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COMPARISONS OF LUMINAIRES: EFFICACIES AND SYSTEM DESIGN

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INTRODUCTION

Lighting designs for architectural (aesthetic) purposes, vision and safety, and plant growth have many features in common but several crucial ones that are not. The human eye is very sensitive to the color (wavelength) of light, whereas plants are less so. There are morphological reactions, particularly to the red and blue portions of the light spectrum but, in general, plants appear to accept and use light for photosynthesis everywhere over the PAR region of the spectrum. In contrast, the human eye interprets light intensity on a logarithmic scale, making people insensitive to significant differences of light intensity. As a rough rule, light intensity must change by 30 to 50% for the human eye to recognize the difference. Plants respond much more linearly to light energy, at least at intensities below photosynthetic saturation. Thus, intensity differences not noticeable to the human eye can have significant effects on total plant growth and yield, and crop timing. These factors make luminaire selection and lighting system design particularly important when designing supplemental lighting systems for plant growth.

Light from a source (lamp) in a controlled environment chamber, or greenhouse, follows many paths to a plant; not all are direct. Light leaves a lamp in nearly every direction. Luminaire reflectors are designed to redirect much of the light from the lamp into a (more or less) single direction while avoiding redirecting light energy back through the lamp itself. However, not all radiation that leaves a luminaire strikes the plant canopy directly. That part of the light that initially strikes walls and other surfaces within the lighted space should ideally be reflected totally, and re-reflected until intercepted by the plant canopy. That is the ideal. The ideal is never completely realized. Further, from the perspective of the plant canopy, irradiance is from several or many luminaires. Light from multiple sources, even if primarily direct from each, is perceived as an essentially diffuse light environment to the receiver.

Light reflection within a luminaire reflector is primarily specular if the reflector has a bare metal surface and primarily diffuse if the reflector has a white painted surface. Reflection within a lighted confined space is likely to be primarily diffuse. Reflection is never complete and reflectance of a luminaire surface is not the only parameter that determines how much light eventually reaches a plant. Luminaire reflector design and placement are other parameters. With specular reflectors, the shape of the reflector determines almost entirely the distribution of light within the reflected beam, while with diffuse reflectors the shape has only a minor influence (Elmer, 1980).

Supplemental lighting for plant growth must meet several criteria. One is amount (intensity, or integrated total) of light, or PAR, intercepted by plants. A second is spacial uniformity of PAR within the plant canopy. Energy efficiency is a third criterion, particularly in commercial greenhouses, but also in research facilities such as plant growth chambers where an energy inefficient lighting system imposes a double penalty when the additional heat must be removed by a mechanical refrigeration system.

The amount of PAR intercepted by a plant canopy leads directly to total growth and development of the plants. Uniformity can be related to crop timing and consistency. In a research setting, lighting uniformity is likely to be very important if plant-to-plant comparisons are to be valid and adequate statistical test sensitivity is to be achieved.

Lighting plant growth chambers for research is a particularly difficult design problem. The importance of uniformity in commercial greenhouses may be less important, depending on the crop. For example, a crop harvested continuously, such as roses or tomatoes, will be less likely to suffer from lighting non-uniformity. Conversely, a crop harvested as a unit, such as hydroponic lettuce, must be relatively consistent to meet market expectations and light uniformity is crucial to crop uniformity.

Supplemental lighting for plant growth on the scale of commercial greenhouses is a relatively expensive undertaking. Light intensities are often much higher than required for task (vision) lighting, which increases both installation and operating costs. However, and especially in the northern regions of the United States (and Canada, Europe, etc.), supplemental lighting during winter may be necessary to produce certain crops (e.g., tomatoes) and very useful to achieve full plant growth potential and crop timing with most other greenhouse crops. Operating costs over the life of a luminaire typically will exceed the initial investment, making lighting efficacy a major consideration.

This report reviews tests completed to evaluate the efficiencies of various commercially-available High-Pressure Sodium luminaires, and then describes the results of using a commercial lighting design computer program, Lumen-Micro[1], to explore how to place luminaires within greenhouses and plant growth chambers to achieve light (PAR) uniformity and relatively high lighting efficacies. Several suggestions are presented which could encourage systematic design of plant lighting systems.

LUMINAIRES

The purpose of using a luminaire rather than a bare lamp is to direct, distribute and focus both direct and diffuse light. Luminaires generally consist of some or all of the following components (CADDETT, 1991):

- a housing to contain or support the other necessary parts, such as the ballast,
- a reflector (troffer) to direct light into a desired pattern,
- one or more lamps, and

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[1] Version 5, Lighting Technologies, Inc., Boulder, CO.

> a lens or shield to reduce glare, protect the lamp, and perhaps to direct or focus the light. Lenses are less commonly used in luminaires for plant lighting, although a light cap in a plant growth chamber will often be covered on the underside with a transparent layer so the light cap can be separately ventilated.

Luminaire efficiency is typically defined as the ratio of the total number of lumens from a luminaire to the total lumens produced by its lamp(s). This differs from efficacy, defined as the light output from a luminaire related to power input.

The reflector is usually the component that most significantly affects luminaire efficiency. The surface treatment of the reflector and the physical design of the reflector each affect the efficiency. The surface treatment may be white paint, which has a low value of specular reflectance but which can produce a total reflectance from 60 to 80%. Anodized polished aluminum has a high value of specular reflectance and can produce a total reflectance greater than 90%. These values may be, of course, greatly reduced by poor physical design of the reflector or a build-up of surface film. Even in a clean office environment, luminaire efficiency may be reduced by one-third after a decade of not cleaning (Bean & Simons, 1968, although smoking by occupants is likely a factor of less significance today).

SURFACE REFLECTANCE

Surface reflectance is important for luminaire reflector design, but that is a consideration left for luminaire manufacturers to contend with. Lighting <u>system</u> designers are more concerned with reflectance of surfaces within the lighted space. This is particularly true in plant growth chambers where a significant fraction of light reaching a plant canopy will have been reflected at least once from interior surfaces (walls, ceiling, floor). Reflectance of surrounding surfaces may be less important in commercial greenhouses although white mulch may be used, as under a tomato crop, for example, to improve the light environment of the crop. Surface (especially wall) reflectance may be very significant in small research greenhouses.

