PROCEEDINGS
INTERNATIONAL LIGHTING IN CONTROLLED ENVIRONMENTS WORKSHOP

University of Wisconsin - Madison
Madison, Wisconsin

March 27-30, 1994

Organized by
USDA NCR-101 Controlled Environments Technology Use Committee

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NASA Ames Research Center, Moffett Field, CA 94035-1000

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Funding Support

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PREFACE

Lighting is a central and critical aspect of control in environmental research for plant research and is gaining recognition as a significant factor to control carefully for animal and human research. Thus this workshop was convened to reevaluate the technology that is available today and to work toward developing guidelines for the most effective use of lighting in controlled environments with emphasis on lighting for plants but also to initiate interest in the development of improved guidelines for human and animal research.

For plant research, the ultimate requirement has been to provide lighting that mimics sunlight both in intensity and in spectral balance. In the early part of this century, tungsten lamps were tried, then in the 1950's fluorescent lamps, followed by xenon lamps, and more recently high intensity discharge lamps. However research with all of these lamp systems has been plagued with problems with unbalanced spectrum and/or excessive amounts of infra-red energy. As a result most research has been undertaken with light levels that have not simulated sunlight either in intensity or spectrum. With the ongoing concern over global climate change, a renewed interest in duplicating sunlight has surfaced for there is a general recognition that simulation of sunlight is needed for controlled environment research in order to quantify the impact of climate changes on our natural environment. Also NASA is promoting the use of plants in bioregenerative life support systems for long term space bases and needs to optimize the use of lamp lighting for efficient production in these systems.

There are no generally accepted guidelines for plant scientists for lighting intensity or for the required light spectrum for growth of plants. This is partly because requirements differ for different species of plants but principally this has resulted because of the lack of definitive data on plant response to light and also varying opinions by different scientists on what is needed by plants. Yet guidelines are needed. These guidelines are needed to provide direction for manufacturers in the construction of controlled environment facilities and to provide information for cost-effective requests by scientists planning new acquisitions and upgrading existing facilities.

There are a number of established guidelines for lighting in human and animal environments. Development of new lighting guidelines is necessary for three reasons: 1) recent scientific discoveries show that in addition to supporting the sensation of vision, light has profound non-visual biological and behavioral effects in both animals and humans, 2) federal regulations (EPACT 1992) are requiring all indoor environments to become more energy efficient with a specific emphasis on energy conservation in lighting, 3) lighting engineers and manufacturers have developed a wealth of new light sources and lighting products that can be applied in animal and human environments.

The workshop was aimed at bringing together plant scientists and physical scientists to interact in the discussions. It involved participation of biological scientists involved in studying mechanisms of light reactions and those involved in utilizing lighting for production of plants and maintenance of animals in controlled environments. It included participation of physical scientists from universities and government involved in research as well as those from industry involved in producing lamps and in construction of controlled growth facilities.

The specific objectives addressed at the workshop were:

i) in-depth examination of the spectral and intensity requirements for the primary responses in plants that are controlled by light and exploration of the requirements for animals and humans.

ii) discussion of the new technologies in lamps that could have usefulness for controlled environment lighting.

iii) review of the available and new technologies for distribution of light and control of excess infra-red radiation.

iv) discussion of guidelines for lighting of plants in controlled environments and lighting for animals and humans.

Specialists from universities, government, and industry were invited to make formal presentations and help lead workshop discussions. The meeting was open to the scientific community and 152 individuals were registered for the workshop. All attendees were encouraged to participate in the discussions.

These formal presentations are published in the proceedings along with contributions as Short Reports that were prepared by some participants following the workshop.

Draft guidelines, as developed by the organizing committee are included as a final chapter in the Proceedings.

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PLANT REQUIREMENTS

PHOTOSYNTHESIS

GENERAL LIGHTING REQUIREMENTS FOR PHOTOSYNTHESIS

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PROPERTIES OF LIGHT THAT ARE IMPORTANT FOR PHOTOSYNTHESIS

A review of the general lighting requirements for photosynthesis reveals that four aspects of light are important: **irradiance, quality, timing** and **duration**. These properties of light affect photosynthesis by providing the energy that drives carbon assimilation as well as by exerting control over physiology, structure and morphology of plants. **Irradiance**, expressed as energy flux, W m^{-2}, or photon irradiance, μmol m^{-2} s^{-1}, determines the rate at which energy is being delivered to the photosynthetic reaction centers. Spectral **quality**, the wavelength composition of light, is important because photons differ in their probability of being absorbed by the light harvesting complex and hence their ability to drive carbon assimilation. Also the various light receptors for light-mediated regulation of plant form and physiology have characteristic absorption spectra and hence photons differ in their effectiveness for eliciting responses. **Duration** is important because both carbon assimilation and regulation are affected by the total energy or integrated irradiance delivered during a given period. Many processes associated with photosynthesis are time-dependent, increasing or decreasing with duration. **Timing** is important because the effectiveness of light in the regulation of plant processes varies with the phase of the diurnal cycle as determined by the plant's time-measuring mechanisms.

Physiologically Important Measures of Light

Photosynthetic photon flux or PPF (ex. μmol m^{-2} s^{-1}), a combination of **irradiance** and spectral **quality**, is a measure of the photosynthetically active photon irradiance (PAR or photosynthetically active radiation defined as the irradiance between the wavelengths of 400 and 700 nm). PPF is the maximum energy available and only a small proportion of the photons actually are used to assimilate carbon.

Time course of diurnal PPF and *integrated diurnal irradiance*, combinations of **irradiance** and **duration**, have important effects on photosynthetic carbon metabolism and its regulation. Of particular importance is the rapidity with which the light begins. *Maximum* irradiance level and the *duration of high irradiance* are important aspects of the time course of diurnal PPF, potentially affecting the degree of photoinhibition or photoprotection, both of which can lower the efficiency of light use for photosynthesis. It is important that these aspects of irradiance generally be similar to those under which the plant developed.

Daytime spectral quality and *end of day spectral quality* are a combination of **quality** and **timing**. Not only does light drive photosynthesis but irradiance that extends beyond the range of 400 to 700 nm affects plant morphology, physiology, leaf display and chloroplast orientation. Properties of light that affect growth and morphology of the plant, in turn, can affect photosynthesis. Photosynthesis generates a positive feedback system in which photoassimilation

contribute to further growth and so on. The compound interest aspect of the production and growth of leaves obviously is affected by plant properties such as leaf area and thickness, which are regulated by light.

Photoperiod, the **duration** and **timing** of the irradiance, has marked effects on plant physiology and morphology, including carbon allocation, root to shoot ratio and reproduction. A combination of **duration** and **irradiance** comprise the *integrated diurnal light energy* that determines both the total daily assimilation of carbon but also affects morphology and physiology of leaves.

The four properties of light, alone and in combination, are important to consider in the design and evaluation of performance of plant lighting systems. Responses to the various aspects of light are conditioned by *adaptation,* the genetically determined range of possible responses. For example, plants that are adapted to growing in the sun will have a certain maximum photosynthetic capacity which will be considerably higher than that of a shade plant. On the other hand, plants adapted to grow in shade will be able to survive at a lower photosynthesis rate. Within the range of the adaptive possibilities, plants undergo *acclimation* to actual conditions.

SPECTRAL QUALITY

Light Quality Affects Photochemical Reactions

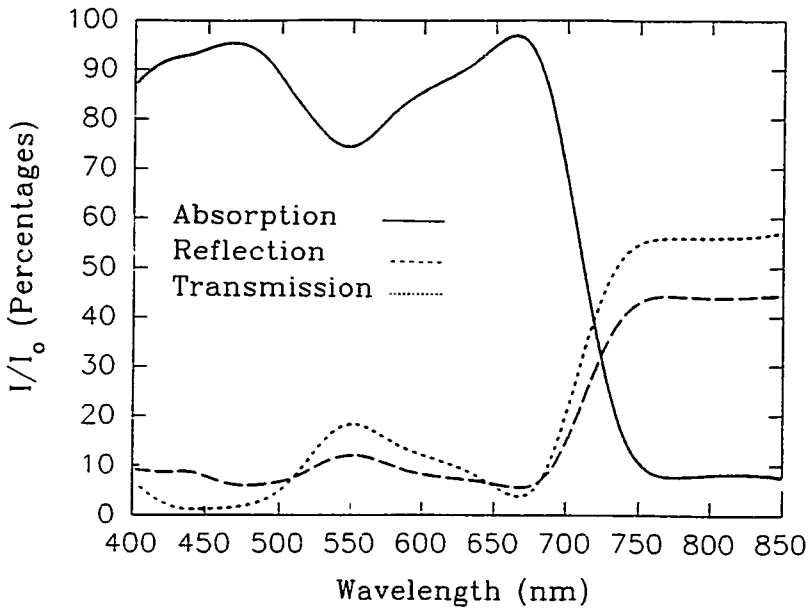


Fig. 1. Absorption, reflection and transmission of light by a typical soybean leaf. I/I_o refers to the radiation absorbed, transmitted or reflected relative to incident radiation at the same wavelength. From Kasperbauer, 1987.

