Components of Radiation Defined: Definition of Units, Measuring Radiation Transmission, Sensors

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Opinion, Warnings, and (hopefully) Perspective

Generally, the objective seems to have been to develop glazings that provide as much solar radiation transmission as possible into the greenhouse. More was presumed better, and in general that can be true. But not always. To determine the maximum value laboratory testing of pristine glazing under ideal transmission conditions provided a relative (between types of glazings) indication of the potential for radiation transmission. When determined in the field, transmission measurement has many more uncontrollable factors to consider so that correct comparisons can be achieved. Procedures for transmission measurement have included the use of electronic sensors, or determined by comparing plant response, or at times just given a good look with the eyeball! Each comes with a level of cost, as well as a level of accuracy.

What will hopefully become apparent with this and subsequent presentations of this workshop, is that it is simply not that simple! Maybe of greatest importance in all the discussions is to remember that the goal should be to provide the environment for the most optimum growth of the plant, or for the most optimum final product that will demand the greatest return on investment. It is the plant response that should be dominant in all the discussions.

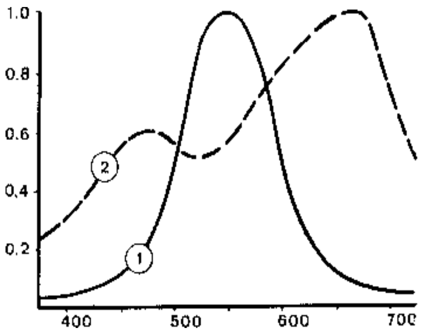


Figure 1. Relative sensitivity of human eye (line 1), and cucumber leaves (line 2) for wavelengths of light (nm).
(from Poot Lichtenergie B.V., 1984)

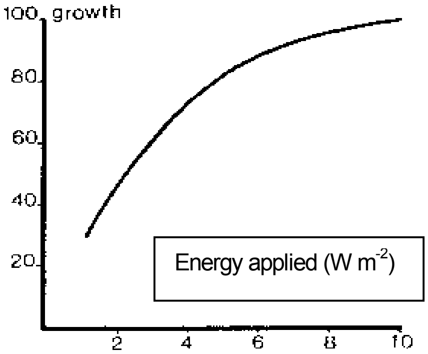


Figure 2. (from Poot Lichtenergie B.V., 1984.)

To this end, we must encourage the proper measurement procedures of the appropriate radiation wavelengths that are important to the plants. The term PAR and its units will, in short order, become tiresome during these discussions, but it is an important concept to understand and use.
See Figure 1, which includes a comparison of what the human eye "sees" (line 1), relative to the wavelengths of light which have been determined important to a plant leaf (line 2). Clearly, the human eye cannot even begin to respond to many of the wavelengths before 500 nm and beyond 600 nm. The plant leaf response, however, extends beyond the PAR waveband of 400-700nm. The take-home

message: You can no longer walk into a greenhouse, look up at the glazing and with the restricted wavelength ability of your eyes determine that a glazing is "brighter" and thus better for the plants. We all can be misled by our eyes!

Finally, consider the concept of "more is better". Figure 2 shows a sloping curve representing the increasing rate of plant growth with increasing radiation energy applied. The sloped curve clearly shows that the growth rate is increasing, but at a decreasing rate, as you follow the curve to the right, which means increasing the energy (light) level. Ultimately the curve turns horizontal, meaning that any additional light energy will not provide any increase in plant growth rate.

Components of Radiation

Radiation from the sun can be described by its quantity and quality. The **quality** is described by the waveband of the light, and the distribution of the wavelengths within the waveband. The **quantity** is the "intensity" or amount of energy within the radiation received. This quantity can be measured as the number of photons, or as a total energy value. Whenever a number for radiation quantity (intensity) is given, the wavelength(s) involved must also be given (quality), or else the number has little useful value.

Radiation from the sun can be described by its wavelength or its frequency. Light, or visible radiation for humans, can be considered as a wave (with an associated wavelength), or as a particle of energy photon (with an associated energy value). When considered as a photon it may be expressed in energy terms, Watts per square meter [$W\ m^{-2}$], or as the number of photons [moles of photons] $\mu mol\ m^{-2}\ s^{-1}$.