Two reflectance factors may be considered: total reflectance, and the spectral variation of reflectance. Table 1 contains data demonstrating the variation of diffuse reflectance (albedo) for common materials. Even the best reflector, white paint, absorbs approximately one-quarter of the incident light. Surfaces that may appear to the human eye to be quite reflective (e.g., pastel paints) are likely to absorb more than half the incident light and be classified, technically, as absorbers rather than reflectors. The human eye is deceptive in this regard. The effect of surface reflectance on lighting system designs in a plant growth chamber will be explored later in this report.

Plant research may require a second reflectance factor be considered in design (especially for plant growth chambers): the spectral dependence of reflectance. Table 2 contains data to demonstrate the magnitudes of spectral dependencies. First, the spectral dependencies of what may appear to be two similar materials vary in opposite directions. Second, the reflectance can vary by more than 10% over the PAR spectrum. Because of the importance of multiple reflections in the light environment of a plant growth chamber, spectral quality should be measured at the plant canopy within the chamber; manufacturer's data for the lamp alone may not apply.

TABLE 1 Surface reflectances of various materials

Material	Albedo for "white" light*
Ordinary white paper	0.6 to 0.7
ZnO (white) paint	0.7
Aluminized paint	0.45
White lead paint	0.75
Yellow paint	0.55
Yellow paper	0.25
Wood, pine	0.4
Sandy loam, dry	0.24
White-washed surface	0.5
Grass (turf)	0.24
Deciduous Woodland	0.18
Coniferous woodland	0.16
Open water	0.05
Dry soil (light color)	0.32

*Handbook of chmistry and physics, 1985; and Campbell, 1986

TABLE 2 Spectral dependence of reflectance of various materials*

	Wavelength, microns			
Material	0.4	0.5	0.6	0.7
ZnO (white) paint	0.74	0.84	0.85	0.86
White porcelain enamel	0.77	0.73	0.72	0.70

*Handbook of chmistry and physics, 1985

LUMINAIRE EFFICACY

Luminaire efficacy is important in two ways for designing systems. First, a luminaire that produces more PAR for each input watt will be more energy efficient and less expensive to operate. Additionally, greater light output for the same wattage rating may permit fewer luminaires to be required for a practical installation, as in a commercial greenhouse. If each luminaire requires less energy, and fewer luminaires are required, the savings are compounded. This precept was explored through a series of tests of nine different HPS (High Pressure Sodium) luminaires currently available for commercial use (Both, et al., 1992, 1994). Only one of each model was tested and the tests were of the luminaires as purchased. No standard ballast (IESNA, 1984) was used, for example. However, the results showed a range of expected efficacies and provided data useful for exploring the inter-relationship of luminaire selection and ultimate system design and operating cost. The same 400 W lamp (seasoned) was used in all luminaires to remove one source of variability.

The luminaires were tested in the testing facility of the Department of Agricultural and Biological Engineering of The Pennsylvania State University, a facility described by Turn and Walker (1987). PAR distribution patterns for eight of the luminaires are in Fig. 1. Ratings by PAR output and energy efficiency are in Table 3, but note that the order of luminaires in Table 3 does not correspond to the order of luminaires in Fig. 1. The data will be used in several examples that illustrate system design procedures and considerations.

