The greenhouse comes ‘alive’ only after its glazing or cover is applied. The greenhouse and plant environment is defined by air temperature, humidity, carbon dioxide, soil temperature and solar radiation, and it must be in balance with the solar radiation entering, and the heat leaving, through the glazing. The greenhouse environment is then modified to the desired needs of the plants by its environmental control systems (heating, cooling) in response to the outdoor environment.

The glazing directly influences the amount (intensity) and the type (diffuse/direct; partial or full spectrum of the sun) of solar energy to reach the plant canopy. The solar energy affects plant growth through plant physiological responses, such as, water movement through the plant (for transpiration); and capture of solar energy (for photosynthesis). This also affects leaf temperature which is indirectly controlled by the plant through leaf evaporative cooling (or evapotranspiration). Subsequently the air moisture content (or humidity) of the greenhouse is increased from the water vapor added by the plants. This moisture of the air can be removed by ventilation which exchanges inside air with outside air, or it may condense on cool surfaces of the greenhouse structure, primarily the glazing.

No glazing is ideal. Each will influence the plant microclimate in unique ways. The plant then responds in its growth behavior to the imposed environment, leading to its final appearance and/or productivity.

Plastics, however, have revolutionized the greenhouse industry in many ways, such as production containers for their growth and sale, irrigation systems, for water and nutrient delivery, and glazings, for greenhouse covers. However, the simplified, less costly procedure (compared to glass) for enclosing the greenhouse structure with plastic film or rigid plastic panels is the most dramatic change. Many new greenhouses, as well as, all temporary structures are covered with plastics. Air-inflated, double-polyethylene film greenhouses represented an estimated 80% of the new greenhouse construction within the United States in 1992, according to Al Reilly.

Total greenhouse area for floriculture crops (cut flowers, potted plants, foliage, bedding plants and cut greens) in the U.S. increased by 11%, from 10,785 to 12,019 acres between 1993 and 2000 (NASS, USDA, 2001). During this same time period, the proportion of films and other plastic greenhouse coverings increased from 57% (6080 acres) to 68% (8205 acres) of this total area. Glass dropped from 1845 acres (17%) to 1593 acres (13%), and fiberglass and other rigid plastics dropped from 2860 acres (27%) to 2228 acres (18%), respectively. The National Greenhouse Manufacturers Association (NGMA) provides figures of similar proportions for polyethylene film, glass, and rigid plastics in their October 2000 report. There may be changes in progress. For the most recent one-year period (1999-2000), total greenhouse area was reduced from 12,220 to 12019 acres, at the expense of plastic covered structures (10,627 to 10,433 acres) and a slight increase of glass (1565 to 1593 acres).
Greenhouse vegetable production is a relatively small, but growing segment of the industry. Dr. Rick Snyder at Mississippi State University estimates that there are about 850 acres of greenhouse vegetables in the US. About 90% are tomatoes and the majority of are glazed with plastic film.

Selecting a greenhouse cover
Purchase of the glazing from a reputable manufacturer assures that the fundamental material properties of strength, consistency, durability, manufacturing quality control, and safety will be present. The grower should then consider:

1. How much energy (light) does it let into the greenhouse, and how much energy (heat) will go out?
2. What are the purchase, installation, and maintenance costs?
3. How well can the grower manage the environment which is imposed by the glazing to produce a quality, salable product for profit?

The physical properties of the material directly influences #1 and 2. Number 2 can best be answered by the glazing manufacturing and sales industry. Number 3 is generally more difficult to describe. However, it is related to other factors such as the experience of the grower, the crop produced, the glazing, the local outside environment, and the greenhouse environmental control systems.

To begin to answer Question #1, consider the following general choices available in glazings.

- single or double-layer -- is the glazing made of a single or double layer construction?
- rigid panel or flexible film -- is the glazing made of rigid plastic or flexible, thin film?
- plastic or glass -- is the glazing material glass or a form of plastic?
- with/without additives -- what special purpose additives are included?