The types, amounts and structural configuration of the photosynthetic pigments present in the photosystems, along with chloroplast orientation, determine the extent to which the various photons are absorbed (Figure 1). The two major absorption peaks are related to the presence of chlorophylls and carotenoids arranged in photosystem antenna complexes and reaction centers. The general correspondence between the absorption and action spectra indicate that the photons that are absorbed are used with generally similar efficiency. Plants adapted to higher light generally have the capacity to develop antenna complexes capable of absorbing these higher irradiances efficiently and, within the range of possibilities, the leaves will acclimate to a specific irradiance range by developing complexes with a certain capacity. Examination of the quantum yield of photons reveals that the photosynthetic efficiency of photons is generally similar between 400 and 680 nm, with a rapid fall off above the latter wavelength (Figure 2). Photosynthesis using light absorbed at wavelengths between the chlorophyll absorption peaks has a slightly lower efficiency.

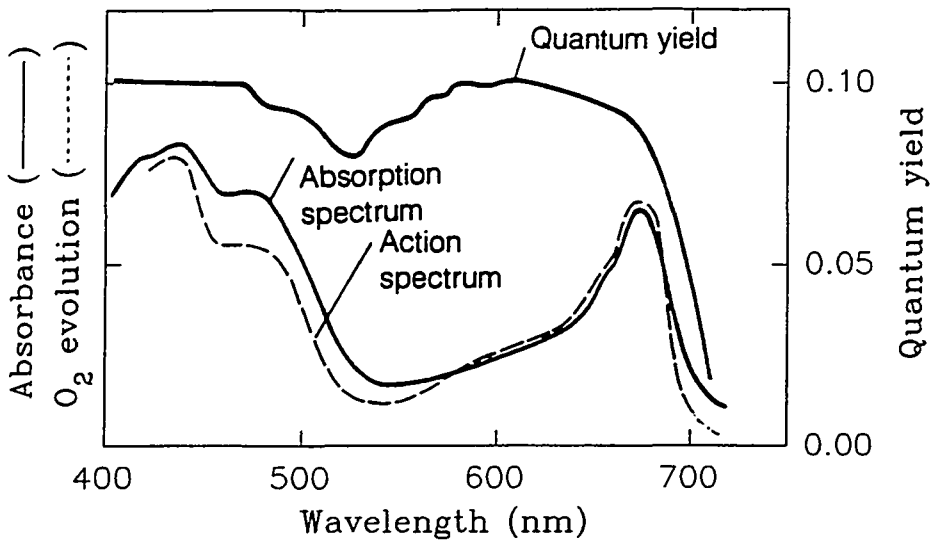


Fig. 2 Comparison of action spectrum and quantum yield for photosynthesis with the chloroplast absorption spectrum. Quantum yield of photosynthesis is the moles of carbon fixed per mole of photons absorbed. From Taiz and Zeiger, 1991.

The energy content of the region of PAR determines the availability of energy for driving photosynthesis while that in the band above 650 is particularly important in photomophogenic processes mediated by phytochromes. Quantum yield of photosynthesis under a given set of conditions depends on absorption of photons by pigments of the antenna complexes, use of the excitation energy transferred from the molecules of the antenna complex to drive photochemistry in the reaction centers, and use of this energy in carbon assimilation. It is important that there be a close match between the amount of light absorbed and the amount actually used to drive photosynthetic carbon assimilation. Environmental factors may result in dissipation of absorbed energy by various processes that result in a decrease in quantum yield (Krause and Weis, 1991; Demmig-Adams and Adams 1992; Ruban et al., 1993).

Light Quality Affects Plant Structure, Morphology and Physiology

Light quality affects morphology, biochemistry and physiology of plants through its action on phytochromes and other pigments associated with light-mediated regulation of processes (Lopez-Juez et al., 1990). Examples of physiological parameters that affect photosynthesis are shown in Table 1.

TABLE 1 Effect of Light Quality on Physiological Parameters for Leaves of Wild Type and Mutant Cucumber. Parameters shown for wild type and long hypocotyl mutant after 20 days in daily photoperiods of 14 h white fluorescent with (+FR) or without (-FR) 20 min of far red light at the end of the day. From Lopez-Juez et al., 1990.

Parameter (units)	Wild type		*lh* mutant	
	-FR	+FR	-FR	+FR
Chlorophyll content (mg g^{-1} fr wt)	2.16	2.07	1.63	1.69
Chlorophyll content (μg cm^{-2})	43.3	36.3	21.1	22.7
Chlorophyll *a/b* ratio	2.7	2.6	2.6	2.5
Total carotenoid (mg g^{-1} fr wt)	0.28	0.27	0.22	0.21
Soluble protein (mg g^{-1} fr wt)	9.3	7.6	7.4	7.2
Photosynthesis rate				
(mg CO_2 m^{-2} s^{-1})	0.29	0.18	0.06	0.08
(μg CO_2 mg Chl^{-1} s^{-1})	0.66	0.48	0.26	0.36

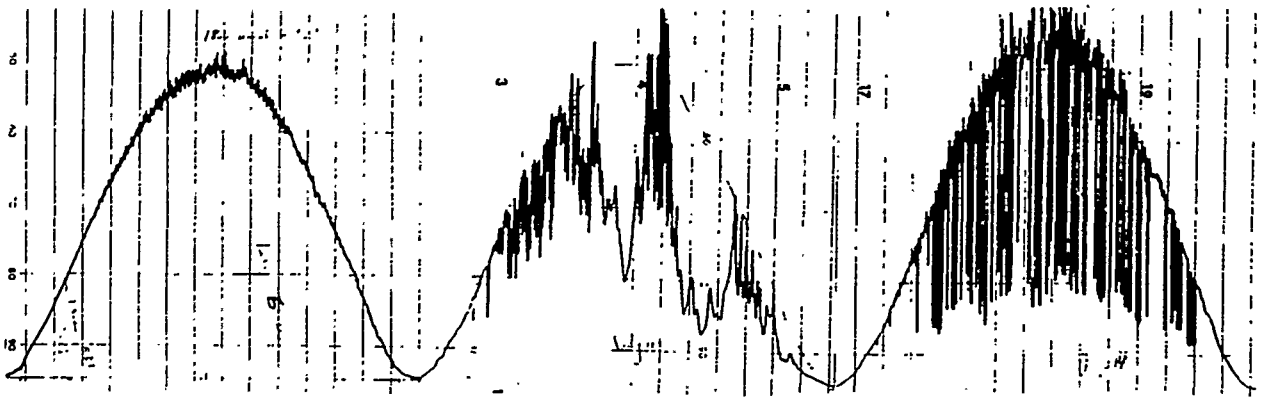
The far red light results in less chlorophyll per area and a lower photosynthesis rate per area, effects that can be explained by the fact that far red light given at the end of the day results in larger but thinner leaves. These leaves also seem to have a somewhat lower efficiency of photosynthesis per unit of chlorophyll. The fact that leaf morphology and physiology can be adjusted by a short period of light that has a specific spectral quality under come conditions may offer an efficient alternative to exposing plants to light with an energy-expensive spectral balance throughout a whole day.

DIURNAL TIME COURSE OF IRRADIANCE

In the Field Irradiance Changes Gradually Throughout the Day

Irradiance is a major factor influencing photosynthesis rate. The amount of sunlight striking a

unit area of the earth at any time in the course of a day is a direct function of the sine of the angle that the sun makes with the earth's surface. On a clear day, irradiance level on a horizontal surface generally follows the sine of the sun's angle with earth's surface (Figure 3). Even when there are clouds irradiance gradually increases and decreases over the course of a



A B C

Fig. 3. Time courses of irradiance during July. A. Clear day. B. Partly cloudy day. C. Partly sunny day.

day. The light available to leaves for photosynthesis depends both on the time course of diurnal irradiance and on factors, such as leaf orientation, that affect the interception of the incident light. Evolution of photosynthesizing organisms under cyclic diurnal irradiance has equipped plants to regulate the photosynthetic process in ways that allow carbon to be assimilated efficiently over the wide range of diurnal cycle irradiance. A particularly important aspect of this diurnal time course is the fact that irradiance begins slowly, generally matching the time constants of processes related to photosynthesis. For instance stomatal opening and induction of photosynthetic carbon assimilation by the Calvin cycle generally have time constants on the order of minutes. Induction of photosynthesis involves building the concentration of metabolite pools and enzyme activities associated with photosynthetic carbon assimilation. Beginning a photoperiod with rapid, practically instantaneous irradiance can lead to light and water stress (Geiger et al. 1994).

Because plants have become adapted to gradually changing daily irradiance, it is advantageous to study regulation of photosynthesis and carbon metabolism in the context of the diurnal light cycle. In particular, timing aspects of carbon assimilation regulation can be analyzed more effectively because the gradual changes in irradiance allow us to observe the step by step progress of the daily acclimation process. A number of researchers used this approach to elucidate mechanisms involved in the regulation of photosynthesis in nature (references in Geiger and Servaites, 1994a). Recently our laboratory has undertaken as series of studies of the regulation of photosynthesis (Geiger et al., 1991, Servaites et al, 1989a, 1989b, 1991) with the help of an apparatus that simulates the gradually changing irradiance of a natural diurnal light regime (Figure 4).

