Glazing Materials, Structural Design, and Other Factors Affecting Light Transmission in Greenhouses

William J. Roberts
Professor Emeritus
Bioresource Engineering
Rutgers University

Transmission of Radiation through Glazings

The primary purpose of a greenhouse covering is to provide a translucent barrier between two environments. One is normally conducive to plant growth and the other is not. Light energy from the sun passes through the glazing providing energy for the photosynthetic process, converting CO_2 and H_2O to a form of $C_6H_{12}O_6$ (carbohydrate) and O_2. This amazing process is the basis for all life, plants taking on CO_2 and giving up O_2. The glazing also makes possible environmental control to allow the photosynthetic process to be carried out at optimum or near optimum conditions. The covering must allow maximum possible light transmission since plant growth in the winter is normally controlled by available light energy from the sun.

Light energy or radiation that strikes a surface is either absorbed, reflected, or transmitted. The thickness of the material often determines the amount of energy absorbed. At a Rutgers research facility wire glass was used in the roof which was 7 mm (~1/4 inch) thick. The normal glazing would have been 4 mm (~1/8 inch). Tests were run comparing the roof wire glass to a 4 mm glass used for the interior partitions in the greenhouse. The results were that the roof glazing transmitted 13% less light than the glass used for the interior partition. Part of this light loss was caused by the wire in the glass but most of it was caused by the thickness of the glass, although the actual glass used in the roof glazing could have been of a different type. The angle of roof as it is presented to the sun determines the amount of energy which is reflected and the amount which is transmitted is determined by the actual light transmission characteristics of the glazing.

Table 1 indicates results obtained with three glazings on three identical greenhouses located side-by-side in Cromwell, Connecticut, and a test facility at Rutgers University. The overall transmission represents the percentage of outside radiation that passes through the greenhouse glazing. Two locations within the greenhouse are examined, one at the canopy level and one just beneath the glazing. The data represent averages for an entire winter period. The PAR transmission measured at the glazing level represents the effect of the glazing material and the PAR measured at the canopy level includes the influence of the structure.

Table 1. Overall PAR transmission in percent.

	Type of Glazing			
Sensor Location	Single Glass	Acrylic	Double Glass	Double PE
At glazing	0.60	0.58	0.58	0.67
At canopy	0.56	0.55	0.56	0.45

It would be expected that the greatest transmission of PAR would be through the single layer glass. However, because of the structure required to support the glazing the net effect is approximately the same transmission as through the other treatments. The double glazing of glass represents and effort to save energy. The roof support system was changed to reduce the number of heavier supporting members. However, the actual installation of the interior glazing was such that it allowed ready access of interior moisture laden air to infiltrate into the space between the glazings. This caused heavy condensation in this area resulting in lower PAR transmission than might have been expected. The acrylic glazing system further reduced the required supporting members with the net effect of that similar PAR transmission was achieved with this glazing system. This data indicates that the supporting structure of the greenhouse and other considerations is as important for determining plant growth as the actual glazing selected.

In the case of the polyethylene film trial, Column 5 in Table 1, the research greenhouse was heavily encumbered inside with overhead equipment including a movable irrigation system, heating system and thermal screen, which begins to explain the relatively low transmission value (Giacomelli and Ting, 1988).

Laboratory tests indicate that measured total transmittance, including both direct and diffuse light for new polyethylene film in the PAR waveband is approximately 90% for a single layer and 80% for two layers. As with most films much of the transmitted radiation is diffused because of its translucent nature. For example, the diffuse component of the total solar energy measured beneath the glazing is 29% and 40% respectively for single and double layers of polyethylene (Godbey et al., 1979).

Influence of Greenhouse Orientation

Guidelines for 40^{o}N latitude:

- Freestanding greenhouses should be oriented East-West in this latitude.
- Multi-bay, gutter connected or ridge and furrow greenhouses should be oriented North-South.

Free-standing greenhouses

Most textbooks will accurately state that a greenhouse oriented with the ridgeline running North-South will receive the most PAR radiation throughout the year. This is a true, but misleading statement. The reason the statement is true is because with the sun traveling over a greenhouse with this orientation there will be two receiving areas, the East roof section (in the morning), and the West roof section (in the afternoon). It is also true that the majority of the radiation enters the greenhouse through these two roof sections when the sun is high in the sky from April to October. The difficulty is that during this time of the year, at latitude 40^o N, we need to reduce radiation because of the resulting high temperatures in the greenhouse. We need the most PAR transmission into the greenhouse from October to March when there is less light available because of the normally low sun angle in this latitude. To achieve this goal, a free-standing greenhouse will receive more light with an East-West orientation during this critical period. Therefore the aim of the designer is not to maximize total yearly radiation but the radiation during the darker periods of the year.