Let’s consider how these choices in glazings will influence the plant environment.

Energy coming In --- Solar Radiation Transmission Through the Glazing
Energy from the sun is transmitted through the transparent greenhouse covering where it powers the photosynthetic process of converting carbon dioxide in the air, and water in the plant to produce a larger green plant which generates oxygen. 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 wavelengths within the group from 400 to 700 nanometers (primarily the visible portion of solar radiation which includes the rainbow colors violet, blue, green, yellow, orange and red) directly influences growth and development in green plants. The importance is so great that this waveband has been defined as Photosynthetically Active Radiation (PAR). The energy intensity within this waveband has been shown to be directly proportional to the activity of specific plant processes, however, it is generally and more simply considered proportional to overall plant growth. That is, the greater the PAR (intensity), and the longer that it is present (day length), the faster the plant growth rate…up to a point, of course.

Other non-visible solar radiation wavebands include the ultra-violet (UV), far-red (FR) and infrared (IR) wavebands. They, too, influence plant growth, although much more subtly, and the extent of their influence is not completely understood or even known.

When buying glazing consider the PAR transmittance of the glazing. Transmittance is a physical property of the material. It is a comparison of the radiation intensity (usually in the visible PAR or a wider band from 400 to 1100 nanometers) measured beneath the covering material to that measured at the same time above the material. The two measurements must be made in the same waveband for a fair
comparison and the value is given as a percentage of transmission (0% (least) to 100% (most)). In general, for single layer glazings the transmission should be approximately 90%, and for double-layer glazings the transmission should be 80%, regardless of the material being glass or plastic, and rigid or flexible.

How important is a claim of 1, 2 or even 5% greater transmission for material ‘A’ than for material ‘B’? Generally insignificant! In practice, the improved transmission of material ‘A’ will be more than counteracted by the shading caused by the greenhouse structure and the other systems located overhead in the greenhouse. Unless extreme care is taken, nearly all greenhouse structures affect the light transmitted to the plant canopy to a greater degree than comparable covering materials of similar transmission (within 1 to 5% of each other). Therefore, even though a material has a slightly greater transmission initially, its advantage is typically lost once applied and used in production. Consider that other factors affect transmission of PAR into the greenhouse structure. They include the: location of greenhouse (especially at latitudes greater than 25° from the equator…which means anywhere in the USA), orientation of the glazing surface to the sun, whether it is free-standing (single ground-to-ground design), or a gutter-connected structure (continuous, multiple bays attached together), season of the year, and number of glazing layers.

Transmission of light is actually the sum of the direct and diffuse components. Transmitted radiation received directly from the sun, without prior reflection, is called direct radiation. It is bright and strong and reaches you (or a sensor, or the plant leaf) from one direction…..the direction of the sun. Diffuse radiation results from the scattering of direct radiation within the atmosphere (by clouds, dust), or by the diffusing nature of the greenhouse cover itself (for example a translucent PE, or a double-layer glazing). Diffuse radiation is the sun’s rays reaching your eye (or the plant leaf) from many directions. Think of a day with a clear, deep blue sky which would have primarily direct radiation. Turning away from the sun easily shades your eyes from the high intensity light. Now think of a diffuse, but brightly lit day, caused by high thin clouds. Even if you turn away from the sun, the light may still bother your eyes, and make you want to squint.

Is diffuse light or direct light more important in the greenhouse? The greenhouse cover transmits both direct and diffuse radiation, but the cover may alter the proportions of each because of its physical properties. The diffuse component will always increase while the direct component is reduced. This is particularly true for most of the plastic films, but all double-layered glazings will also increase the diffuse component of the light.