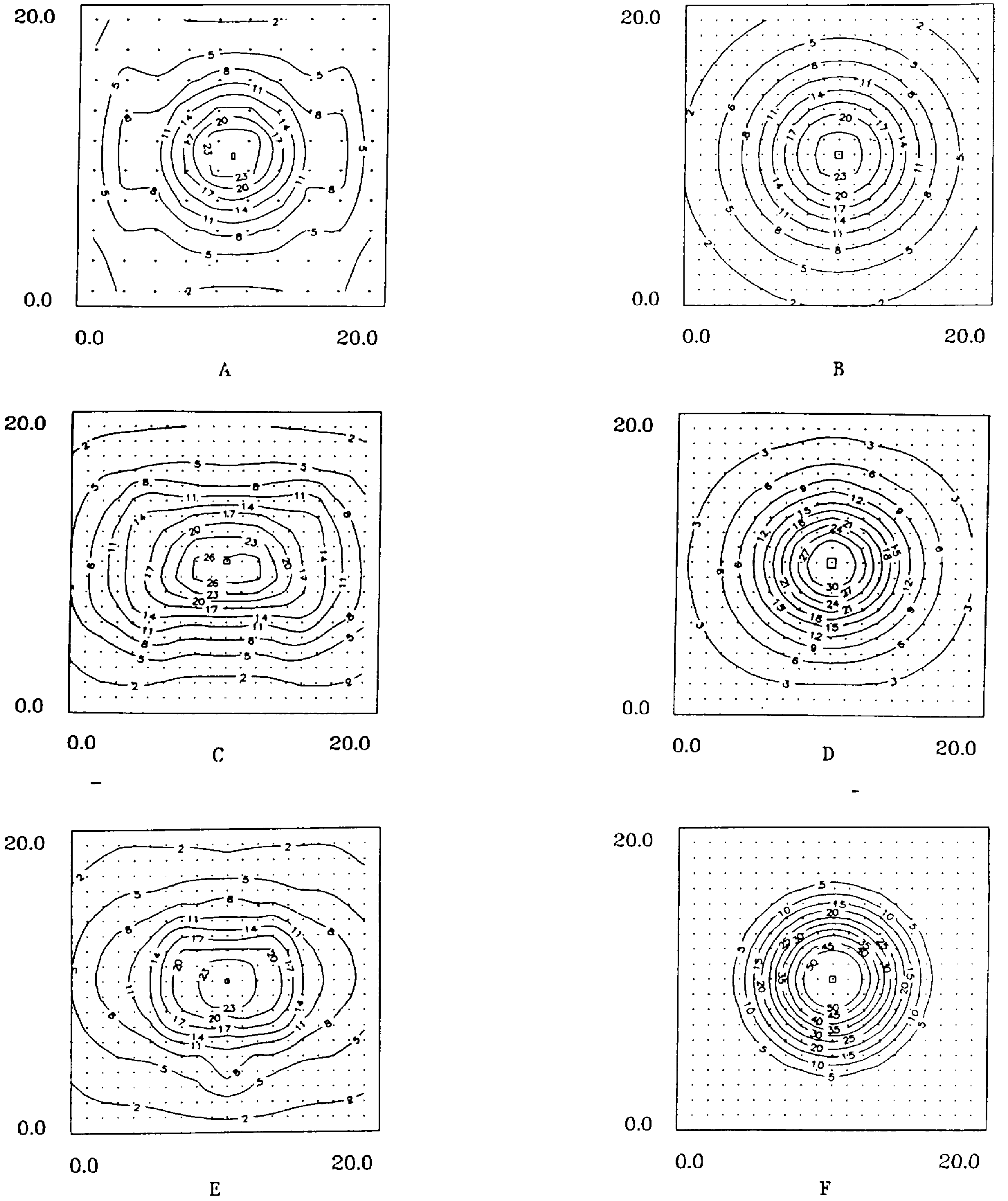
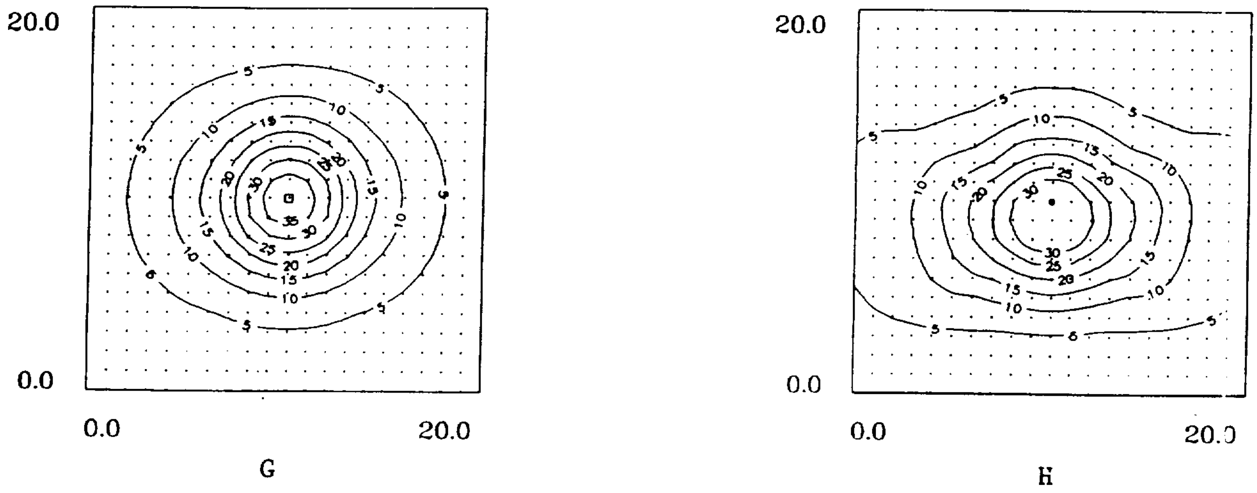


Fig. 1. PAR distribution patterns of eight 400 W HPS luminaires at a mounting height of 1.5m (5'). Contour lines are in μmolm^{-2}s^{-1}, horizontal dimensions are in feet. Luminaire axis E-W, transverse axis N-S. Continued on next page.



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H

Fig. 1. Continued

TABLE 3 Luminaire ratings by PAR output and efficacies.

Luminaire	Average watts	Average umol s^{-1}	mol PAR per kWh	mol PAR per kJ	Lumens per watt
A	426	346	2.92	811	58.0
B	435	424	3.51	975	69.7
C	461	365	2.85	792	56.6
D	414	326	2.84	789	56.3
E	424	360	3.06	850	60.7
F	476	372	2.81	781	55.8
G	398	356	3.22	895	63.9
H	396	318	2.89	803	57.4

COMPUTER PROGRAMS FOR LIGHTING SYSTEM DESIGN

Many luminaire manufacturers have developed computer programs useful for designing lighting systems. Such programs are generally proprietary. A commercially available program, Lumen-Micro, was used to obtain the results presented in this report. The luminaire data files were originally created in IES format (IESNA, 1986). However, the standard IES format includes candela values for each vertical angle at each applicable horizontal angle at which data were taken for the luminaire. Candela values in the data file lead to foot-candle values of light intensity as the program's output, not units useful for plant lighting. For this report, the candela data were multiplied by the factor 0.1318 (for the spectrum of HPS lamps) to calculate PAR units of $\mu molm^{-2}s^{-1}$. Total lamp output, lumens, was converted to $\mu mols^{-1}$ after multiplying by the factor 0.014.

PAR UNIFORMITY CRITERIA

Several criteria have been proposed as measures of lighting uniformity. One is the ratio of the minimum light value within a lighted space to the maximum value (Philips Lighting, 1991), with a suggested minimum value of 0.7. A second is the ratio of the minimum light value to the average (Stolze, et al., 1985). A third is a Uniformity Criterion (UC1) defined as follows (Schwab, et al., 1981):

$$UC1 = 1 - \Sigma(|y_i - y_{ave}|)/(Ny_{ave}) \qquad (1)$$

where y_i represents the individual values, y_{ave} is the mean over the lighted area, and N is the number of values (readings). In practical terms, UC1 is the complement of the average deviation from the mean divided by the mean. A minimum value of 0.75 was suggested.

A fourth Uniformity Criterion (UC2) is suggested here based on the statistical concept of the Coefficient of Variation (CV), the standard deviation divided by the mean (Steel and Torrie, 1960):

$$UC2 = 1 - CV = 1 - (\Sigma(y_i - y_{ave})^2/(N - 1))^{1/2}/y_{ave} \qquad (2)$$

The primary difference between UC1 and UC2 is the greater weight UC2 gives to values greatly different from the mean, values that would, in an experiment, significantly reduce the sensitivity of testing a hypothesis by statistic means.