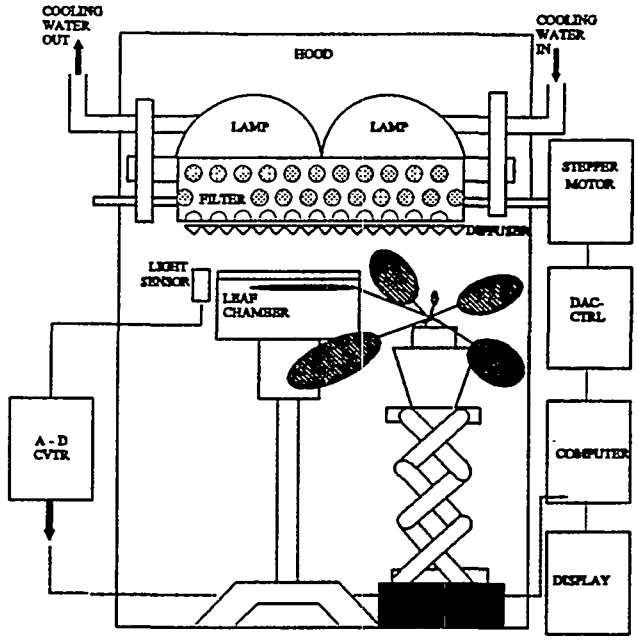


Fig. 4. Apparatus for regulating irradiance to simulate the irradiance under a natural light regime. The light level is sensed and converted to digital input (A-D CVTR) for processing by a computer. A signal is sent to a controller (ADC-CTR) which then directs the motor to transport the neutral-density film to produce the required irradiance. From Geiger et al., 1991.

Physiological Aspects of Gradually Changing Diurnal Irradiance

To keep pace with changing PPF, flux through the carbon assimilation cycle changes over a wide range during the course of a single day. Unless prevented by some overriding factor, diurnal regulation enables the photosynthesis rate to match closely the capture and use of solar energy by the light reactions. In leaves of C_3 plants, the Calvin-cycle acclimates to the constantly changing irradiance of the diurnal light cycle by a combination of light-mediated changes in the activation state of phosphoribulkinase (PRK), ribulosbisphosphate carboxylase oxygenase (Rubisco) and glyceraldehyde 3-phosphate dehydrogenase (Gal3PDH), coarse control, and self-regulating mechanisms involving the levels of ribulose bisphosphate (RuBP) and phosphoglyceric acid (PGA), metabolites associated with these enzymes, fine control. The activation states of the various light regulated enzymes of the Calvin cycle appear to change separately and at different rates in response to light (Figure 5; Geiger and Servaites, 1994a). In all cases the time constant leads to changes over a span of a number of minutes. To balance flux throughout the Calvin cycle under these conditions requires additional control based on emergent properties of the system of control metabolites interacting with a series of responsive enzymes (Figure 6; Geiger and Servaites, 1994b). The resulting self-regulation involves interaction of metabolites not only with a single enzyme but also with other enzymes in the

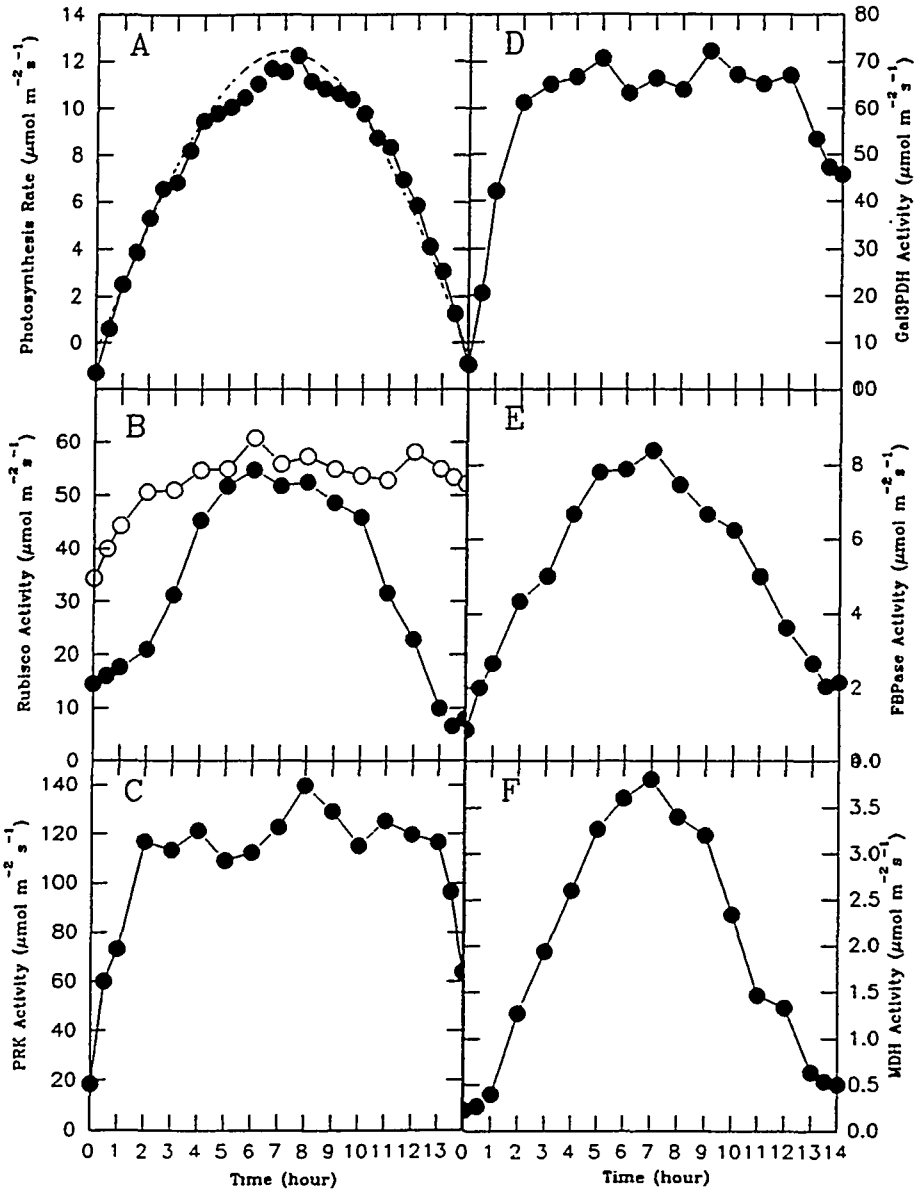


Fig. 5. Time courses of photon irradiance, net carbon exchange (NCE) rate, and enzyme activation state during a simulated natural day period. A. Photosynthesis rate (●), photon irradiance (---) maximal photon irradiance was 800 μmol m^{-2} s^{-1}, B. initial Rubisco activity (●) and total Rubisco activity (○). C.-F. activities of other Calvin cycle enzymes. From Servaites et al., 1991.

pathway. The increasing levels of complexity in regulation are needed so carbon assimilation can be matched closely with the rate of ATP and NADPH synthesis by the light reactions during the diurnal cycle. As a consequence, the light-activated Calvin cycle enzymes and their associated metabolites such as RuBP and PGA show a characteristic diurnal time course in response to the diurnal light regime, reflecting their role in regulation of the Calvin cycle (Geiger et al., 1991, Servaites et al, 1989a, 1989b, 1991).

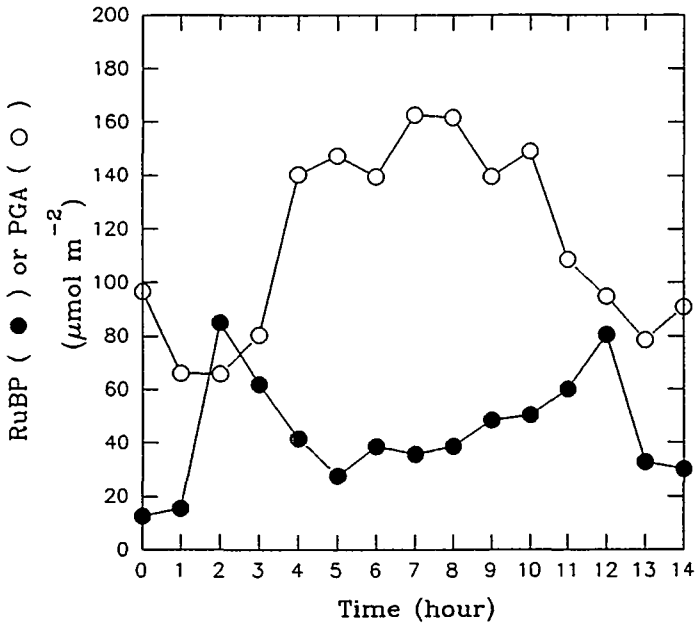


Fig. 6. Time courses of RuBP and PGA levels in a sugar beet leaf during a 14-h light regime that simulates a natural day. From Servaites et al., 1989a

Metabolic Flexibility

The result of these two forms of regulation is a condition that can be termed metabolic flexibility which enables the plant to achieve a particular metabolic state in a number of different ways. The concerted action of a number of parameters bring to bear various control processes that can achieve a stable condition, homeostasis, by a number of different combinations. Depending on the starting conditions, adjustment may be made by any one of a number of combinations of enzyme levels, enzyme activation states and metabolite levels. The response of photosynthesis to diurnal irradiance patterns provides an example of metabolic flexibility and of the various factors that need to be considered in programming a diurnal time course of PPF. In such situations the `memory' of how a stable state was reached affects future regulatory responses.

