72

[z] *Giacomelli et al. (1990).*

All films lose light transmission capabilities over time. Dust, dirt, and air pollutant accumulation cause the greatest reduction. Tests of 4-year exposure of PE film (UV-stabilized, non-IR barrier) on a multi-bay, gutter-connected greenhouse revealed a 6.8% reduction in transmission (measured at the roof) within the PAR waveband, compared to the identical new film (Giacomelli et al., 1990) (Table 3). Simpkins et al. (1984) reported comparative laboratory tests for PAR transmittance of two types of double-layered polyethylene films on single-bay, free-standing greenhouses. The outer layer of the covering from each greenhouse was tested and compared to new film unexposed to the sun. The transmittance of the W-stabilized, non-IR barrier, 2-year film changed from an initial 0.87 to 0.80, and the W-stabilized, IR barrier, 2-year film changed from an initial 0.86 to 0.82 after 18 months of exposure (Table 4).

Techniques of co-extruding films and multi-layering of films during the extrusion process have been developed. These films offer even further opportunities for improved performance of the covering material. The most recently developed films have included an IR barrier, condensate control, and/or wavelength-selective properties.

Table 4. ***Laboratory measurements of PAR transmittance of UV-stabilized, 2-year PE film, with and without IR-barrier properties. Values for new material after 18 months on the greenhouse.***[z]

	Transmittance	
Film	New	After 18 months
Without IR barrier	0.87	0.80
With IR barrier	0.86	0.82

[z] *Simpkins et al. (1984).*

Heat loss by radiation for films can be significant. The average infrared transmission for wavelengths >2800 nm of single- and double-layer 4-mil (0.l-mm) PE film without an IR barrier is 80% and 63%, respectively (Godbey et al., 1979). In contrast, the same property for single layer glass is 3%, and for single layer FRP 12% (Table 5).

Additives incorporated into PE film reduce infrared radiation transmission. They absorb and re-emit infrared radiation from the greenhouse, thereby reducing heat transfer by radiation and improving the energy-conserving capability of the film. A double-layer PE film tested at Rutgers Univ., later manufactured as “Cloud Nine” by the Monsanto Company (currently CT Films), demonstrated a savings in nighttime supplemental heating of between 20% and 25% over the standard double-layer Monsanto 602 film for a single-bay, free-standing greenhouse (Roberts et al., 1985). The energy savings was primarily a result of the IR-absorbing film properties; however, it was also determined that an interaction with the hot air heating system contributed to this savings. The effect was a mean air temperature near the glazing (overhead) that was always significantly greater [3F (1.7C)] for the non-IR film-covered greenhouse than for the greenhouse with the IR barrier film. This occurred because the heater required more frequent operation in the non-IR film covered greenhouse to maintain the same air temperature at the plant canopy. When the effect of the heating system was eliminated, a savings of 13% was directly attributable to the IR barrier feature alone (Simpkins et al., 1984).

Anti-drip properties of PE film for condensation drip control are obtained by modifying the surface tension of the film. Upon condensing, the

Table 5. ***Long-wavelength transmittance (>2800 nm) of solar radiation for single- and double-layer PE film (without IR barrier), single glass and fiberglass sheet.***[z]

Material	Transmittance
Single-layer PE (1.0 mm)	0.80
Double-layer PE (0.1 mm)	0.63
Single-layer glass (3.2 mm)	0.03
Single-layer FRP (0.63 mm)	0.12

[z] *Godbey et al. (1979).*

water vapor does not form droplets, but rather remains a continuous sheet whose flow is directed by the curvature of the roof toward an edge for collection. Potential damage from falling water droplets to the plants below is minimized. The scattering of solar energy (and subsequent loss of radiation transmission) caused by droplets on the covering material also is reduced. This film property is not permanent because of the migration of the additives to the surface of the film. However, it reportedly lasts for most of the useful life of the cover.

PE films can be co-extruded with different layers, each of which contributes a desirable attribute, and which together combine to create a more-versatile product. For example, a tri-layer film that locates the IR barrier properties from a copper additive within the middle layer is available commercially (Moens, 1990). Triple-layer films also can be manufactured with an inner layer having a high percentage of vinyl acetate in the EVA copolymer. This improves the *W* degradation resistance and the mechanical properties of the film. It reduces creep or stretching over time, which is common with films containing high percentages of vinyl acetate. EVA film has properties quite similar to non-IR barrier PE. It has an infrared radiation transmittance of 0.55 for a single layer, which is slightly less than PE.