A fifth means to quantify lighting uniformity will be considered here, based on a frequency graph. That is, all PAR measurements within a lighted space are listed, sorted (ascending order) and graphed as a function of their sequence number. Zones of acceptable uniformity (for example, within ±10% of the mean) can be added to the graph to indicate, visually, which regions of the lighted area meet or exceed the acceptable uniformity criterion. As a note regarding the Lumen-Micro program, contour graphs of light intensity are provided to the user and the contour lines can be color-coded so zones where the PAR is above or below the criterion (e.g., ±10%) can be readily identified. The combination of frequency graphs and color-coded contour graphs can be a powerful tool a designer can use to assess the extent of non-uniformity and then understand where it occurs. Such visual clues can, perhaps, lead a designer to alter luminaire layouts for better uniformity.

Each of these criteria will be presented for the three examples to follow.

EXAMPLE 1, LARGE COMMERCIAL GREENHOUSE

As an example of commercial greenhouse supplemental lighting, a square greenhouse section of approximately one-half hectare (approximately one acre) was considered. The luminaire mounting height was assumed to be 3.05 m (10'), with the top of the plant canopy at 0.91 m (3') and each luminaire suspended with its opening 0.91 m (3') below the mounting height. Wall and ceiling reflectance of 0.1 and a floor reflectance of 0.2 were assumed. A luminaire maintenance factor of 0.9 (relatively clean) was assumed and all luminaires for each calculation were considered to be installed with the same orientation (no rotation of individual luminaires, and vertically). For illustrative purposes, supplemental PAR of 50 μmolm^{-2}s^{-1} was the design goal. The luminaire models listed in Table 3 were considered.

To provide an example conforming to what might be considered conventional practice, luminaire layout was in a rectangular grid. No attempt was made, initially, to search for a layout to maximize uniformity. The example will then be continued, choosing one of the luminaire types and exploring alternative layouts to improve uniformity.

Although it was not practical to achieve exactly 50 μmolm^{-2}s^{-1} using each luminaire model in grid patterns that would be reasonable (relatively regular), all designs provided an average within 4% of the design goal. The grid of calculated values provided 400 data values (20x20) within the lighted space and the grid for calculations was not a multiple of the luminaire installation grid, which could have led to erroneous estimates of the average by including repetitive sequences of intensity values. It should be noted that edge effects were limited in the uniformity analyses by omitting PAR values along the outer 0.6 m (2') perimeter of the hypothetical greenhouse section.

A summary of calculated PAR values is in Table 4. Several features of the data should be highlighted. First, not all installations require the same number of luminaires. Installing model H requires only 676 luminaires; installing model D requires 840. The added expense of installing 164 luminaires, alone, could be reason to reject some of the models. With essentially the same PAR level provided by each of the eight designs, installed kW relate proportionally to electricity used, showing a difference of 30% from the lowest to the highest in expected energy use and operating cost. Individual luminaire efficacy is, by itself, shown not to be the sole consideration in electricity use.

TABLE 4 Design results from Example 1, a 0.5 ha commercial greenhouse

	Luminaire							
	A	B	C	D	E	F	G	H
Number Required*	784	676	728	840	728	728	728	676
Watts/Luminaire	426	435	461	414	424	476	398	396
Installed kW	334	294	336	348	309	347	290	268
Ave. μmolm^{-2}s^{-1}	49.8	51.4	49.8	49.1	50.2	51.3	49.2	48.4
Std. Deviation	6.15	11.4	10.0	4.45	7.11	18.4	6.59	7.31
Minimum/Maximum	0.59	0.42	0.47	0.68	0.57	0.15	0.58	0.48
Minimum/ Average	0.74	0.66	0.70	0.86	0.78	0.25	0.77	0.68
UC1	0.90	0.82	0.83	0.93	0.88	0.69	0.89	0.87
UC2	0.88	0.78	0.80	0.91	0.86	0.64	0.87	0.85
Fraction within ±10%	0.59	0.38	0.34	0.78	0.47	0.07	0.58	0.48
Fraction within ±15%	0.73	0.49	0.45	0.91	0.69	0.15	0.67	0.71

Frequency graphs of the eight cases are grouped in Fig. 2. As an example of a uniformity criterion, the ±10% (horizontal) lines are included. Although corresponding contour graphs are not included because of the space they would require, it should be noted that PAR values outside the ±10% boundaries occurred in small regions and in patterns with the recurrence intervals of the luminaires.