Consequences of Rapidly Initiated or Gradually Changing Irradiance

Depending upon initial conditions and the path taken to reach stability, different regulatory elements may assume different degrees of importance. This metabolic flexibility is a result of probabilistic behavior during regulation, in which the path taken to reach stability cannot be described by a unique mathematical solution. The general pattern of response will be conditioned by a number of factors, such as the immediate past history of the plant. This point is well illustrated by observing the response of carbon assimilation in leaves of a sugar beet plant to two different light regimes on successive days. Depending upon how fast illumination reached a maximum at the beginning of the day, different combinations of activation states and associated levels of metabolites were observed for the three enzymes of the assimilatory segment (Servaites et al., 1991; Geiger et al., 1991). Although the leaf maintained similar maximal midday photosynthesis rates under the different light regimes (Figure 7), considerable differences in the degree of Rubisco and PRK activation (Figure 8) and the levels of RuBP and PGA (Figure 9) were observed. Under the gradually increasing light of a diurnal light regime,

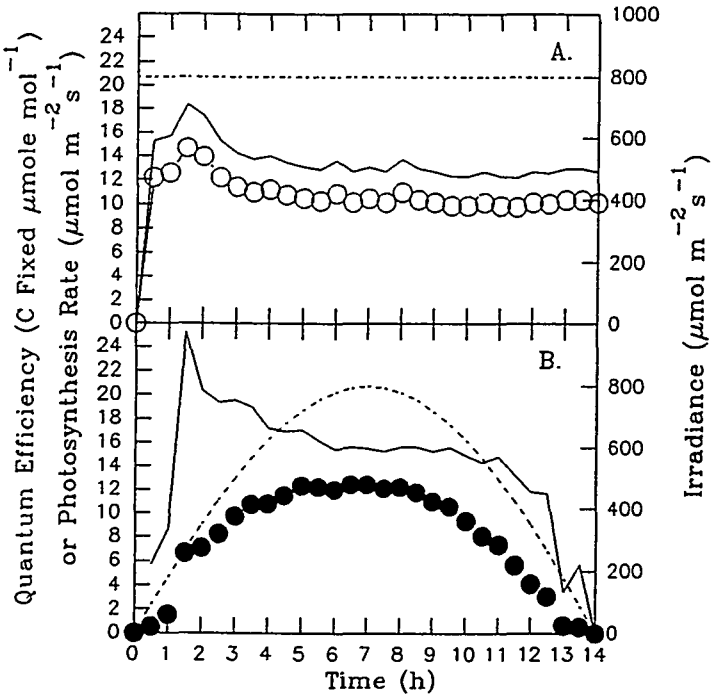


Fig. 7. Time course of photon irradiance, NCE rate and apparent quantum yield for sugar beet leaves. Data under (A.) rapidly initiated or (B.) gradually changing irradiance. NCE (○, ●), photon irradiance (- - - -) and apparent quantum efficiency (-------). Data from Geiger et al., 1991.

the midday level of Rubisco activation state was nearly 100% and the RuBP level was about twice Rubisco binding site level. By contrast, when light increased to a maximum rapidly, as often occurs under growth room conditions, the midday level of Rubisco activation state was maintained at only 60% throughout the day, while the RuBP level was nearly twice that observed in the same leaves under gradually increasing light. Regulation by light-mediated enzyme activation was favored under gradually increasing irradiance while metabolite-mediated mechanisms were relatively more important when irradiance increased rapidly. The different forms of regulation achieved similar photosynthesis rates through different combinations of activation states and metabolite levels, an expression of the metabolic flexibility of photosynthesis. As a consequence of the physiological state resulting from metabolic flexibility in regulatory responses, plants may respond differently to stress. The response of photosynthesis to application of glyphosate depends on whether the day began with rapidly initiated irradiance or under gradually changing irradiance (Figure 10). When irradiance was begun rapidly at the start of the day, RuBP level was high, Rubisco activation state was only about 70% (Figure 10 A-C). Under these conditions, inhibition of photosynthesis does not occur until about 4 h after glyphosate is applied, when RuBP level has fallen to a point where its level begins to be a significant factor determining photosynthesis rate (Servaites et al., 1987). In contrast, under gradually changing diurnal irradiance (Figure 10 D-F), Rubisco activation state is full, RuBP is lower and is a significant factor regulating photosynthesis rate. In this case photosynthesis rate begins to decrease along with RuBP leave almost immediately after glyphosate is applied (Figure D-F).

Shieh et al., 1991). The physiological state clearly affects the response of photosynthesis to the imposed stress of the inhibition of the shikimate pathway by glyphosate.

A recent study of carbon allocation throughout the day-night cycle revealed that allocation of carbon to the synthesis of sucrose is regulated by an endogenous signal that is adapted to the usual time course of diurnal irradiance (Geiger and Shieh 1994). When the photoperiod begins with rapid onset of high light carbon allocation is changed markedly. Under these conditions, sucrose is synthesized from newly fixed carbon by two biochemical pathways and no starch is produced for several hours. Similarly, if irradiance remains high at the end of the day starch synthesis stops and sucrose synthesis and export nearly double. Clearly, carbon metabolism is changed by departure from the usual daily time course of irradiance. As a result of metabolic flexibility the plant acclimates to the step time course of irradiance often used in growth under artificial light but the metabolic state of the plants are changed.

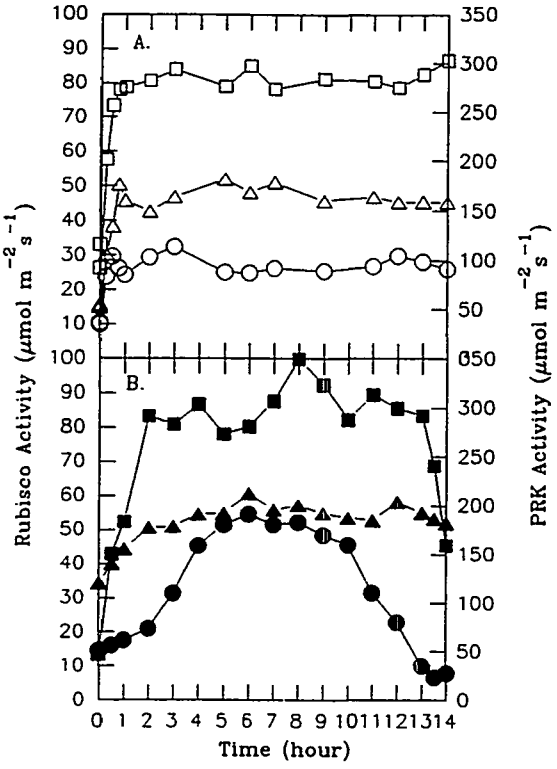


Fig. 8. (left) Rubisco and PRK activities in sugar beet leaves. Data for plants under (A.) rapidly initiated or (B.) gradually changing irradiance. (○,●) PRK activity; total (△,▲) or initial (■,□) Rubisco activity.

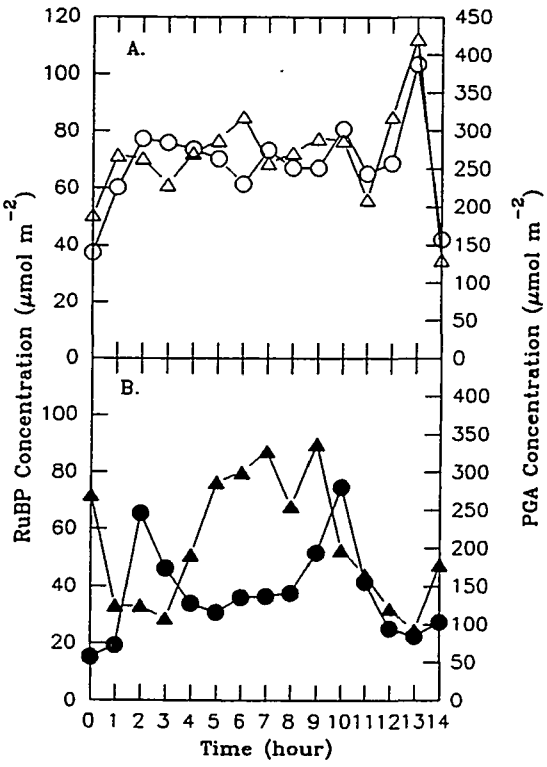


Fig. 9. (right) Levels of RuBP and PGA in sugar beet leaves from plants shown in Figure 8. (△,▲) PGA levels, (■,□) RuBP levels. From Geiger et al., 1991.