Wavelength has units of meters, typically nanometers (nm) [one billionth of a meter] or micrometers (um) [one millionth of a meter]. **Frequency** has units of cycle per second. Together they are related as parameters of a photon of light by the constant c, the speed of light. The frequency of the photon is equal to the speed of light divided by wavelength of the photon.

The **energy of a wavelength** of light is equal to Planck's constant (h) multiplied by the frequency of the light, or alternatively, the energy of a wavelength is equal to Planck's constant (h) multiplied by the speed of light and divided by the wavelength. From this relationship, an important fact is determined. **For radiation (light), as its wavelength increases, its energy decreases, and as the wavelength decreases, the energy increases. Thus short wave blue light has more energy than longer wave red light.**

The Spectrum and Various Wavebands

The radiation spectrum contains various wavebands of interest (Figure 3).

Ultra-Violet or **UV** is the wavelengths less than 400 nm. These high-energy wavelengths can cause skin damage [sunburn]. The UV is divided into UV-A waveband (320-400 nm), UV-B waveband (280-320 nm), and UV-C (100-280 nm). The shorter wavelengths have higher energy, thus UV-B and UV-C can be dangerous. Whereas, UV-A has practically no effect on humans, UV-B will cause "tanning" and ultimately "sunburn" of the skin, and it helps form vitamin D for the body. UV-C has a strong germicidal effect and is hazardous to plant and animal cells. Natural sunlight has a large amount of UV-A, a small amount of UV-B, and no UV-C.

Visible light is based on the sensitivity of the human eye and is within the 380-770 nm waveband. All combined visible light is "white" light, when separated into its components, it is the individual colors. PAR, Photosynthetically Active Radiation, in the 400 to 700 nm waveband, is the primary waveband important for providing the energy for plant photosynthesis. In Figure 5, the relative absorption of the wavelengths of PAR for the chlorophyll molecules (type a & b) show that there is a strong absorption between 400 to 480 nm (blue), and also between 630 to 680 nm (red). Note that there is some absorption at almost all the remaining PAR wavelengths, but at a significantly reduce relative value.

The "colors" of the radiation visible to humans can be divided into the following wavebands:

Waveband	**Color**	**Function in the Plant**
380-436 nm	violet	=> uncertain, but may support effect of blue light
436-495 nm	blue	=> a minimal quantity is necessary to prevent tall, weak plants
495-566 nm	green	=> unnecessary, but contributes to photosynthesis
566-589 nm	yellow	=> unnecessary, but contributes to photosynthesis
589-627 nm	orange	=> optimize for maximum photosynthesis
627-770 nm	red	=> optimize for maximum photosynthesis; enhances flowering, stem elongation; Red/Far-red ratio is important

Infrared or **IR** is the wavelengths greater than 770 nm and up to 1,000,000 nm, and it includes the **Near Infrared** or **NIR** which is within the 770-850 nm waveband, and the **IR-A** or the **short wave infrared** (770-1,400 nm). The IR-A waveband has the greatest heating effect. The NIR does include wavelengths that influence the growth of the plant. We cannot "see" infrared (without expensive night-vision equipment), we can, however, "feel" the effect of infrared, as it contacts our skin, we get a warming sensation.

Red: Far-red (R:FR) ratio consists of two narrow wavebands which influence plant growth responses.