Technically, the plant cannot distinguish the difference between direct or diffuse light. Each type will cause photosynthesis equally if provided at the same intensity in the PAR waveband. Diffuse light is direct light that has taken an indirect path to reach the plant. Look at the sharp shadow patterns of the overhead structures created on the floor within a glass-covered greenhouse compared to the blurred-edged shadows within a double-layer, plastic film greenhouse. The glass provides more direct light to the crop below. Consider that if there were no diffuse light, only the upper portions of the upper leaves would be brightly lighted by the sun, and that it is the diffuse light reflecting within the greenhouse that provides energy to the lower tiers of plant leaves.

A double-layer glazing whether glass or plastic will provide more diffuse light to the plants than a single-layer glazing. Two layers will also reduce the intensity at the crop more than a single layer. Plastic glazing will generally provide more diffuse light than glass because of its translucent nature. To maximize solar radiation for the plant, covering materials with the highest direct visible radiation transmission have been traditionally used. This was typically glass. However, there have been
discussions and claims that diffused light can improve plant growth, compared to direct light. The potential is greater for the diffuse light to reach more parts of the plant than direct light, since diffused light is scattered more uniformly about the greenhouse. Therefore, plants grown under diffuse light at the same intensity as direct light within the greenhouse, have the potential to receive more of the light for growth.

Should I select a glazing that increases the diffuse light?
This is still unclear. However, consider that clouds, dust and air pollution in the atmosphere all contribute to the diffusing nature of the sky that changes the direct solar radiation to diffuse radiation. Light passing through the glazing can only increase in its proportion of diffuse relative to direct light. Unless the greenhouse is located in a cloudless, dustless, non-pollution-filled sky with primarily direct solar radiation (deserts may be the closest to ideal), then this may be an unimportant concern.

Consideration of flexible film or rigid panels, both with and without additives?
Light transmission for films or panels (of equal numbers of layers) will decrease light transmission over time due to aging (yellowing), and to the accumulation of dust and air pollutants, because of the material surface properties. Transmission losses may become as much as 10% (or more) during the 3 or 4-year life of plastic films. Longevity of a glazing (15 to 20 or more years) and their subsequent higher price, such as for rigid plastic panels or glass, require a stable, washable material (either mechanically such as with glass, or by natural rainfall) to help maintain the maximum light transmission. Short-lived 3 or 4-year plastic films resolve the cleaning requirement, but need more frequent replacement than glass or rigid plastic panels.

Films and rigid panels are available that can modify very specific wavelengths of sunlight that have been demonstrated to change the plant growth response, specifically, the height of many types of flowering plants, without the need for growth regulators. The amount of the red light to the far-red light that the plant receives will increase (if less red, or more far-red) or decrease (more red, or less far-red) the final plant height. This concept of specific color light management opens many new opportunities for manipulating plant growth with greenhouse coverings.

Finally, consider that a glazing which is lighter in weight will require supporting structures with fewer, smaller support members, thereby reducing the shading and light transmission reduction caused by the greenhouse structure itself. Therefore the relatively narrow and heavy glass panels, will require more support structure than the wider and lighter plastic panels. Other structural factors such as, 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, and the type of attachments, will be affected by the choice of glazing based on its cost and its light transmission.

Energy going out --- Heat Transmission Losses Through Glazing
Solar energy can be transmitted, reflected or absorbed by the greenhouse covering. The transmitted portion of the visible (PAR) light is needed for plant growth, but only a small fraction (1 - 5%) is actually utilized by the plant. The unused PAR (and the remainder of the solar radiation other than PAR) is absorbed by the plant and the greenhouse internal components (soil, concrete) and structure. The absorbed energy, warms the components, and they re-emit the energy as infrared (IR) heat, and warm the greenhouse air. This "greenhouse heating effect" is the welcome result of radiation transmission into a closed space, and the prevention of some of the heat from leaving through the cover of the space.
The more insulated the cover of the greenhouse, the lower rate of heat lost, and thus the easier to maintain air temperature in the cool season. The insulating ability of transparent coverings is primarily dependent on whether it is a single or double-layer. This obviously is a very important consideration when selecting a glazing where supplemental heating is required. If the cover is constructed of two layers (for example, double-layer, air-inflated PE, or structured two-layer rigid PC), then it can insulate against heat loss better than a single layer (for example glass, or PC). Always select a double-layer material over a single-layer for greater heat energy savings. Double-layer covers will require less solar energy in the day, and fossil fuel energy at night, to maintain the inside air temperature, than will single-layer covers during the cool season.