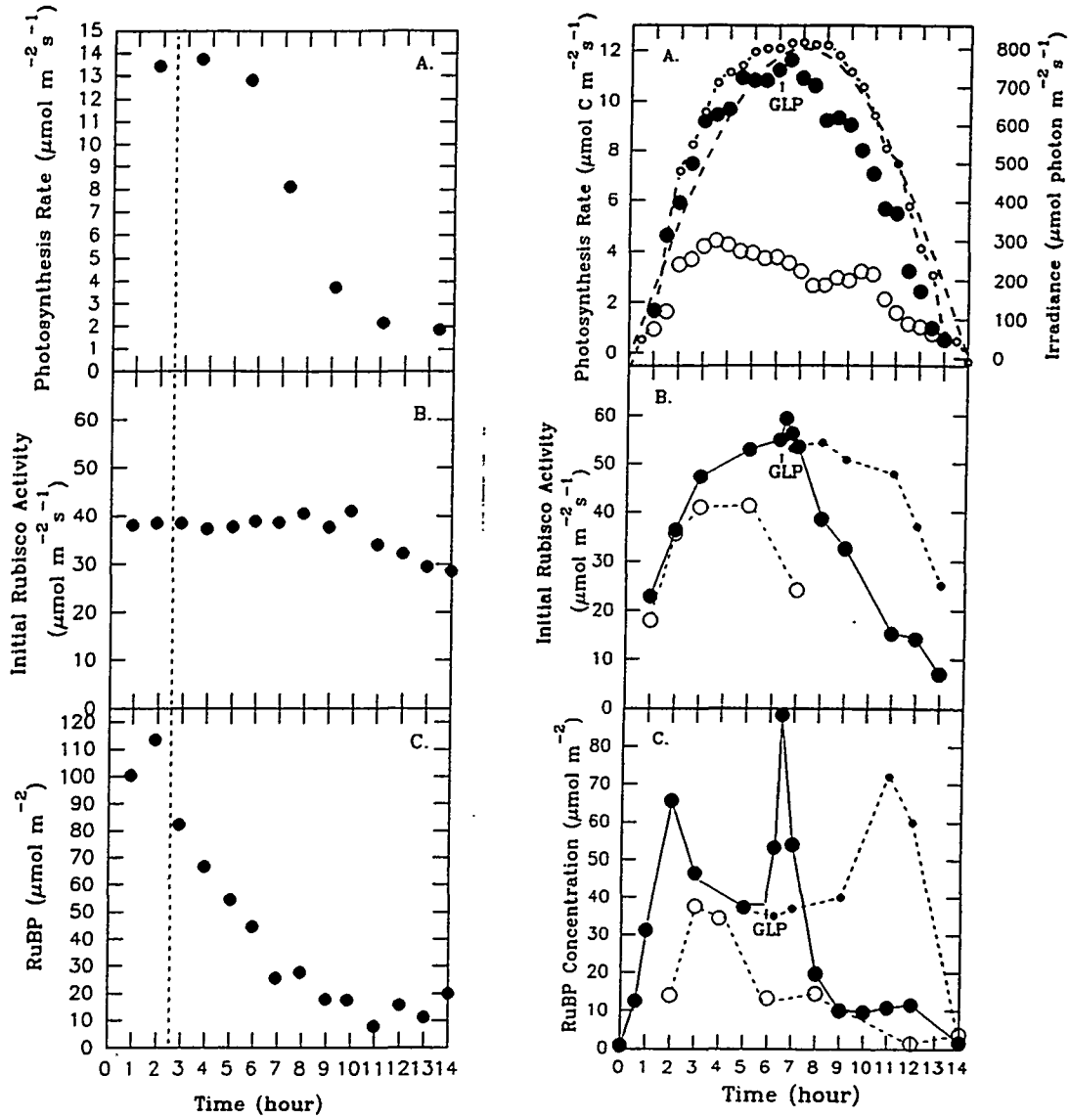


Fig. 10 Time courses of NCE, initial Rubisco activity and RuBP following application of glyphosate to leaves under contrasting light regimes. Data for day of application (•), for second day (o), and for control plants (- - • - -). Vertical dashed line and GLP mark the time of application of glyphosate. A.-C.: Leaf under rapidly initiated irradiance. From Servaites et al., 1987. D.-F.: Leaf under gradually changing irradiance. From Shieh et al., 1991.

RESPONSE TO DIURNAL IRRADIANCE LEVEL

Irradiance Level Affects Photosynthetic Quantum Yield

A measure of successful diurnal regulation of photosynthesis is the ability of the plant to lessen the impact of environmental stresses and so use what light is available efficiently. The result is a general correspondence between carbon flux through the assimilatory segment of the cycle and the course of diurnal irradiance. Recently we conducted a series of studies that dealt with diurnal acclimation of photosynthesis, both in the field and in the laboratory under a light regime that simulated a clear day (Servaites et al., 1989a, 1989b, 1991). Photosynthetic performance was assessed by the apparent quantum yield (Φ_i), that is, the moles of carbon fixed per mole of incident photons based upon NCE rate and PPF.

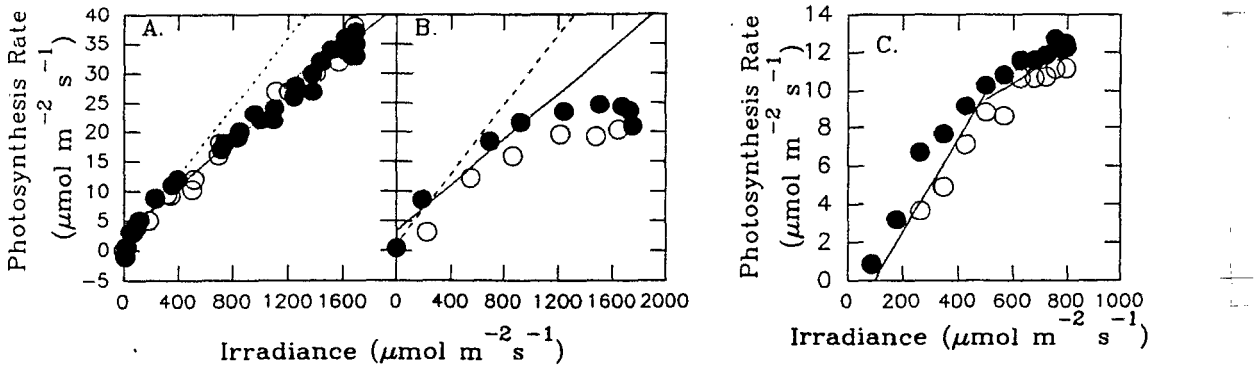


Fig. 11. NCE rate of sugar beet leaves as a function of PPF. A. and B. field-grown plants, on a clear summer day. C. Laboratory-grown plant in moderate light. Data for plants under increasing (●) or decreasing (○) photon irradiance. From Servaites and Geiger, 1994.

Experiments with field-grown sugar beet plants that were acclimated to growing outdoors showed differences in the maximum diurnal NCE rate attained under the high PPF of summer sunlight (Servaites and Geiger, 1994). In some circumstances, NCE rate increased in nearly direct proportion to PPF throughout the day while in other cases the rates stopped increasing or even decreased with increasing PPF near midday, resulting in a second decrease in Φ_i. In general, Φ_i decreased to a new level when irradiance reached about a quarter that of full sunlight (Figures 7, 11), both under moderate light in the laboratory (Figure 11C) and in the field (Figures. 11A,B). More often than not, Φ_i decreased again under the midday summer sun when irradiance exceeded about half the level of full sunlight (Figure 11B). The initial decreases in Φ_i at low to moderate PPF likely resulted from photoprotective mechanisms while the midday decrease likely was caused by inactivation or turnover of photosystem II or by photoinhibition (Krause and Weis, 1991; Demmig-Adams and Adams, 1992; Ruban et al., 1993). High temperatures, high leaf-to-air water vapor pressure differences or other environmental factors that show diurnal changes and that can result in stress may have a part in inducing the second change in Φ_i (references in Bunce 1990). A recent review (Demmig-Adams and Adams, 1992) provides a model representing the responses of the photosynthetic apparatus to increasing levels of PPF. In brief, at first the increase in irradiance can bring about photoprotective responses. If irradiance continues to increase under a certain degree of stress to the photosynthetic apparatus responses may occur that result in greater or lesser damage. It seems reasonable to conclude that the two phases of decrease in Φ_i correspond generally to these stages of severity in the response to increasing irradiance.

Integrated Daily Light Energy Is Important in Determining Leaf Adaptation to Light

Leaf anatomy and NCE rate per unit dry wt can be modified during leaf expansion to reflect the predominant light conditions (Jurik et al., 1979). Leaf structural and NCE per unit dry wt were similar under environments where the integrated daily light energy was the same even though peak PPF was different (Table 2, Chabot et al., 1979). High total quanta, even at relatively low peak irradiance, produced sun type leaves (Chabot et al. 1979). Total daily incident quanta is a key factor determining leaf thickness, leaf weight per area, and mesophyll cell volume and surface per leaf area. Photosynthetic capacity, the light saturated rate of NCE measured at 25°C

and 34 Pa external CO_2, could be modified by changes in environmental conditions after leaves had become net exporters of carbon but prior to full expansion (Bunce 1991). Up to a point, photosynthetic capacity increased with leaf mass per area (Figure 12). Photosynthetic capacity is increased by total daily light energy incident on those leaves but not by that incident on other leaves. The net available photoassimilate (supply minus use), increases the leaf mass per area (Figure 13) and so is a key factor in acclimation of leaves to light.

The material presented in this paper present data that suggest some criteria for evaluating growth chamber and greenhouse lighting. Effective lighting should produce plants that perform according to the goals of the project. For example, for physiological studies the plants probably should exhibit morphology and physiology similar to that found in field-grown plants. For other projects the criteria will obviously will be set according to the reason for raising the plants.

TABLE 2 NCE and Leaf Anatomy of *Fragaria Virbiniana* Under Conditions of Nearly the Same Constant Peak PPF, But Variable Total PPF.
Values in the same row followed by the same letter are not significantly different. Data from Chabot et al., 1979.