Multi-bay, gutter connected or ridge and furrow greenhouses

In the orientation of multi-bay greenhouses structural components come into play. Although an East-West orientation allows more light to enter the greenhouse there are permanent shadows throughout the greenhouse caused by the structural members, particularly the gutter and thermal screen installations. These permanent shadows remain in the same position and become wider or narrower depending upon the time of year. A North-South orientation, however, will cause the shadows to move from the west side of any gutter section in the morning to the east side of the gutter section in the afternoon. This moving shadow pattern is more desirable for crop growth because there is no part of the crop subjected to shadow throughout the entire day. Some Dutch researchers have experimented with locating the aisles in the area of the shadow within an East-West oriented greenhouse, but that often causes serious problems with materials handling systems. Newer growing systems such as movable bench systems, transportable bench systems and floor growing system also use up to 90% of the floor area. Permanent shadow patterns cause unequal growth and unequal growth in a moveable bench system, for instance, causes severe problems when it is time to sell and market the crop. It is mandatory with these systems that the entire crop be at a uniform maturity when it arrives in the headhouse or several paths of transport have to be provided and this is expensive in equipment and time consuming for the workers.

Influence of Structural Design

Roof slope is an important parameter in greenhouse design. The maximum amount of light energy transmitted occurs when the glazing surface is perpendicular to the sun. Essentially this happens only for a short time of the day, at best. The appropriate roof angle or slope of the greenhouse on December 22 in our latitude, 40^{o}N, is approximately 68^o. This means that at 12 noon on December 22 the sun angle would be perpendicular to the roof of the greenhouse if it were at the 68^o angle. On the other hand on June 21, the appropriate angle would be 12^o. The design objective is to maximize the light energy entering through the roof of a greenhouse during the time of year when light is at a premium, October to March. In actual current design practice a roof slope of 27^o-30^o is used. It is interesting that a slope of 1 in 2 equals a 27.5^o angle which makes me feel that maybe the carpenters and builders decided the 'correct' roof slope and not the engineers or plant scientists.

Glazing materials of difference strength require supporting members at various spacings. For wider spacing the individual structural support members will be heavier but produce less overall shadow than closely based supports. Some glazings have less unit weight but the design of the greenhouse structural members should be essentially the same because the primary loads are live loads of wind and snow and the dead load of the glazing is small in comparison to the total loads experienced by the greenhouse.

Influence of Location

Figure 1 indicates the available solar radiation at 40^{o}N throughout the year. On June 21 the radiation is 3 times that available on December 21. An alternative way to state this is that the available light for the winter crop in November, December and January is only one third of that available during the summer months. Note that the units of Figure 1 are Langley per day. To convert to Watt per square meter (W m^{-2}), multiply by 0.484. Table 2 gives an indication of cloud cover to be expected at various locations in and around New Jersey. No engineering design can remedy these problems but it must be recognized as a potential limiting factor in any system.

Table 2. Mean sky cover, sunrise to sunset, for sites in and surrounding New Jersey.

Station	Years of data*	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Ann.
Scranton	14	7.3	7.3	7.0	6.9	6.6	6.1	6.3	6.1	5.9	5.8	7.5	7.6	6.7
Allentown	25	6.6	6.4	6.2	6.5	6.4	5.9	5.9	5.7	5.5	5.2	6.4	6.3	6.1
New York (Central Park)	42	6.0	5.8	5.7	6.0	5.7	5.6	5.5	5.5	5.2	4.9	5.8	5.9	5.6
Newark	24	6.4	6.3	6.1	6.4	6.4	6.0	6.2	5.9	5.4	5.2	6.2	6.2	6.1
Trenton	26	6.2	6.2	5.9	6.3	6.2	5.9	6.0	5.8	5.5	5.0	6.1	6.1	5.9
Philadelphia	29	6.6	6.4	6.2	6.6	6.5	6.2	6.2	5.9	5.6	5.4	6.3	6.3	6.2
Wilmington	22	6.6	6.4	6.2	6.5	6.5	5.9	6.0	5.8	5.5	5.2	6.2	6.3	6.1
Atlantic City Airport	11	5.9	6.4	5.9	6.4	6.2	5.9	6.4	6.1	5.4	4.9	6.0	6.2	6.0
Atlantic City Marina	60	6.2	5.6	5.7	5.8	5.6	5.5	5.3	5.2	5.1	4.8	5.4	6.0	5.5

*Up to 1969 except for Central Park and Atlantic City Marina.