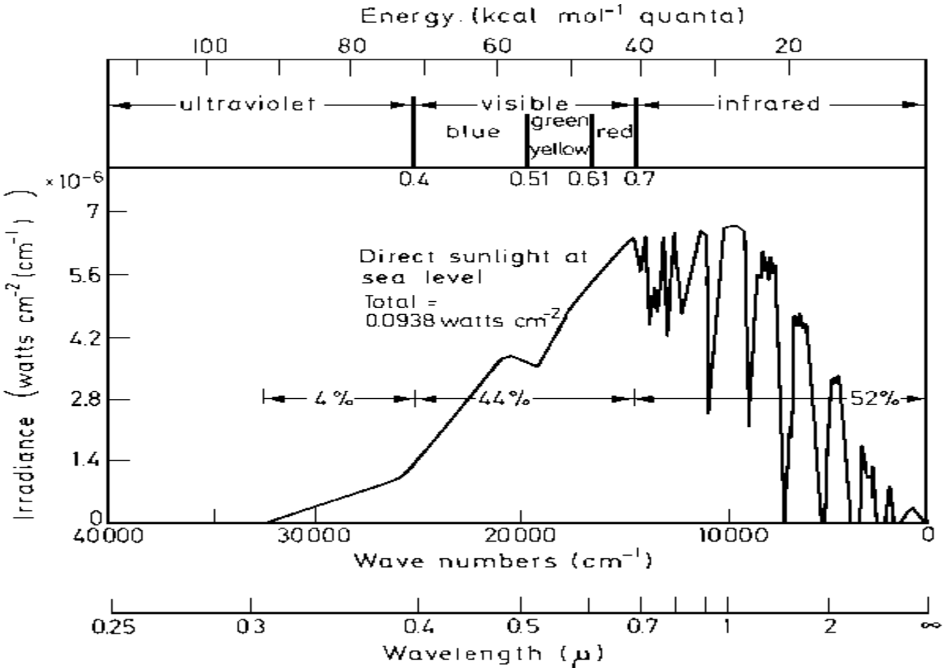


Figure 3. (from Hanan, 1998)

Of the total solar radiation reaching the earth's surface, 97% of the spectral distribution is within the 280-2,800 nm. Of this, about 44% is PAR or visible, about 4% is UV, and the remainder 52% is IR

(Figure 3). Table 1 provides a further breakdown of the PAR into its color components. The quantity or intensity of the radiation from 400-800 nm is shown as the Photon Irradiance (first column) for a very clear day. The quality or distribution of the wavebands of radiation is shown as a percentage of each waveband of light. These are contrasted for direct sunlight, and for under dense leaf shade (compare rows).

Table 1. Proportion of total light within specific "color" wavebands (from Kendrick and Kronenberg (eds.), 1986).

	Photon Irradiance (400-800 nm) umol m^{-2} s^{-1}	**Waveband**			
		Blue (400-500 nm)	**Green** (500-600 nm)	**Red** (600-700 nm)	**Far-red** (700-800 nm)
Direct sunlight	1,700	0.23	0.26	0.26	0.25
Leaf Shade **[with LAI = 4]**	60	0.04	0.15	0.11	0.70

Leaf Area Index (LAI) is defined as the ratio of total leaf area to occupied ground area.

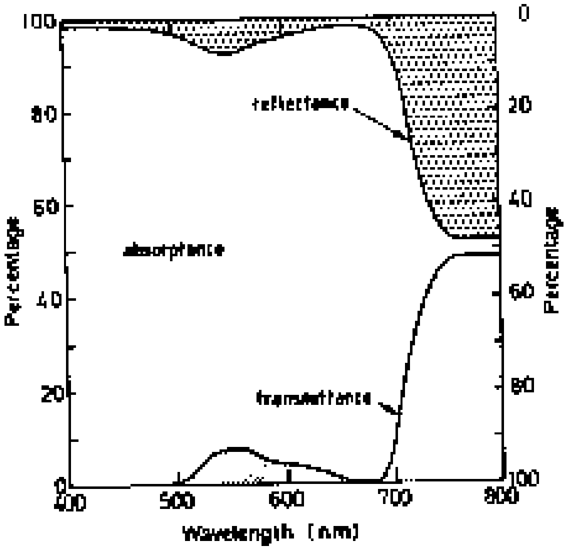
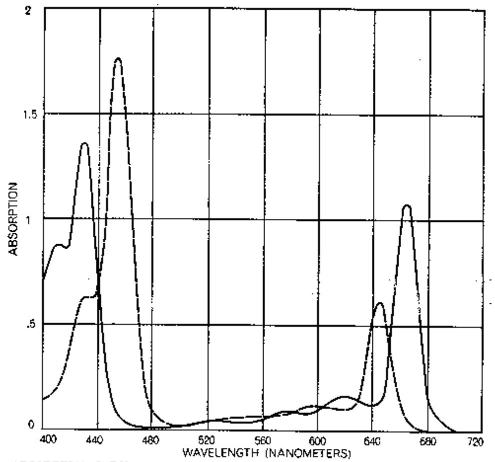


Figure 4. (from Kendrick and Kronenberg (eds.), 1986)



ABSORPTION SPECTRA show that chlorophyll *a* (*solid line*) and chlorophyll *b* (*broken line*) strongly absorb blue and far-red light. The green, yellow and orange wavelengths lying between the peaks are reflected and give both pigments their familiar green color.