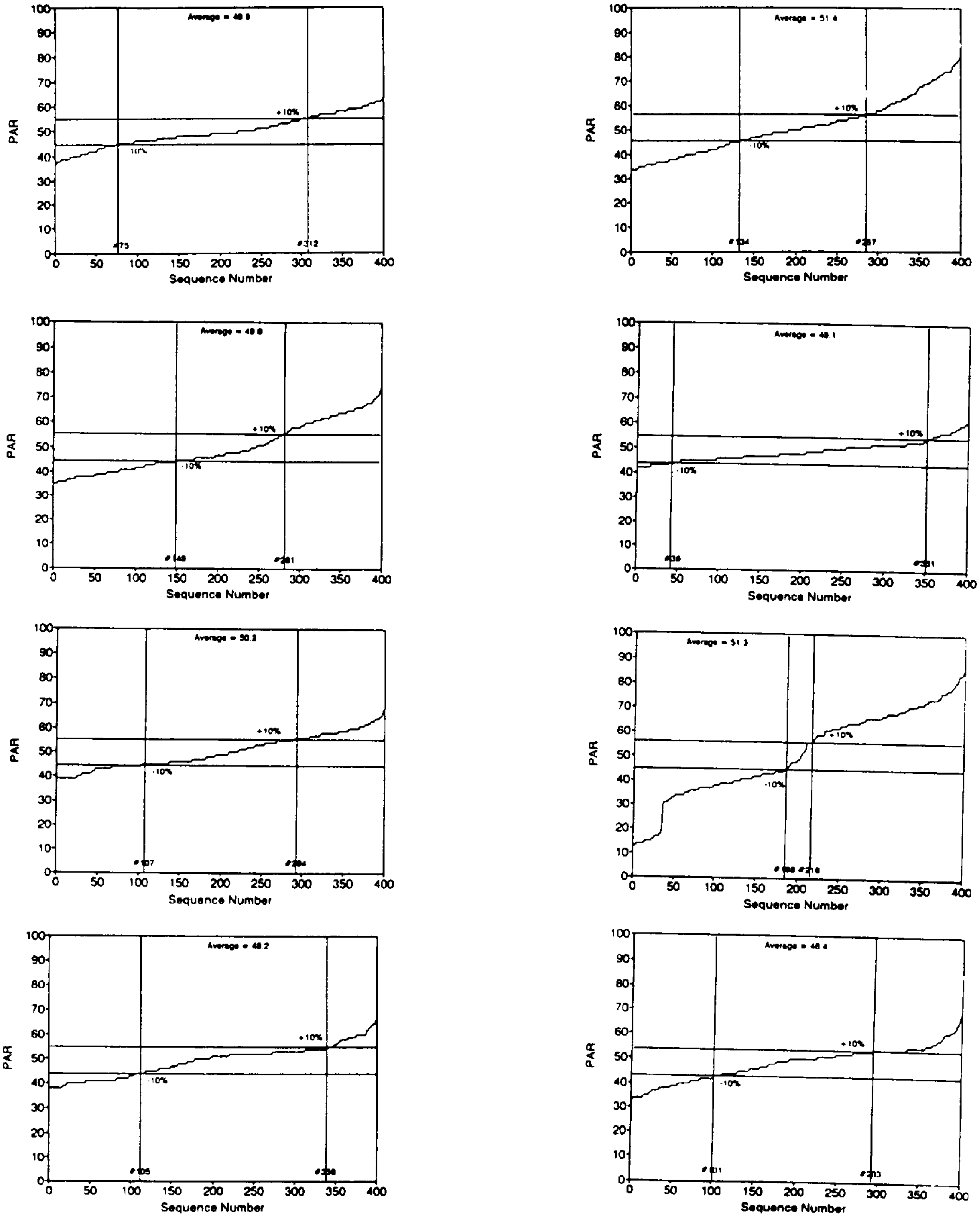


Fig. 2. Frequency graphs for Example 1, corresponding to the luminaires listed in Table 4.

To continue the example, one of the luminaires was selected for further design analysis. From Table 3, a choice for discussion purposes is luminaire B, for only 676 units were required, the PAR was slightly above the design goal, and its uniformity values were not high. The goal is to improve uniformity. A first change in design is to re-arrange the luminaires from a rectangular to a checkerboard pattern. The PAR pattern from luminaire B is not symmetrical, thus another option is to rotate the luminaires in every other row by 180 degrees, while keeping them in a checkerboard pattern. These two modifications were entered into Lumen-Micro; the results are in Table 5. First, the change to a checkerboard pattern reduced the average supplemental PAR from 51.4 to 50.7 μmolm^{-2}s^{-1}, with a concomitant reduction in the number of luminaires from 676 to 652. Further, using a checkerboard pattern increased uniformity, but not to a level of high uniformity. If the goal is to have most (e.g., 85%) of PAR values within ±15% of the average, none of the design changes are satisfactory. The solution would be to use another of the luminaires, probably with a layout to yield a pattern with a higher uniformity (in this example, perhaps H) so as to use a minimal number of luminaires (that is, luminaire D already provides a high degree of uniformity when measured as ±15% of the average, but 840 luminaires are required).

TABLE 5 Design results from Example 1, large commercial greenhouse.

	From Table 4	Checkerboard Pattern	Checkerboard 180 Deg Spin
Ave, μmolm^{-2}s^{-1}	51.4	50.7	50.7
Std. Deviation	11.4	9.28	9.23
Minimum/Maximum	0.42	0.48	0.48
Minimum/ Average	0.66	0.71	0.71
UC1	0.82	0.88	0.88
UC2	0.78	0.82	0.82
Fraction within ±10%	0.38	0.49	0.44
Fraction within ±15%	0.49	0.64	0.64

It should be noted that Example 1 has posed a difficult design problem if uniformity is the goal. The relatively low light level leads to relatively wide luminaire spacing and a resulting PAR nonuniformity. Greater PAR values will be explored in Example 2.

EXAMPLE 2, SMALL RESEARCH GREENHOUSE

For illustrative purposes, a small greenhouse section is considered to represent research greenhouses. The section is assumed to be square and 12.2 m (40') on each side. The same mounting height, plant canopy height, reflectance, maintenance factor and suspended distance as in Example 1 are assumed. Surface reflectances are more important in this, a smaller greenhouse, thus careful thought should be expended to estimate them. Finally, edge effects are likely to be a major concern in small greenhouses; it is assumed the outer meter of floor perimeter will not be used for plant growth except, perhaps, for guard plants.