However, the night heating costs can be further reduced if the cover has an additive that acts as an infrared heat barrier (low transmission of infrared radiation). Glass has traditionally had an excellent barrier to infrared transmission, but the plastic film covers (such as PE) may not. The IR barrier improves the “greenhouse heating effect” by trapping the IR radiation so that it can be absorbed within the greenhouse for warming the air, instead of passing through the glazing to the outdoor environment.

The amount of heating fuel costs for night period of equal outside air temperature are more dependent on whether (1) the glazing is a single or double-layer, and (2) whether the glazing is a continuous surface (reduced air leakage), or constructed of individual panels (potentially more infiltration), then whether the glazing has the IR barrier. The insulation developed by the air-gap within the twin-walled glazings will generally reduce energy loss from 35 to 40% compared to single layer covers, regardless of the type of plastic or glass used. Infiltration rates may vary from as little as ½ of the greenhouse volume air change per hour for continuous sheet film-covered greenhouses, to more than 1½ for rigid panel glazings. Both are increased by winds. A smaller unit width of panel glazing provides a greater proportion of edges that must be kept sealed to prevent infiltration heat losses. 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.

Condensation of water vapor from the warm moist air onto the cool surface of the covering material represents another method for heat loss from the greenhouse. The energy released from the water vapor as it changes to liquid is immediately lost to the glazing (and then to the outside). More importantly, this represents an undesirable situation for the crop, as excessive moisture on the glazing will cause dripping which can damage the quality of the crop and enhance the spread of disease. Efforts to incorporate inhibitors to droplet formation, particularly on plastic coverings, have somewhat reduced this problem. A sloped roof (rise to run of 1:2) will encourage moisture to flow toward the gutter, and collect without dripping, as compared to roof with a shallow slope. A double-layer glazing will have a warmer interior layer surface temperature, because of the air-gap insulation between the layers, and thus less condensation. Condensation during the sunlight hours will also reduce solar energy transmission.

**The need for more information**

This introduction to the fundamentals of greenhouse glazings can be greatly enhanced with information provided by research and extension publications, as well as, industry design and application experiences. To obtain a greater depth of understanding, other sources listed below should be considered. It is especially important to include up-to-date reports, in addition to fundamental information, because of the rapidly changing materials, products and greenhouse systems within the marketplace.

For a fundamental, research-based background on the subject of greenhouse glazings relating to light transmission and to night time heat losses, see *Energy Conservation for Commercial Greenhouses,*
NRAES-3. For general information on planning, constructing, and controlling a commercial greenhouse, see *Greenhouse Engineering, NRAES-33*. Both can be obtained from NRAES, Cooperative Extension, 152 Riley-Robb Hall, Ithaca, New York 14853-5701. Phone (607) 255-7654 e-mail at nraes@cornell.edu, or http://www.nraes.org

The National Greenhouse Manufacturers Association is a professional trade organization for the manufacturers and suppliers of greenhouses and greenhouse components. NGMA has produced standards for greenhouse design, which provides the experience and knowledge of manufacturers in the industry. See NGMA, 20 West Dry Creek Circle Suite 100, Littleton, CO 80120, FAX 303-798-1315, or http://www.ngma.org for more information.

The CCEA, Center for Controlled Environment Agriculture, Rutgers University sponsored an industry-academic workshop in October 1998, entitled: “Greenhouse Covering Solar Radiation Transmission Workshop”. Proceedings from the workshop are available. Contact Gene Giacomelli at giacomel@ag.arizona.edu.

**References**


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