All films transmit particular wavelengths of the total solar spectrum, based on their particular chemical formulation. They respond much like a filter, allowing certain wavelengths to pass, while excluding others. The transmittance property of the material is the average of all those wavelengths that can pass. Recently, films have been manufactured to achieve selective transmission capabilities when used as a covering material. Friend and Decoteau (1990) found a 12% increase in transmission of the specific ratio of the wavelengths 735 and 645 nm for white polyethylene when compared to clear polyethylene. In this example, 735 is a far-red (FR) wavelength and 645 is a red (R) wavelength. The change of this light ratio of FR:R (735:645nm) resulted in longer plant stems and leaf petioles. A recently available photo-selective tri-layer film is claimed by the manufacturer to influence the FR : R and thereby affect the growth and development of several plant species.

Another potential application is with modification of UV radiation. Within the UV radiation waveband, only those wavelengths between 315 and 400 nm have a positive effect on the seedling growth (Zanon, 1990). The stem length is shortened. In addition, the leaf color as well as taste and smell of plant has been modified by these *W* wavelengths. Other *W* wavelengths are damaging.

PVC film has been used mostly in Japan as a single-layer cover and, in 1985, there were more than >34,000 ha (84,000 acres) (Takakura, 1988). The film used has a transmissivity of <0.45 for a single layer, which is the best IR barrier property among commonly used films. At first, PAR transmission compares to glass, but the surface of the PVC film attracts sufficient dust and dirt within one season to significantly reduce transmission. It is manufactured only in relatively narrow widths [1.8 m (5.9 ft)]. Pieces can be joined by heat-sealing or by using a special tape.

Rigid structured plastics-FRP, PC, PMMA, and PVC

Modern rigidly structured plastic coverings, such as FRP, PC, PMMA, and PVC are normally corrugated or have multilayered cross-sections for strength (Fig. 1). They are strong, have a long life (lo-year guarantee with minimal light transmission reduction), and the double-walled panels improve energy savings. In Europe, the double-walled panels are generically labeled SDP (stegdoppelplatte), which, literally translated, means "two plates connected by bridges."

The properties of the structured sheets are such that UV below 385 nm is not transmitted. Thermal radiation transmission is also very low. Transmittance is <0.02 in the waveband between4000 and 10,000 nm (Aldrich and Bartok, 1989).

Acrylic (PMMA) and fiberglass (FRP) panels have potential fire problems. A typical warning about methods used to protect wood and other

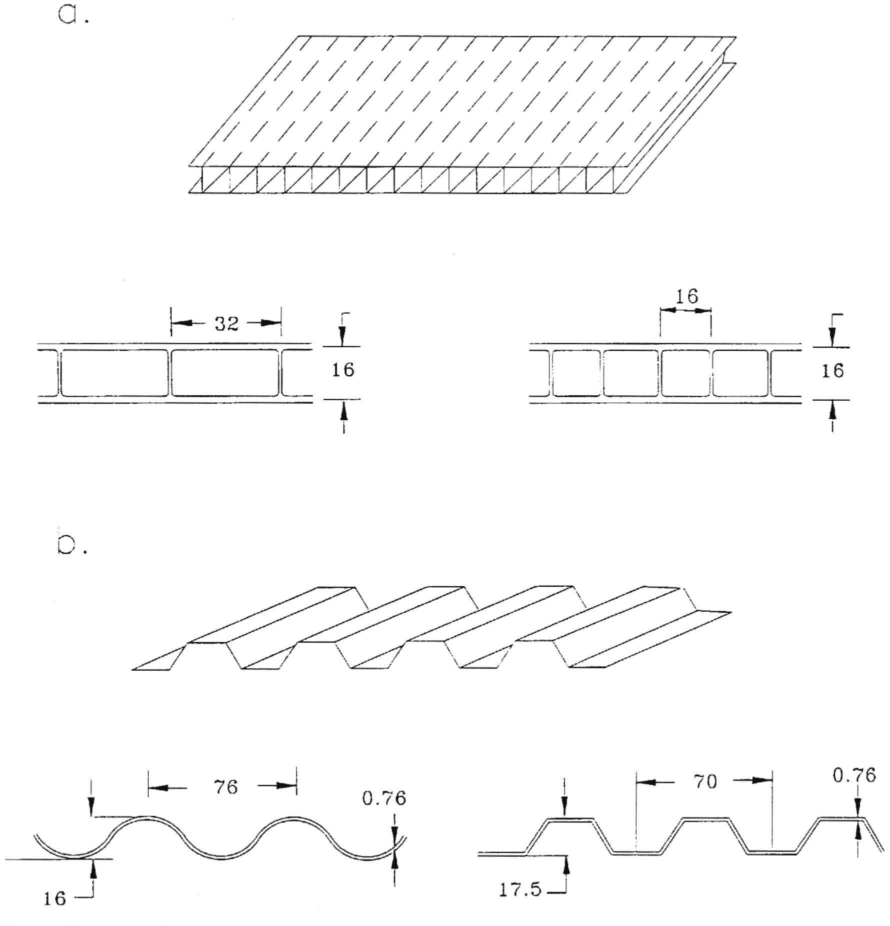

Fig. 1. ***Structural plastic panels and cross-sections, (a) double-wall panel; (b) corregated panel (in millimeters).***