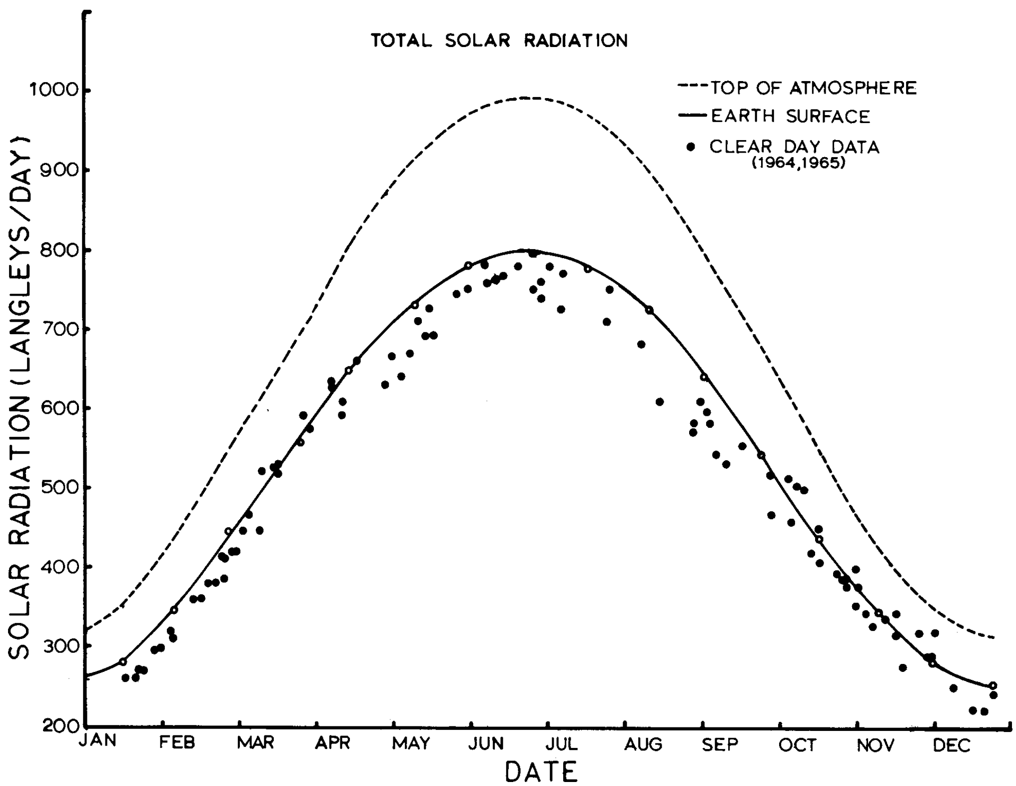

Figure 1. Comparison of the computed solar radiation (from Smithsonian Meteorological Tables, 6th edition) at the top of the atmosphere at 40°N, the computed clear day radiation (solid line) based on Black's equation, and the observed clear day radiation (solid circle) at New Brunswick, New Jersey.

Influence of Interior Greenhouse Components and Systems
With the advent of thermal screens, supplemental lighting and other greenhouse handling systems along with traditional overhead heating systems concern has been expressed for obstruction of PAR lighting which is caused by these overhead mounted components of the growing system (Table 1, PE film, Column 5). Under bench heating and in-floor heating systems have reduced the number of overhead heating pipes necessary to meet the demand load. Thermal screens which are installed and move gutter to gutter can reduce shading because the thermal screen shares the shadow pattern with the shadow caused by the structural gutter and does not add an additional shadow which is caused by the system which moves from truss to truss. There has been an attempt to reduce the size of supplemental lighting fixtures to reduce the shadow patterns they produce. The grower must be concerned with the adoption of new practices which add significant overhead components.

Influence of Weathering on Glazings
The design of sophisticated greenhouse glazing films have nearly eliminated this problem. It is also true that not all waveband are attenuated the same over time of exposure of greenhouse glazings. Table 3 is data reported by Giacomelli et al. (1989) indicating the difference of daily transmission for new and 4-year weathered film. There are distinct differences between the new and weathered film, particularly in the lower PAR region.

Table 3. Daily average transmittance for wavebands between 300 and 1,100 nanometers for new and weathered (4 year old) polyethylene greenhouse film.

Waveband (nm)	New Glazing	Weathered Glazing	Percent Change
300-400	0.675	0.564	-16.4%
400-500	0.709	0.632	-10.9
500-600	0.736	0.679	-7.7
600-700	0.753	0.714	-5.2
700-800	0.772	0.749	-3.0
800-900	0.788	0.772	-2.0
900-1,000	0.792	0.778	-1.8
1,000-1,100	0.792	0.841	+6.2

Influence of Condensation on the Glazing
Condensation is found on most glazings and is useful at night for reducing energy loss for direct radiation to the sky from polyethylene glazed greenhouses which are not glazed with IR film. During the day, however, excess condensation can cause reduced PAR transmission and create localized disease potential if dripping occurs on the crop. Condensation between the two layers of polyethylene film can be reduced or eliminated by using outside air to supply the fan used to inflate and separate the two layers of film. Air which is introduced into the space within the film envelope will always be warmed if it taken from outside. Warm moist air taken from within the greenhouse will be cooled when it enters the air envelope. The moisture will be condensed on the cooler surfaces causing buildup of moisture between the two layers. Although helpful from an energy standpoint it can be detrimental from a light transmission viewpoint. Installing the inflation fans properly can completely overcome this problem. The use of IR films also is helpful in controlling condensation because the plastic film itself is usually at a higher temperature than conventional grade polyethylene greenhouse glazing.