Figure 5. (from Levine, 1969)

Definition of Units of Measurements

The **PAR, Photosynthetically Active Radiation**, is the waveband 400 to 700 nm, which are the limits of wavelengths that are of primary importance for plant photosynthesis. The **PPFD, Photosynthetic Photon Flux Density** is the number of photons in the PAR waveband that are incident on a surface in a give time period (µmol m^{-2} s^{-1}). The quantum sensor will measure this value. A very clear sky value will approach 2,000 µmol m^{-2} s^{-1} PAR.

Irradiance is the measure of the quantity of radiation within a given waveband (W m^{-2}). A very clear sky irradiance value will approach 1,000 W m^{-2} (280-2,800 nm waveband). The **PI, Photosynthetic Irradiance** is the radiant energy stream in the PAR waveband which is incident on a surface in a given time period (W m^{-2}). The relationship between these two terms PPF and PI cannot be generalized, since their relationship depends on the spectral properties (radiation distribution) of the radiation source (or sun), as well as, the transmission properties of the glazing between the sun and the sensor (or plant).

Spectral irradiance (SI) determined from a spectroradiometer where the number (μmol m^{-2} s^{-1} nm^{-1}) or energy value (W m^{-2} nm^{-1}) of photons is measured at every wavelength. The mol units are more appropriately used for the spectral irradiance of PAR, because the number of photons absorbed by the leaf is more important than the total energy absorbed for determining photosynthesis. Note that for photosynthesis to occur at least eight photons must be absorbed in the chlorophyll molecule, and each must have an energy value greater than a wavelength of 680 nm.

R:FR ratio of the sky always averages about 1.15 throughout the day, under all weather/cloud conditions, as long as the sun angle is greater than 10^o above the horizon.

Measuring Radiation Transmission

Radiation can either be reflected, absorbed or transmitted once it impacts a surface. The properties of the material will determine what proportion of the three will be; however, the sum of the energy reflected, absorbed and transmitted must be 100%. The properties are often abbreviated by the Greek symbols ρ, α and τ, which represent **reflectance** (ρ), **absorbtance** (α), and **transmittance** (τ). There are standard test procedures for determining each.

The leaf will typically absorb nearly 95% of wavelengths between 400 – 700 nm, while only 5% of the 700-800 nm waveband is absorbed. Of the remaining 95% of the 700-850 nm waveband, approximately 45% is reflected, and 45% is transmitted (Figure 4).

Extra-terrestrial solar radiation has a greater intensity and spectral distribution than ground level solar radiation because of the wavelengths of light that are absorbed while passing through the atmosphere. Major atmospheric components that absorb or reflect certain wavelengths of light include: ozone (O_3), carbon dioxide (CO_2), methane (CH_4), water vapor (H_2O), and CFC's (Chlorofluorocarbons). In Figure 6, there are two curves, with one representing the intensity of radiation above the atmosphere (smooth, slightly higher curve in figure), and one representing the intensity of radiation at the earth's surface (irregular shaped, slightly lower curve in figure). The significant reduction of energy by each atmospheric component is labeled along this curve.

The **Clearness Index (CI)** indicates the percentage of the radiation that passes through the atmosphere. It quantitatively is the transmittance of the atmosphere, and essentially describes the "cloudiness" of the day. It is determined by the ratio of the intensity of radiation measured at the ground to that calculated to be above the atmosphere, using the same units for both. It can have units of either μmol m^{-2} s^{-1} or W m^{-2}, that is, in terms of number of photons, or in energy terms, respectively. A CI of 0.75 is a very clear day, while a CI of 0.25 is a cloudy day.