combustibles from flames and high heat sources also should be used with these panels. Flames will continue to propagate once ignited. An additive is available for FRP panels, but adds to the cost, shortens the life, and reduces the light transmission through the panels. Polycarbonate (PC) and polyvinyl chloride (PVC) panels have less of a fire problem because burning will cease after removal of the flame source.

FRP has been a popular choice for covering the entire greenhouse in Florida and in some sections of Colorado because of its resistance to hail damage. The weatherability of FRP varies with manufacturer and formulation. Untreated panels have a tendency to degrade on the surface directed to the sun and expose the reinforcing glass fibers. These exposed fibers become dirty, thereby reducing light transmission. Various treatments are available to eliminate this problem. One of these adds a thin film of Tedlar to the surface of one side of the panel during manufacture.

Acrylic panels constructed into a double-walled channel cross-section provide good structural strength, and the heat-saving advantages of double glazing. They were installed first in Germany in 1969. Dimensions range from 8 × 15.9 mm (0.3 × 0.6 inch) to 16 × 32 mm (0.6 × 1.3 inch) for the channeled cross-section. Panel dimensions include widths of 1.2 m (3.9 ft) and lengths from 2.4 to 4.9 m (7.9 to 16 ft). Fewer structural elements are required for mounting the panels than are needed for the smaller and heavier glass panes. Acrylic panels are available with a tongue-and-groove configuration for attaching adjacent panels to one another. This can help reduce shading of the crop by eliminating additional structural supports. Bradenbeck (1985) measured daily average PAR transmission at the plant canopy of 60% to 64% for double-walled acrylic panels.

Polycarbonate panels are similar in cross-section construction to the acrylic panels. They are manufactured in a variety of sizes, which include 6, 8, 10, and 16 mm (0.2 to 0.6 inch) in cross-section thickness. The thinner cross sections are quite flexible and will bend to an arch roof shape. Panel dimensions range from widths of 1.2 to 2.4 m (3.9 to 7.9 ft) and lengths from 2.4 to 9.7 m (7.9 to 32 ft). Polycarbonate panels are affected adversely by UV radiation and will discolor if not protected. Panels are either co-extruded with acrylic or use an acrylic coating. They are available in a triple-layer cross-section for improved energy savings, but with a higher PAR radiation loss. They also can be manufactured in a corrugated, single-layer cross-section (Fig. 1b).

The channels of the cross-section have introduced some problems with condensation and subsequent algal growth within the double-wall structural panels. Sealing both ends of the channels does not eliminate this problem, as the polycarbonate (and acrylic) materials are not completely impervious to water vapor. If the channels are not sealed at the bottom, condensate can drain from the panel. This practice will reduce the thermal efficiency of the panel. A fiber-covered aluminized tape can be used to allow drainage, but this reduces air movement within the channels.

Surface condensate control is available for structured or corrugated sheets of polycarbonate, as well as for the acrylic panels, to reduce the potential for water dripping.

Tests in the Netherlands and in Germany for resistance to impact damage have revealed that polycarbonate panels have a greater tolerance to hail than the acrylic. They are being used by growers in some areas prone to this type of weather.

Conclusion

All coverings discussed can perform well and could be considered quite suitable for greenhouse glazings, depending on the desired application. Many factors determine the optimum choice for a given situation. The geographic location of the greenhouse (because of microclimate), grower experience and/or preference, and the local industrial support all have an important influence on the design and selection of a glazing system for a greenhouse operation. The crop and its required heating and/or cooling costs also enter into the decision.

The glazing is one component within an organization of interrelated systems of the greenhouse. Its selection has become more challenging with the advent of various plastic polymers. Their unique characteristics provide numerous alternative glazing choices. The decision on selecting a glazing system must include its physical properties of radiation transmission and heat transfer, as well as its construction, maintenance, and operational requirements.

Literature Cited

Aldrich, R.A. and J. W. Bartok, Jr., 1989. Greenhouse engineering. NRAES-33. Northeast Reg. Agr. Eng. Serv., Cornell Univ., Ithaca, N.Y.

Ametek, Inc. 1984. Solar energy handbook-Theory and applications. Chilton, Radnor, Pa.

Blows, T.J. and F.J. Ingratta. 1985. The use of polyethylene film as greenhouse glazing in North America. Acta Hort. 170:69-80.