Light Regime*					
High PPF Duration (h)	3.7	7.6	15.0	6.3	15.0
High PPF (μmol m^{-2} s^{-1})	305	305	302	363	371
Integrated PPF (mol m^{-2} d^{-1})	6.45	9.88	16.3	10.1	20
Leaf Traits					
Maximum NCE					
(μmol m^{-2} s^{-1})	23.6^a	28.2^b	29.6^b	20.8^a	31.6^b
(μmol g^{-2} s^{-1})	0.50^a	0.58^a	0.51^a	0.47^a	0.47^a
Thickness (μm)	113	126	151	138	179
SLW (mg m^{-2})	48.6^a	49.9^a	59.5^b	44.4^a	69.0^c
Mesoph Cell Vol (mm^3 m^{-2})	3.9×10^4	4.8×10^4	6.5×10^4	4.9×10^4	8.0×10^4
A^{mes} / A	10.3^a	11.7^a	15.3^b	11.4^a	16.0^b

*The treatments with less than 15h of high PPF were supplemented with a low PPF of 59 μmol $m^{-2}s^{-1}$ (0.21 mol $m^{-2}hr^{-1}$) to provide a 15h photoperiod.

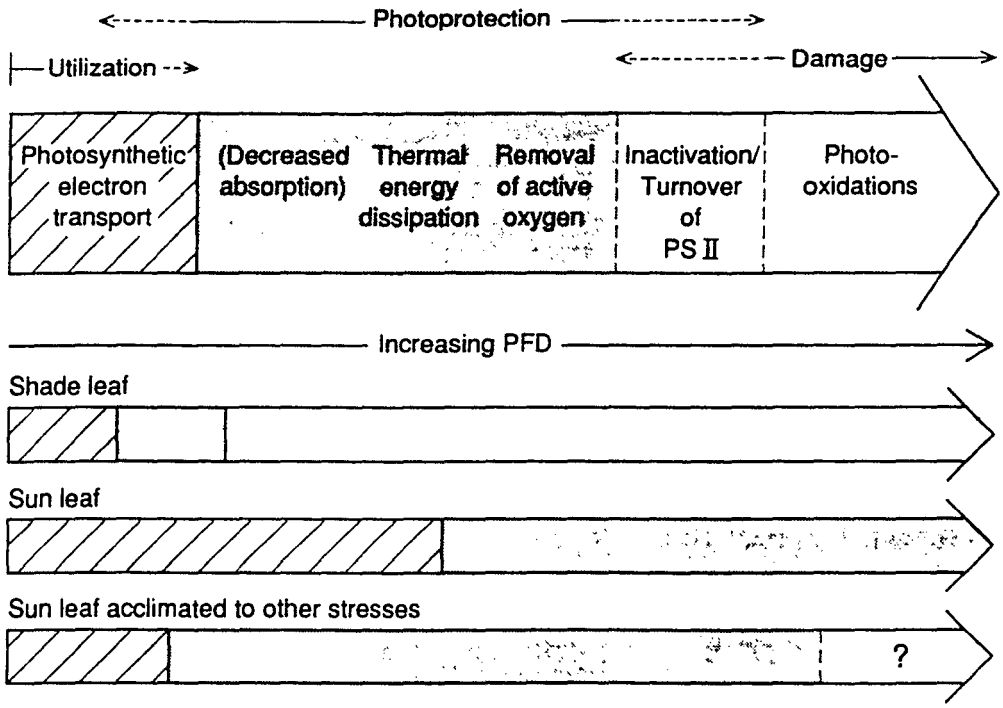


Fig. 12. Photosynthetic capacity as a function of dry mass per unit of area. From Bunce, 1991.

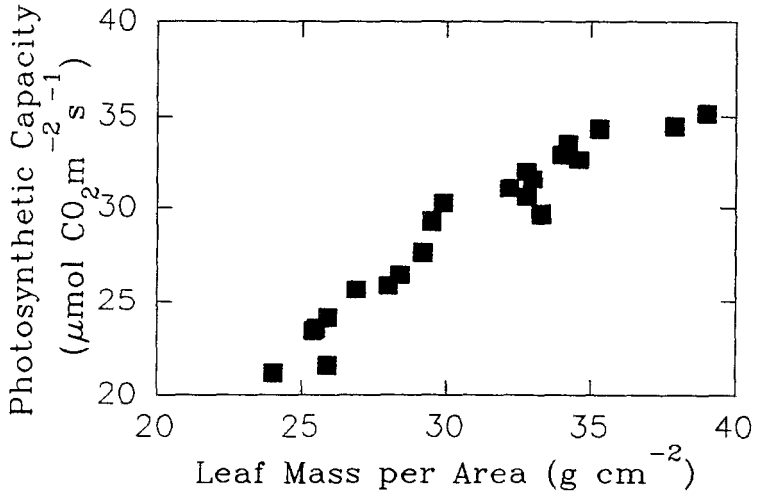


Fig. 13. Increase in mass of leaflets of third trifoliate leaves of soybean compared to dry mass income calculated from the mean 24-h NCE rate for the last 3 days before full leaf expansion. From Bunce, 1991.

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REGULATION OF ASSIMILATE PARTITIONING BY DAYLENGTH AND SPECTRAL QUALITY

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INTRODUCTION

Photosynthesis is the process by which plants utilize light energy to assimilate and transform carbon dioxide into products that support growth and development. The preceding review provides an excellent summary of photosynthetic mechanisms and diurnal patterns of carbon metabolism with emphasis on the importance of gradual changes in photosynthetically-active radiation at dawn and dusk (Geiger, this volume). In addition to these direct effects of irradiance, there are indirect effects of light period duration and spectral quality on carbohydrate metabolism and assimilate partitioning. Both daylength and spectral quality trigger developmental phenomena such as flowering (e.g., photoperiodism; Deitzer, this volume) and shade avoidance responses (Pausch et al., 1991), but their effects on partitioning of photoassimilates in leaves are less well known. Moreover, the adaptive significance to the plants of such effects is sometimes not clear.

DAYLENGTH

The light period normally occupies only part of the 24 h cycle, but photosynthesis during the light must support the carbon requirements of the plant during the dark as well. Thus, photosynthetic productivity frequently exceeds the capacity of the plant to transport and/or utilize the products of photosynthesis during the light period alone. Excess capacity is often stored in leaves or other tissues as polymers of glucose or other sugars (e.g., starch, sucrose, fructans). Temporary storage of photosynthate as large molecular weight compounds provides immediate benefits for photosynthesis, since it releases phosphate that would otherwise be sequestered in phosphorylated sugars (potentially inhibiting photosynthesis).

However, carbohydrate storage serves another important purpose. Many plants accumulate large amounts of starch or other carbohydrates in photosynthetic tissues during the light and then breakdown and utilize this material in the dark. This temporal redistribution of photosynthetic products allows plants to support growth and respiration during long dark periods. Mutants unable to accumulate starch are disadvantaged when grown under light-dark cycles as compared to continuous light (Caspar et al., 1985).

Early experiments conducted in greenhouses indicated that plants accumulated a greater proportion of photosynthate as starch under short day conditions (Challa, 1976). Subsequent

experiments were largely performed in controlled environment chambers and documented that similar responses to daylength could be observed in a wide range of species and that plants could adapt to sudden changes in daylength, sometimes within 24 h of the switch (Britz, 1990a). Note that photosynthate partitioning into starch was approximately halved when soybean plants were transferred from a 11.5 h daylength into a 16 h daylength (Table 1; Britz, unpublished data). Partitioning under a 7 h daylength, however, was similar to that under 11.5 h, indicating the transition between short and long-day response was between 11.5 and 16 h. In several well-documented cases, daylength regulation of assimilate partition was demonstrated to result from timing of dark period duration involving circadian rhythms initiated at the transition between light and dark periods (Britz et al., 1987). Detection of the light-dark transition apparently was perceived by non-photosynthetic photoreceptors capable of suppressing rhythms above certain low irradiances (Britz, 1986; Britz, 1991).

TABLE 1 Effect of Daylength on Carbohydrate Allocation in Soybean

Daylength Treatment*	Leaf Number **	Starch Accumulation (percent of photosynthesis) ***
11.5 h → 7h	TF_3	34.7
	TF_4	36.3
11.5 h → 11.5h	TF_3	35.3
	TF_4	32.9
11.5 h → 16h	TF_3	18.7
	TF_4	19.7

* Plants were grown (Chatterton and Silvius, 1981) for 24 days at a daylength of 11.5 h (12.5 h dark period) and shifted for 4 days to the indicated daylength prior to measurement. ** Third and fourth trifoliolate leaves (TF3 and TF4, respectively). *** Rates of starch accumulation were determined under growth conditions between 1 and 6 h after lights-on and referenced to rates of intact leaf net photosynthesis expressed as carbohydrate assimilation (Britz, 1990b).

In spite of the early greenhouse work, some researchers (e.g., Geiger et al., 1985) speculated that the daylength response was peculiar to the complex lighting manipulations used in controlled environments (e.g., Britz et al., 1985). However, an extensive series of greenhouse experiments conducted with natural daylight at 12 intervals during a growing season showed that the proportion of assimilate partitioned into starch (TF4, 4th trifoliolate) increased steadily under standard measurement conditions as prior daylength shortened between the summer solstice and the autumnal equinox (Britz, 1990b). About one-third of photosynthate was stored as starch at midsummer, but this fraction increased to 80% in early autumn. Temperature in the greenhouse was controlled with a heat pump, so the effect of this variable was minimized. Growth intervals were adjusted so that TF4 of comparable developmental status (i.e., plastochron), but differing in

daylength history, were obtained for each harvest. In fact, photosynthetic rates of TF4 measured under standard conditions declined only by about 10% at later harvests in the fall.