Important Points

Transmission of Radiation through Glazings

The primary purpose of a greenhouse covering is to provide a translucent barrier between two environments. One is normally conducive to plant growth and the other is not. Light energy from the sun passes through the glazing providing energy for the photosynthetic process, converting CO_2 and H_2O to a form of $C_6H_{12}O_6$ (carbohydrate) and O_2.

Light energy or radiation that strikes a surface is either absorbed, reflected, or transmitted. The angle of roof relative to the sun determines the amounts of energy that are reflected and transmitted.

Laboratory tests indicate that measured total transmittance, direct and diffuse for new polyethylene film in the PAR waveband is approximately 90% for a single layer and 80% for two layers.

As with most films, much of the transmitted radiation is diffused because of its translucent nature. For example, the diffuse component of the total solar energy measured beneath the glazing is 29% and 40% respectively for single and double layers of polyethylene.

Influence of Greenhouse Orientation

Guidelines for 40^{o}N latitude:

- Freestanding greenhouses should be oriented East-West.
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Free-standing greenhouses

The need for the most PAR transmission into a greenhouse is from October to March when less light is available because of the low sun angle. To achieve this goal, a freestanding greenhouse will receive more light with an East-West orientation of its ridge during this critical period.

Multi-bay, gutter connected or ridge and furrow greenhouses

Although an East-West orientation allows more light to enter the greenhouse there are permanent shadows throughout the greenhouse caused by the structural members, particularly the gutter and thermal screen installations. A North-South orientation, however, will cause the shadows to move from the west side of any gutter section in the morning to the east side of the gutter section in the afternoon. This moving shadow pattern is more desirable for crop growth because there is no part of the crop subjected to shadow throughout the entire day.

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Influence of Location

The available light for the winter crop in November, December, and January at 40^{o}N is only one third of that available during the summer months. No greenhouse design can remedy this situation, and it must be recognized by the engineer as a potential limiting factor in any system.

Influence of Interior Greenhouse Components and Systems
With the advent of thermal screens, supplemental lighting, and other greenhouse handling system along with traditional overhead heating systems, concern has been expressed about the obstruction of sunlight caused by these components. Under bench heating and in-floor heating systems have reduced the number of overhead heating pipes necessary to meet the heating demand load. Thermal screens that move from gutter to gutter can reduce shading because the retracted thermal screens share shadow patterns with the shadows caused by the gutters. In contrast, a curtain system that moves from truss to truss adds additional shadows.

Influence of Weathering on Glazing
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Influence of Condensation on the Glazing
Condensation is found on most glazings and is useful at night for reducing energy loss by direct radiation to the sky from polyethylene film covered greenhouses that are not glazed with IR film. Condensation between the two layers of polyethylene film can be reduced or eliminated by using outside air to supply the fan used to inflate and separate the two layers of film.

Definitions

Single-span *-- an independent, single-bay structure, separate from adjacent structures.*

multi-bay or gutter-connected *-- construction where modular structural units are connected at the gutters to cover large ground areas.*

lean-to *-- structure which is attached to another building along its ridgeline.*

over-wintering *-- temporary, unheated structure for winter protection of hardy crops.*

single-layer *-- cover or glazing composed of one layer of rigid or flexible film material.*
multi-layer *-- cover or glazing consisting of two or more layers of rigid or flexible film materials.*
air inflated *-- separation of two layers of flexible film by sealing the edges and inflating with pressurized air.*

roof slope *-- angle of the face of the roof relative to the horizontal.*

arch roof *-- continuous curved roof face.*

gable roof *-- flat roof face.*

truss *-- structural framework used to support the roof.*

purlin *-- longitudinal members of the structural framework that support the glazing material on the roof.*

bow or hoop *-- pipe or tube framework used to support the glazing on an arched roof.*

pipe or post or column *-- vertical structural member which supports the gutters and end walls.*

gutter *-- water transport channel, supported by posts or columns, and providing attachment for the roof bows.*

ridge *-- peak or high point of the roof that spans the long length of the structure.*

headhouse *-- separate or attached building to the structure used as a preparation area.*

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