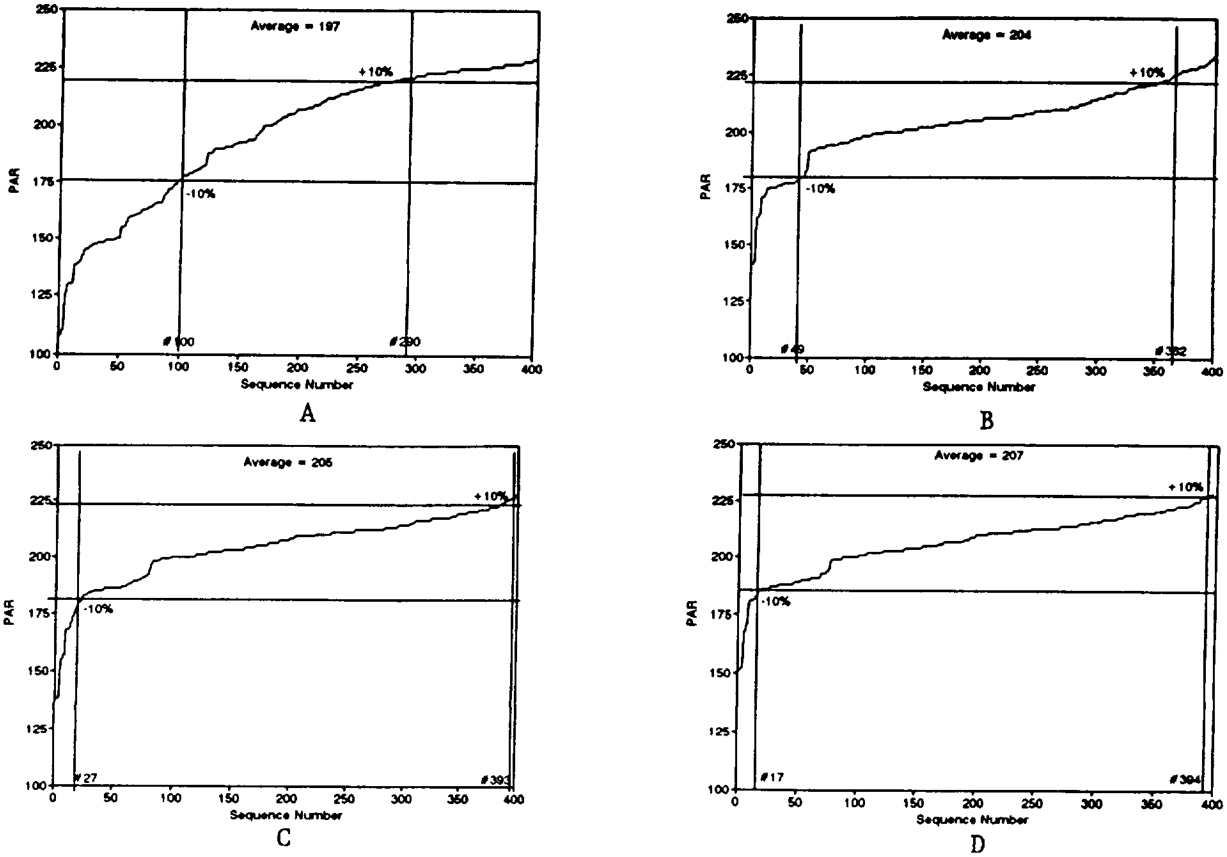
Only one of the luminaire types will be considered in the following simulations. The same concerns of non-uniformity and number required as in Example 1 should be of concern, of course. Luminaire G is used in this example because its light pattern is reasonably square and there appears not to be a "hot" spot directly under the luminaire.

As a base case, a uniform, rectangular grid was assumed, with 100 luminaires (10x10 grid) starting 0.91 m from each boundary and spaced at 1.15 m (3.78'). Such close spacing is required to achieve a design goal of 200 μmolm^{-2}s^{-1}. These assumptions result in an average PAR level of 197 μmolm^{-2}s^{-1}, considered to be within the error level of the assumptions. Other uniformity data are in Table 6.

TABLE 6. Design results from Example 2, small research greenhouse.

	Base Case	Change 1	Change 2	Change 3
Ave, μmolm^{-2}s^{-1}	197	204	204	207
Std. Deviation	29.4	15.7	14.9	13.3
Minimum/Maximum	0.47	0.60	0.60	0.66
Minimum/Average	0.55	0.69	0.67	0.73
UC1	0.87	0.94	0.95	0.95
UC2	0.85	0.92	0.93	0.94
Fraction within ±10%	0.48	0.78	0.92	0.94
Fraction within ±15%	0.81	0.97	0.96	0.98

Analysis of the base case resulted in the graph in Fig. 3a. As can be seen, there is not a great deal of uniformity over the growing area, although the data showed a high degree of uniformity (but levels near 220 μmolm^{-2}s^{-1}) over the center section of the greenhouse. PAR around the perimeter, however, was nonuniform. The number of luminaires was relatively adequate, the arrangement was not.



ig. 3. Frequency graphs, Example 2: (a) base case, (b) change 1, (c) change 2, (d) change 3

As a next step, more luminaires were placed around the perimeter, with fewer in the center section. The central area (starting 1.83 m from each boundary) was filled with a rectangular pattern of 64 (slightly more widely spaced) luminaires (8x8 grid). Twelve luminaires were placed along each boundary of the perimeter, starting 0.91 m from each wall, for a total of 44 units at the perimeter and a total of 108 within the greenhouse (8 more than the base case). Results are tabulated in Table 6 as Change 1 and the uniformity is summarized in Figure 3b. There is an obvious improvement over the base case, but nearly a quarter of the grid points remain outside the ±10% region.

Examination of Change 1 showed regions near two opposing boundaries with numerous PAR values above the +10% limit and two regions near the other opposing boundaries with numerous PAR values below the -10% limit. One luminaire was removed from each of the two opposing boundaries that were above the +10% limit and the remaining luminaires in those two boundaries re-spaced evenly. One luminaire was added similarly to the other two opposing boundaries. The modified design, tabulated as Change 2, yielded data as shown in Table 6 and Fig. 3c. The change improved the uniformity significantly, leaving only 5 or 6 grid points at each corner below the -10% limit. A smattering of grid points scattered along the boundaries fell very slightly below the -10% limits. No grid points fell above the +10% limit and 92% were within ±10%.

A final modification was to add one more luminaire to the two (opposing) boundaries that had yielded the scattered values falling slightly below the -10% limit, bringing the total number of luminaires to 110. The results, tabulated as Change 3, are summarized in Table 6 and Fig. 3d. The simulation predicted four grid points at each corner of the space would still fall below the -10% limit, but all other grid points would fall within the ±10% band. Corners of square regions are very difficult to light and are suggested to be considered additional "edge effect" regions, along with the outside boundaries. Corners constitute a small part of the total growing space (less than 10%) and, although adding and carefully aiming another luminaire at each corner could bring the four regions closer to the uniformity limits, it is questionable whether to do so would be useful because of the rather different microclimates (also affecting plant growth) that exist at corners.