Bredenbeck, H. 1985. Influence of different glazing materials on light transmissivity of greenhouses. Acta Hort. 170:111-117.

Buclon, F. 1966. Comparisons of agricultural uses ofplastics in France, Italy, Japan, Russia and the United States. Proc. 7th Natl. Agr. Plastics Congr. p. 21-32.

Clark, M.M. 1965. A two-season polyethylene film for greenhouse glazing. Proc. 5th Natl. Agr. Plastics Congr. p. 33-35.

Critten, D.L. 1987a. Light transmission losses due to structural members in multispan greenhouses under diffuse skylight conditions. J. Agr. Eng. Res. 38:193-207.

Critten, D.L. 1987b. Light transmission losses due to structural members in multispan greenhouses under direct light conditions. J. Agr. Eng. Res. 38:209-215.

Duffie, J.A. and W.A. Beckman. 1980. Solar engineering of thermal processes. Wiley, New York.

Friend, H.H. and D.R. Decoteau. 1990. Spectral transmission properties of selected row cover materials and implications in early plant development. Proc. 22nd Natl. Agr. Plastics Congr. p. l-6.

Giacomelli, G.A., K.C. Ting, and S. Panigrahi. 1988. Solar PAR vs. solar total radiation transmission in a greenhouse. Trans. ASAE 31(5):1540-1543.

Giacomelli, G.A., K.C. Ting, and W. Fang. 1990. Wavelength specific transmission of polyethylene film greenhouse glazing. Proc. 22nd Natl. Agr. Plastics Congr. p. 129-134.

Giacomelli, G.A. 1991. Introduction to the horticultural engineering aspects of hydroponic crop production. Proc. 12th Annu. Conf. on Hydroponics. Hydroponic Soc. Amer., Concord, Calif. p. 38-49.

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. ASAE 22(5):1137-1144.

Gray, H.E. 1992. Greenhouse glazing uncovered. Greenhouse Grower 10(8):54-57.

Henniger, F. and E. Pedrazzetti. 1990. Evaluation of the light stability of greenhouse cover films. Proc. XI Intl. Congr. on the Use of Plastics in Agriculture. Oxford & IBH Publishing, New Delhi, India. p. G.31-G.59.

Moens, F. 1990. Agricultural films in Western Europe: Progresses and trends. Proc. XI Intl. Congress on the Use of Plastics in Agriculture. Oxford & IBH Publishing, New Delhi, India. p. G.75-80.

Reilly, A. 1992. New developments in greenhouse structures and equipment-part I: Structures and coverings. Foliage Dig.15(1):1-3 [In Florida Foliage 18(l): 33-40.]

Roberts, W.J. and D.R. Mears 1969. Double covering a film greenhouse using air to separate film layers. Trans. ASAE 12(1):32-33.

Roberts, W,J., J.C. Simpkins, D.R. Mears, and H. W. Janes. 1985. Performance of IR polyethylene film over two years trial. Acta Hort. 170:81-90.

Roberts, W.J., J.W. Bartok, Jr., E.E. Fabian, and J. Simpkins. 1989. Energy conservation for commercial greenhouses. NRAES-3. Northeast Reg. Agr. Eng. Serv., Cornell Univ., Ithaca, N.Y.

Robbins, F.V. and C.K. Spillman. 1980. Solar energy transmission through two transparent covers. Trans. ASAE 23(5): 1224-1231.

Simpkins, J.C., D.R. Mears, W.J. Roberts, and H.W. Janes. 1984. Evaluation of an experimental greenhouse film with improved energy performance. Amer. Soc. Agr. Eng., St. Joseph, Mich. ASAE Paper 84-4033.

Takakura, T. 1988. Protected cultivation in Japan. Acta Hort. 230:29-37.

Thimijan, R.W. and R.D. Heins. 1983. Photometric, radiometric and quantum light units of measure: A review of procedures for interconversion. HortScience 18(6):818-822.

Ting KC. and G.A. Giacomelli. 1987a. Availability of solar photosynthetically active radiation. Trans. ASAE 30(5):1453-1457.

Ting, KC. and G.A. Giacomelli. 1987b. Solar photosynthetically active radiation transmission through greenhouse glazings. Energy in Agr. 6:121-132.

Ting K.C. and G.A. Giacomelli, 1992. Automation-culture-environment based systems analysis of transplant production, p. 83-102. In: K. Kurata and T. Kozai (eds.). Transplant production pystems. Kluwer, Dordrecht, Netherlands.

Zanon, M. 1990. Synergy between plastics research and protected agriculture. Proc. XI Intl. Congr. on the Use of Plastics in Agriculture. New Delhi, India. Oxford & IBH Publishing, New Dehli, India. p.F.31-F.39.