Transmittance is a ratio of the intensity of the transmitted radiation (below the glazing surface) within a given waveband, to incident radiation (above the surface) within the same waveband. A maximum value of transmission for a material can be measured for beam radiation (non-diffuse) that is perpendicular to the surface (directly overhead of a horizontal surface), and the sensor beneath the surface is located directly under it.

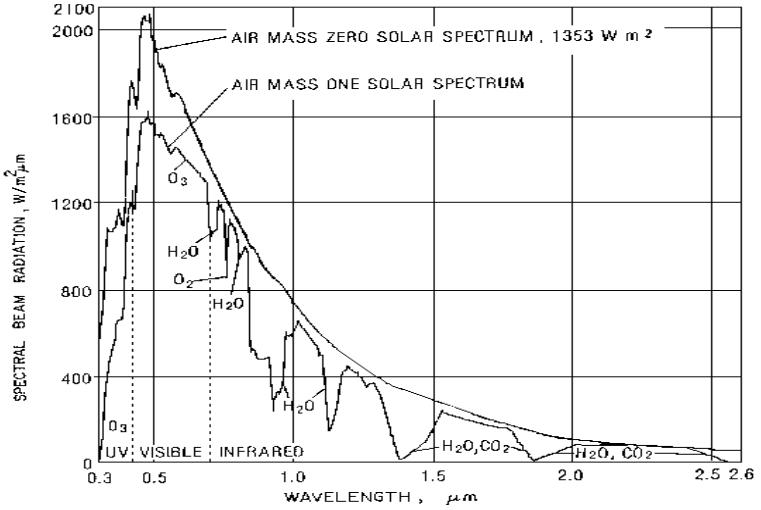


Figure 6. Spectral distribution of solar radiation with indications of major atmospheric absorptions.

(from Hanan, 1998)

However, within a greenhouse, the sensor underneath the glazing may not always be located directly adjacent to it. If located just above the canopy, then it will measure an intensity lower than if located up just beneath the glazing surface, primarily because of the structural materials and other systems located between the canopy and the glazing. Thus position of the sensors must be identified to define transmittance of the greenhouse system **(canopy transmittance)**, or transmittance of the glazing **(glazing transmittance)**. Both of these will be less than the ideal transmittance value measured and determined in the laboratory. Transmission values measured within the greenhouse will be significantly different (less than) than when measured in the laboratory for a particular glazing material.

The proportion of **direct (straight beam) radiation** and **diffuse (reflected)** solar **radiation** will vary depending on the sky conditions. A cloudy day (low Clearness Index) will provide more diffuse radiation, and less direct radiation than a clear day (high Clearness Index). A diffuse day essentially means that the light energy is not as concentrated from one direction (location of the sun in the sky), and light appears to arrive from all overhead directions with nearly equal intensity. In practical terms, there will be less distinct shadows on the greenhouse crops resulting from the shading by overhead structural members, on a diffuse (low CI.) day than on a day with clear sky.

The diffuse radiation can be measured independent of the direct component of radiation with the use of a **shadow-band instrument**. This instrument has a small opaque piece of metal fixed between the sensor and the location of the sun, thus always keeping the sensor in the shadow. It therefore approximates the diffuse component of the solar radiation. If simultaneously the total radiation is measured, then by subtracting the value of the diffuse from this total value, the direct component can be determined.

Sensors

Pyranometer sensors are for measuring solar radiation over most of its entire waveband, usually from 280-2,800 nm. Note that 97% of the sun's spectral distribution is within this waveband. This value could be considered "total solar" radiation. Units are $W\ m^{-2}$

Quantum sensor is limited to the PAR waveband (400-700 nm), and is typically measured as $\mu mol\ m^{-2}\ s^{-1}$.

Net Radiometer measures the difference of the radiation arriving from above to that being reflected from below. It is important for energy evaluations of the greenhouse.

Spectroradiometer is an instrument that can split the incoming light into individual wavelengths or prescribed wavebands, and then measure the irradiance of the photons in these wavelengths. It typically measures spectral irradiance **(SI)** in the units $\mu mol\ m^{-2}\ s^{-1}\ nm^{-1}$ or $W\ m^{-2}\ nm^{-1}$.