It should also be noted that changing the surrounding surface reflectances brought the boundary grid points to within the -10% limit without adding more luminaires than were used in the base case. However, the higher reflectance caused the second and third grid points (away from the boundaries) to rise above the +10% limits, not helping uniformity. Further, it is not clear that greenhouse surfaces will have reflectances much greater than 0.1.

EXAMPLE 3, PLANT GROWTH CHAMBER

Surface (wall, etc.) reflectance becomes an increasingly important parameter as the size of a lighted space (room) grows smaller. This factor is accentuated when one considers lighting plant growth chambers. However, reflectance may be considered as an opportunity, not necessarily a problem. Careful design can use walls as additional reflectors to yield greater uniformity near the walls than might otherwise exist. The effect will be explored below.

For discussion, a walk-in chamber with a 2.44 x 3.66 m (8'x12') floor and 2.44 m (8') high side walls was assumed. Surface reflectances of 0.6 and 0.2 were assumed for the walls and ceiling, and floor, respectively. HPS luminaires were considered to evaluate their suitability for growth chamber lighting, and to achieve the desired high PAR levels. The lighted plane was assumed to be 0.76 m (2.5') above the floor, with the luminaires flush with the ceiling. The same lamp maintenance factor, 0.9, was assumed. This factor is particularly important when designing for growth chambers where a shield is often placed between the luminaires and the growing area. The value of 0.9 assumes a clear and clean shield, with the luminaires in "like new" condition. Two PAR values were considered, 200 and 300 $\mu molm^{-2}s^{-1}$.

Luminaire C was chosen, more for the shape of its light pattern than for its light pattern uniformity. That is, the space to be lighted was rectangular; the light pattern from luminaire C is relatively rectangular.

As a base case, 12 luminaires were considered, aligned along the four walls of the chamber, 0.3 m (1') from the walls. Five luminaires were assumed along each long wall, spaced evenly, with one additional luminaire placed in the center of each of the short walls, for a total of 12 luminaires. Each luminaire was assumed to be aimed vertically. For this base case, the average PAR at the work height was calculated to be 214 $\mu molm^{-2}s^{-1}$. Other data are in Table 7 and the resulting uniformity graph is in Fig. 4a. For a beginning, uniformity was reasonable with 90% of the grid points within the ±10% limits.

TABLE 7. Design results from Example 3, plant growth chamber

	Base Case	Change 1	Change 2	Change 3
Ave, $\mu molm^{-2}s^{-1}$	214	201	296	302
Std. Deviation	14.8	10.8	15.8	8.9
Minimum/Maximum	0.73	0.75	0.76	0.86
Minimum/Average	0.79	0.80	0.80	0.89
UC1	0.94	0.96	0.96	0.98
UC2	0.93	0.95	0.95	0.97
fraction within ±10%	0.90	0.94	0.94	0.98

Nonuniformity in the base case arose, expectedly, from values along the four walls. Reflections from walls were enhanced to improve uniformity in a modification of the hypothetical design, termed Change 1. Each luminaire along the two long walls was tilted by 15 degrees toward the wall. Luminaires along the short walls were also tilted by 15 degrees toward their walls. The calculated results, Change 1, are tabulated in Table 7 and the uniformity graph is shown in Fig. 4b. Some improvement is evident. The average PAR was reduced to 201 $\mu molm^{-2}s^{-1}$ (the walls absorbed more of the PAR), which improved the design. But more important was the uniformity increase; 94% of the grid points fell within the ±10% limits and those that exceeded the limits were at the four corners of the chamber. Most values along the perimeter fell within the limits, limiting "edge effect" problems. If all perimeter grid points are discounted, the uniformity increased significantly with most points within 3% of the mean of the smaller region. This result provided encouragement that, with careful luminaire placement and aiming, very good uniformity can be achieved using HPS luminaires in plant growth chambers.