Increased partitioning into leaf starch was observed under short days at the end of the growing season, in spite of the fact that daily integrals of photosynthetically-active radiation were reduced by 50% and that plants were filling pods at the axil of TF4. These results suggest that daylength effects on assimilate partitioning within a source leaf may take precedence over the demand of nearby sinks. It may also explain why soybean seed development is sometimes found to be sink limited, while leaves may at the same time contain high levels of starch (Streeter and Jeffers, 1979). Clearly, regulation of assimilate partitioning by factors operating at the level of the leaf can be an important component of overall plant productivity.

SPECTRAL QUALITY

It has been known for some time that spectral quality affects plant tissue composition. In particular, carbohydrate levels are higher, while protein and amino acids are lower, in plants raised under red-biased as compared to blue-biased spectra (e.g., Warrington and Mitchell, 1976). It is important to determine if photosynthate partitioning contributes to morphological and physiological adaptation to altered spectral quality (e.g., canopy shade). A crucial question is whether spectral quality affects photosynthate partitioning directly at the level of source leaf metabolism or indirectly as a result of photomorphogenetic effects on the strength of developing sinks. For example, high starch content in the first leaf of cucumber was shown to correlate well with the growth of the developing third leaf leaf as controlled by blue light and/or ultraviolet-B radiation (Britz and Adamse, 1994). It seems likely that starch content in the first leaf was an indicator of sink demand.

Soybeans raised under relatively high photosynthetically-active radiation from blue-deficient low pressure sodium (LPS) lamps manifested many of the characteristics of shade plants (Britz and Sager, 1990). The leaves contained baseline (i.e., end-of-night) starch levels three fold higher than plants raised under broad spectrum fluorescent light. Moreover, 35% more photosynthate was partitioned into starch and sugar during the first half of the light period, apparently causing a decline in export from 52 to 37% of photosynthate (Table 2; Britz and Sager, 1990). Some of the retained carbon may have been used to support leaf growth at the expense of root growth (Table 2). High ratios of total leaf area to total dry matter compensated reduced photosynthesis on an area basis and maintained similar total Relative Growth Rates under the two different spectral quality conditions (Table 2). Note that net photosynthesis (total leaf basis!) was equal for first trifoliolate leaves measured under growth conditions for the two different light qualities even though the area of leaves from blue-deficient conditions was much greater. These data confirm the importance of generating high leaf area and suggest that changes in source leaf partitioning may be a form of resource rationing that maintains high photosynthesis under perceived shade conditions.

TABLE 2 Photoassimilation, Export and Growth Parameters in Soybean

Parameter	Broad Spectrum Fluorescent Lamps	Blue-deficient Low Pressure Sodium Lamps
First Trifoliolate Leaf*		
Leaf Area (dm^2)	0.559 b***	0.656 a
Net Photosynthesis (mg-C $leaf^{-1}h^{-1}$)	3.46 a	3.47 a
Starch + Soluble Sugar Accumulation (percent of net photosynthesis)	34	46
Export (percent of net photosynthesis)	52	37
Relative Growth Rates**		
Total Cry Matter ($g\ g^{-1}\ d^{-1}$)	0.226 ab	0.218 b
Leaf Dry Matter ($g\ g^{-1}\ d^{-1}$)	0.195 b	0.212 b
Stem Dry Matter ($g\ g^{-1}\ d^{-1}$)	0.252 a	0.230 ab
Root Dry Matter ($g\ g^{-1}\ d^{-1}$)	0.253 a	0.208 b
Leaf Area ($dm^2\ dm^{-2}\ d^{-1}$)	0.157 c	0.202 b
Leaf Area Ratio ($dm^2\ g^{-1}$)		
14 days	2.09 a	2.19 a
18 days	1.59 b	2.07 a

*Determined 16 days after planting.
**Determined 14 to 18 days after planting.
***Values followed by different letters are significantly different at the 5% confidence level.

More detailed experiments with younger soybean seedlings (8 to 10 days after planting) revealed significant reductions in the partitioning of ^{14}C-labelled photosynthate to the roots of plants transferred from blue-sufficient to blue-deficient lighting (Verkleij and Britz, unpublished data). Alterations in translocation preceded discernible changes in the partitioning of growth to the root but were accompanied by only small changes in primary leaf assimilate accumulation, raising questions about the cause-and-effect relationship between leaf carbohydrate storage and growth patterns. Under these conditions, high levels of leaf starch were shown to result from small and gradual increases in the proportion of photosynthate stored as starch during the light coupled with small reductions in the amount of starch broken down in the dark.

CONCLUSIONS

The effects of daylength and spectral quality on assimilate partitioning and leaf carbohydrate content should be considered when conducting controlled environment experiments or comparing results between studies obtained under different lighting conditions. Changes in partitioning may indicate alterations to photoregulatory processes within the source leaf rather than disruptions in sink strength. Moreover, it may be possible to use photoregulatory responses of assimilate partitioning to probe mechanisms of growth and development involving translocation of carbon or adaptation to environmental factors such as elevated CO_2. It may also be possible to steer assimilate partitioning for the benefit of controlled environment agriculture using energy-efficient manipulations such as daylength extensions with dim irradiances, end-of-day alterations in light quality, or shifting plants between different spectral qualities as a part of phasic control of growth and development. Note that high starch levels measured on a one-time basis provide little information, since it is the proportion of photosynthate stored as starch that is meaningful. Large differences in starch content can result from small changes in partitioning integrated over several days. Rate information is required.

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SPECTRAL COMPOSITION OF LIGHT AND GROWING OF PLANTS IN CONTROLLED ENVIRONMENTS

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The main conclusions of many investigations about general requirements of plants for spectral composition of PAR are based on phylogenetic aspects of plant growth (Kleshnin et al., 1980; Geiger, 1994; et al). We think that these aspects are not the main criteria in choosing the spectral composition required for growing plants in controlled conditions. Our approach to this problem is based on plant and crop reaction under long duration growth with specific spectra and intensity. Only in this way can we determine correctly the role of light characteristics for developing crops.

Why does it happen? In this connection it will be useful to examine the curve of the action spectrum of photosynthesis. This classical curve is formed under controlled influence of light that involves av 3-5 minutes irradiation with one specific spectral flux. The form of this curve is similar for green leaves of different species of plants. We've obtained different curves for spectral affectivity of green leaf photosynthesis (on the example of radish), when plants have had long duration adaptation (for some days) to lamps of different spectral composition and PAR intensity (Fig. 1, curves 1 and 2). The spectral of these lamps is shown in the Short Note by Prikupets and Tikhomirov in this publication. We feel the obtained differences have the following reasons. During short time intervals, only reactions of quick photoregulation are possible. These reactions affect only functional characteristics of the photosynthetic leaf system. In that time, structural changes do not occur and these reactions to light aren't observed. The classical action spectrum of photosynthesis (Fig. 1, solid line) shows the universal characteristics of green leaves of different plant species. Plants have the same types of green pigments (chlorophyll), photosystems, reaction centers, pathways of energy migration to reaction centers and so on (Tikhomirov et al., 1987; 1991).

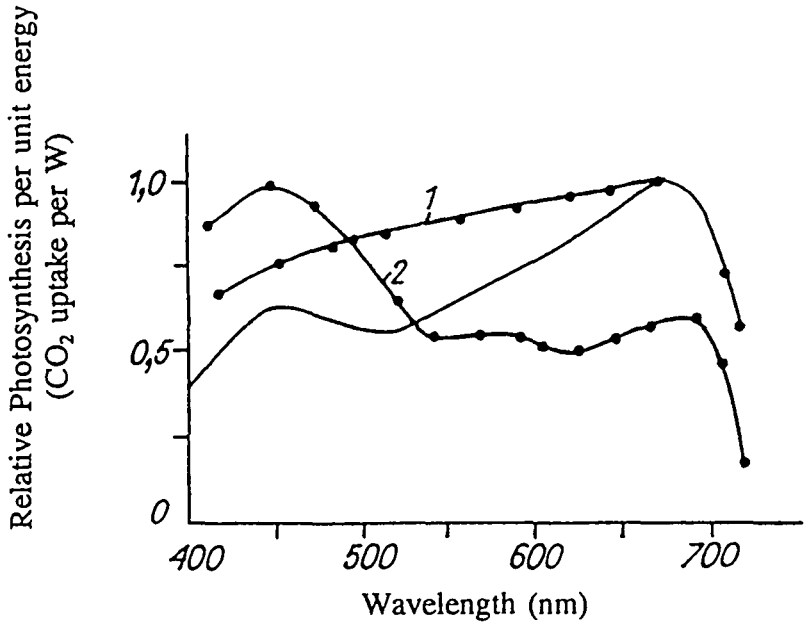

Fig. 1. The relative spectral efficiency of photosynthesis of green leaves of radish plants grown for 15 days under different PAR spectral lighting. Photosynthetic measurements for 400-500 mm were taken with plants grown under blue-light lamps, for 500-600nm under green light lamps, for 600-700nm under red-light lamps. 1) radiation intensity during growth of plants was 50 W m^{-2} PAR (radiation intensity for unsaturated photosynthesis). 2) radiation intensity growth of plants was 200 W m^{-2} PAR (radiation intensity for saturated photosynthesis) (Tikhomirov et al., 1987;1991). Solid line is average value of relative spectral photosynthetic efficiency of green leaves according to McCree (1972), Inada (1976, 1977).

Therefore, usage of the curve for action spectrum of photosynthesis is not correct in light regulation under long-term stationary regimes, since certain reactions to spectrum and intensity of PAR aren't taken into consideration. All spectral requirements obtained under short light influence tests have similar limitations.