Conversions

1 lux = 1 lumen m^{-2} = 0.0929 foot-candle
1 $W\ m^{-2}$ = 1 $J\ s^{-1}\ m^{-2}$ = 0.317 $BTU\ h^{-1}\ ft^{-2}$ = 0.001433 Langley min^{-1}

<u>For daylight clear sky PAR only:</u>

	A	**B**
(1)	0.199 $\mu mol\ m^{-2}\ s^{-1}$ per foot-candle	or 5.13 foot-candle/$\mu mol\ m^{-2}\ s^{-1}$ PAR
(2)	4.57 $\mu mol\ m^{-2}\ s^{-1}$ / $W\ m^{-2}$ PAR	or 0.22 $W\ m^{-2}$/ $\mu mol\ m^{-2}\ s^{-1}$ PAR
(3)	0.018 $\mu mol\ m^{-2}\ s^{-1}$ / Lux PAR	or 54 Lux / $\mu mol\ m^{-2}\ s^{-1}$ PAR

Use Column "A" and multiply a know value of foot-candles, $W\ m^{-2}$, or lux by (1), (2), or (3), respectively to obtain $\mu mol\ m^{-2}\ s^{-1}$ PAR for **<u>daylight clear sky condition only.</u>**

Use Column "B" and multiply a know value of $\mu mol\ m^{-2}\ s^{-1}$ PAR by (1), (2), or (3), to obtain foot-candles, $W\ m^{-2}$, or lux, respectively for **<u>daylight clear sky condition only.</u>**

Definitions

Transmittance *-- ratio of transmitted to incident radiant energy.*
Absorbtance *-- ratio of absorbed to incident radiant energy.*
Reflectance *-- ratio of reflected to incident radiant energy.*

Direct radiation *-- straight beam radiation directly arriving from the sun to the sensor or plant.*
Diffuse radiation *-- solar radiation, which is reflected by the atmosphere or greenhouse structure before reaching the sensor or the plant.*

Clearness Index (CI) *-- ratio of the irradiance at the surface of the earth to the irradiance above the atmosphere; the "transmissivity" of the atmosphere for solar radiation.*

Solar radiation spectrum *-- all the wavelengths included in radiation from the sun.*

PAR, Photosynthetically Active Radiation (400-700 nm) *-- waveband of the radiation spectrum used by plants for photosynthesis. The units are* $\mu mol\ m^{-2}\ s^{-1}$.

PPFD, Photosynthetic Photon Flux Density *-- number of photons in the PAR waveband that are incident on a surface during a give time period. The units are* $\mu mol\ m^{-2}\ s^{-1}$.

PI, Photosynthetic Irradiance -- *radiant energy stream in the PAR waveband, incident on a surface during a given time period. The units are* $W\ m^{-2}$.

Photons *– units of radiation (smallest "particles" of light; also called quanta).*

Photon frequency *– the energy of a photon is proportional to its characteristic frequency.*

Pyranometer *-- sensor measuring solar radiation usually from 280-2,800 nm. Units are* $W\ m^{-2}$.

Quantum Sensor **--** *sensor measuring the PAR waveband (400-700 nm). Units are* $\mu mol\ m^{-2}\ s^{-1}$.

Spectroradiometer *-- instrument that can measure the irradiance of photons in each wavelength of a waveband.*

Spectral Irradiance (SI) *-- energy value or distribution for each wavelength within a waveband is measured as* $\mu mol\ m^{-2}\ s^{-1}\ nm^{-1}$ *or* $W\ m^{-2}\ nm^{-1}$.

$\boldsymbol{\mu mol\ m^{-2}\ s^{-1}}$ *-- micromoles per square meter per second (intensity) .*

$\boldsymbol{W\ m^{-2}}$ *-- Watt per square meter.*

wavelength *-- way to measure and describe the photon of light.*

waveband *-- a grouping of wavelengths, e.g., PAR is the waveband between 400 and 700 nm.*

nm or nanometer *-- unit of measure of the wavelength of light; one billionth of a meter.*

µm or micrometer *-- unit of measure of the wavelength of light; one millionth of a meter.*

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