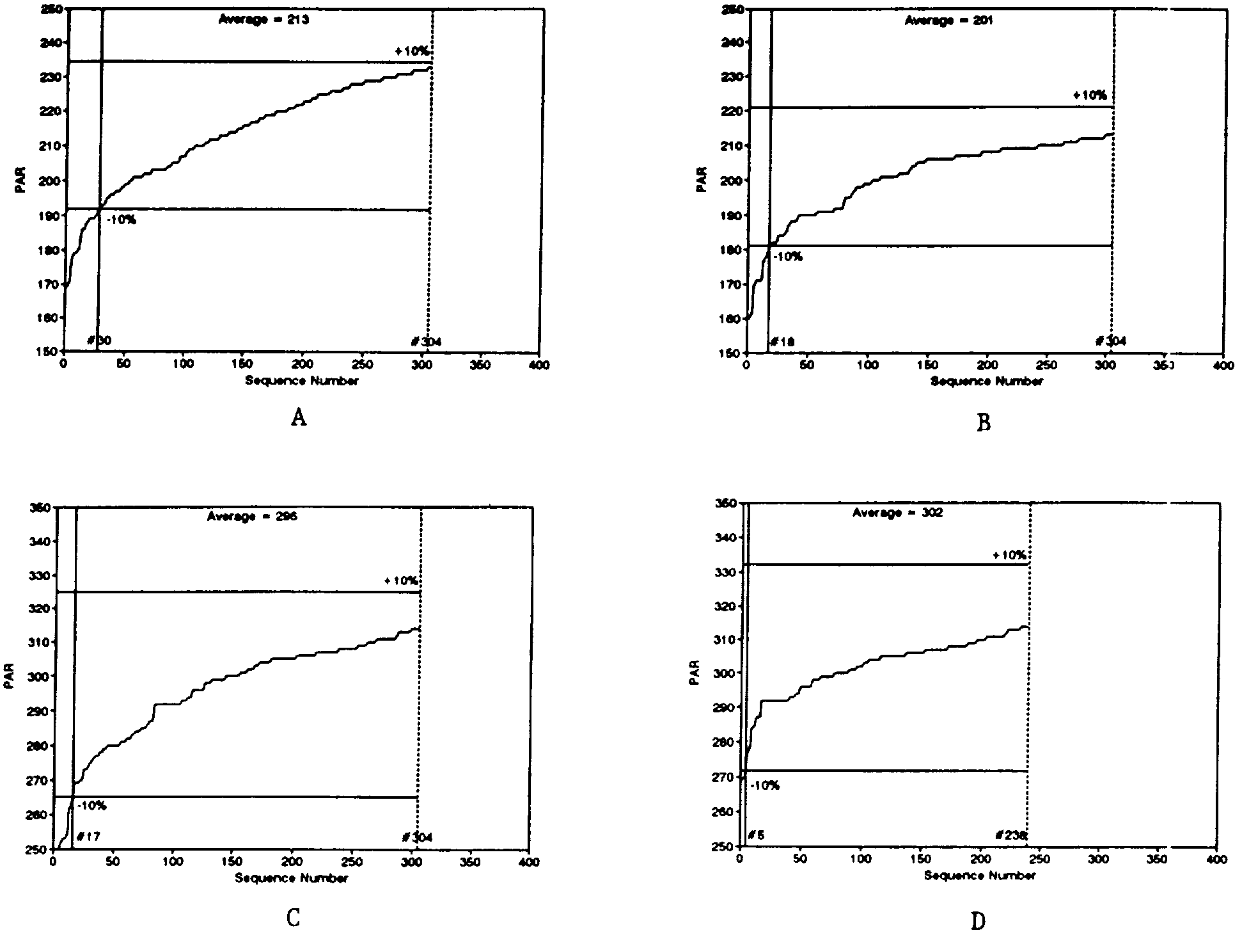


Fig. 4. Frequency graphs, Example 3: (a) base case, (b) change 1, (c) change 2, (d) change 3

But, to reach a daily total of 26 molm^{-2} of PAR within the chamber (with 24 hour lighting), 300 μmolm^{-2}s^{-1} are required. The next change was to add luminaires to reach this PAR level. Two more luminaires were added along each long wall (7 total along these walls) and one more was added along each short wall, for a total of 18 luminaires in the chamber. It should be noted this type of design is essentially what is termed "perimeter" design and is the only way to achieve uniformity. Several trials of tilt angles of the luminaires showed the best uniformity was achieved when tilt angles were increased from 15 to 17.5 degrees. The result of this calculation is in Table 7 as Change 3, with the uniformity graph shown in Fig. 4c. Uniformity increased slightly compared to Change 2, primarily because of the different tilt angle. The results demonstrated the possibility of achieving good uniformity at high PAR levels in small spaces.

Finally, grid data for Change 3 showed the greatest variation of values still clustered along the perimeter. Perimeters of growth chambers have traditionally not been used for plant growth because of edge effects. As a final design consideration, the outer grid points were discounted and only the region at least 0.3 m (1') from any wall was considered. The result, Change 4, is summarized in Table 7 and Fig. 4d. Uniformity for this case was within ±5% for 90% of the grid points, and only a few points at the corners were outside the ±10% boundary.

SUMMARY AND CONCLUSIONS

After reviewing basic information, three design examples have been presented to demonstrate a process of supplemental lighting design. The sequences of each example suggest careful thought and analysis are required to obtain supplemental lighting designs that provide both high levels of PAR and suitable uniformity. The end results of the three examples that have been presented here are not intended to suggest ultimate design paradigms. Rather, they should suggest how an analysis can evolve to achieve desired results, and the types of tools and adjustments required.

It appears possible to design research greenhouses and plant growth chambers to achieve a ±10% PAR uniformity using HPS luminaires. Further, HPS luminaires (and, by extension, MHD, etc.) are required to achieve high PAR levels and have the decided advantage of providing the possibility of aiming, which reduces the region of the "edge effect". This is a feature not readily possible using fluorescent lamps. However, tight control of uniformity appears unlikely without access to carefully obtained data from commercial luminaires and access to a computer-based design procedure. Further, for designing plant lighting systems, a modification of the standard IES luminaire data file structure is potentially useful. Instead of luminaire data presented in candelas, a standardized data structure is suggested to give designers access to luminaire data files (as from manufacturers or independent laboratories) with zonal data in $\mu mols^{-1}$, leading to results in $\mu molm^{-2}s^{-1}$.

Luminaire installation is an important factor to obtain PAR uniformity. Spacing and mounting height are critically important, for luminaires are spaced closely to obtain high PAR values and horizontal or vertical displacements by only a few inches can result in overlapping PAR patterns that go significantly outside the desired limits of uniformity. Additionally, the mounting angle of each luminaire must be carefully adjusted (and adjustable later, perhaps?) to conform with design assumptions. A tilt error of only a few degrees can lead to overlapping PAR patterns that disrupt uniformity. This is true for both plant growth chambers and greenhouses.

Surface reflectances are particularly important when designing for small lighted regions such as plant growth chambers and research greenhouses. It is not obvious, just from looking at a surface, what its reflectance is. It is suggested that an effort be mounted to develop valid surface reflectance data to be used by designers. It would be useful to develop and publish a data base of effective (diffuse) reflectance values for the types and conditions of materials and configurations common to greenhouses and plant growth chambers. Further, the importance of the surfaces (particularly the walls) in achieving PAR uniformity suggests the importance of periodic cleaning/maintenance to retain initial reflectance values.

DEFINITIONS

Albedo: Fraction of incident light reflected (diffusely) from a surface.

Diffuse Reflection: Light is scattered in every direction from the reflecting surface.

Efficacy: Light output of a luminaire in relation to power input, expressed as lumens/watt or similar units.

Efficiency: The proportion of input power that is transformed into useful light, expressed as a percentage.

Irradiance: Radiant energy flux expressed in W/m^2, or similar units. Spectral irradiance is irradiance integrated over a bandwidth.

Lighting Power Density: Power used for lighting over an area, expressed in $watts/m^2$, or similar units.

Luminaire Efficiency: Ratio of light energy emitted from a luminaire to the lamp total light energy output.

PAR: Photosynthetically Active Radiation, 400-700 nm.

Specular Reflection: Light is reflected in one direction, at an angle equal to the angle of incidence.

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