What should be done? It's necessary to be guided by data obtained under long-term influence of spectral and intensity characteristics on photosynthetic plant systems and even better on canopies of plants. These are the photosynthetic structures which ultimately form to produce the harvested yield. We've obtained some results which support this conclusion. These are some of the universal responses (Tikhomirov et al., 1991):

1) The time for maximum affectivity of photosynthesis of plant canopies appears earlier with red (600-700 nm) and later may shift to shorter wave length regions of PAR. This shift depends on specific plant reaction to spectrum of PAR;

2) The relative effectiveness of blue rays increases and green and red rays decreases with higher levels of irradiation (Fig. 2 and 3);

3) Maximum photosynthesis of canopies is possible only under combinations of blue, green and red radiation. Any kind of combinations of two of these wavebands or with only one spectral region, always reduces productivity.

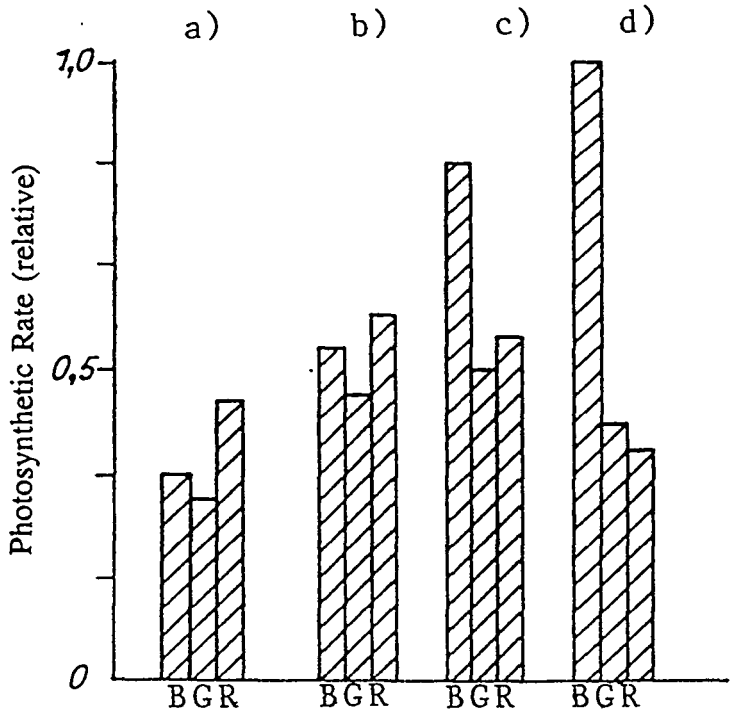

Fig. 2. The relative spectral efficiency of photosynthesis of cucumber leaves adapted to long duration growth with radiation of different energy and spectral composition. B = 400 - 500nm, G = 500 - 600nm, R = 600 - 700nm. a) 12 W m^{-2} (Ko, 1974); b) 24 W m^{-2} (Ko, 1982); c) 50 W m^{-2} (Tikhimirov et al., 1991); d) 100 W m^{-2} (Tikhomirov et al., 1991).

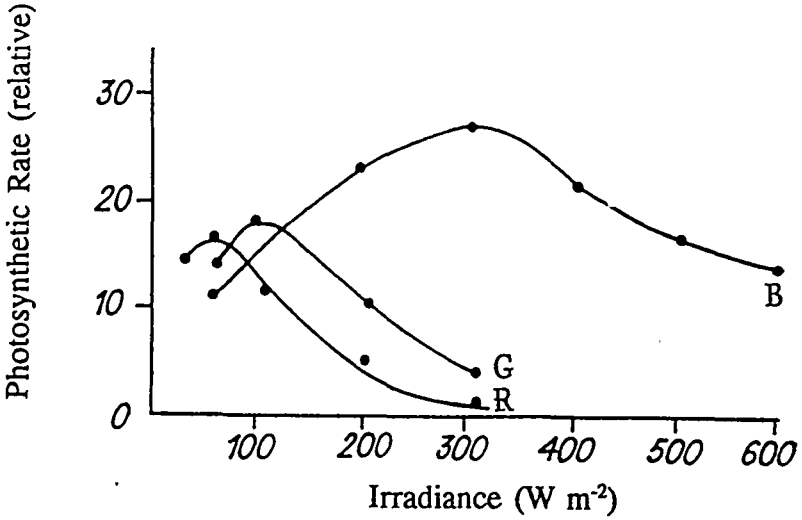

Fig. 3. The photosynthetic rate of 15d-old radish canopies with irradiance of differing spectral composition and intensities (B = 400-500nm, G = 500-600nm, R = 600-700nm). (Tikhomirov, et al., 1991).

It is not necessary to provide light conditions for maximum photosynthesis of every plant leaf but to provide light conditions for optimal photosynthesis of the plant canopy. As a general rule over long periods, photosynthesis systems grow old very quickly. The effect of leaf age on photosynthic rate is shown in Figure 4 using cucumbers.

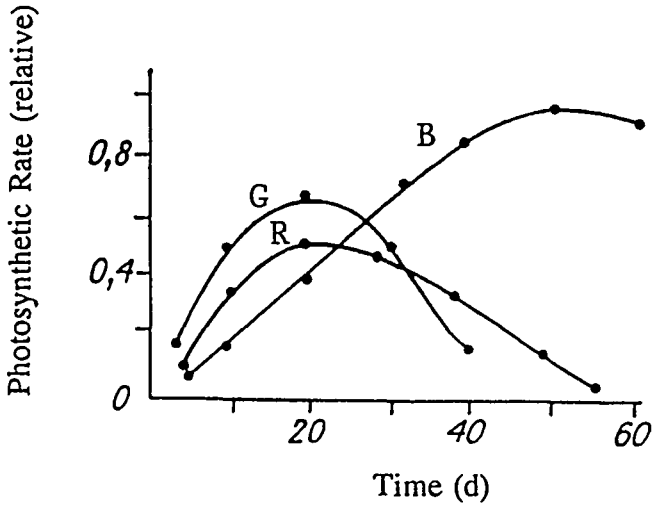

Fig. 4. The photosynthetic rate of cucumber per canopy area for PAR irradiances of 100 W m^{-2} with 400-500nm (B), 500-600nm (G), or 600-700nm (R) during canopy development (Tikhimirov et al., 1991).

Optimal photosynthesis of plant leaves involves a harmonious relationship between spectrum and the intensity of PAR. Thus, plants "work" to obtain the maximum photosynthetic efficiency (but the photosynthesis is not maximum for each leaf) (Tooming, 1984).

There is a question. Is it necessary to prepare optimal light conditions for the photosynthesis of all leaves on the plant or not? What way is it determined? The correct decision on spectral composition of light depends very much on certain morphological characteristics of plants. There is a dependance upon the distribution of fruits along a stem (Tikhomirov, 1990). For example, cucumber has equal distribution of fruits along the stem. There every leaf supplies assimilate to its fruit. In this connection cucumber leaves at all layers must be provided with optimal light conditions. This requires a large portion of green rays in PAR (about 40%). Red rays in PAR (about 40%) provide high level of photosynthesis of upper leaves. Green rays penetrate into middle and lower leaves of plants. Blue rays have regulatory function, but its part in PAR is not very big (about 20%) (Tikhomirov, 1989).

We have another situation, where fruits of a plant concentrate in the upper part of the stem. Classical example is wheat. The ear of wheat is supplied with assimilates, primarily from the upper leaves. With this crop, PAR must have approximately 60-70% red rays (Tikhomirov, 1990). We've obtained data on

specific reactions of plants for the spectral composition of PAR. It's particularly important during plant development processes. According to this point of view plants may be divided into two groups (Tikhomirov et al., 1991):

1) The first group is characterized with restricted growth and development processes at definite ontogenetic phases if the PAR spectrum and intensity are not optimized (i.e., cucumber, sunflower);

2) The second group include plants capable of passing through all ontogeneticS phases and producing a harvest irrespective of the PAR spectrum and intensity provided (for example: tomatoes, wheat).

Wheat is capable of passing through all phases of ontogenesis regardless of any specific spectral irradiation. It's correct for PAR range of 100-600 W m^{-2} and possibly even higher. Tomatoes have more restricted PAR range in comparison with wheat. With a PAR of 200 Wm^{-2} and higher, tomato productivity is lowered in red rays. PAR range for radish appeared to be more narrow. Even when red and green light is equal at a PAR of 200 Wm^{-2},plants of radish perish. Cucumbers appeared to be the most greatly influenced by the spectrum of PAR. For example in red wavelengths with less than PAR of 50 Wm^{-2}, plants die.

We shouldn't ignore these great differences in reaction of plants on spectrum and PAR intensity. All compromising decisions including introduction of universal spectrum of irradiation lead to partial loss of productivity.

Equal-energetic spectrum ("white" light) or a spectrum similar to curve of the action spectrum of photosynthesis have been proposed for use as a universal spectra for plants growing under lamp lighting. The first might be chosen because of consideration of phylogenesis of plants, the second - because of research familiar to you (McCree, 1972; Inada, 1976). Either of these options could be accepted as a temporary compromise for initial research.

I do not believe that we have to copy illumination of plants in natural conditions for use in controlled environment growing. For example there's no need to grow some species of plants under alternative light dark periods. Our research showed that productivity of some plants (radish, wheat) can be increased under continuous irradiation (Tikhomirov et al., 1976; Lisovsky et al., 1987). Also, we should not strictly aspire to duplicating morphophysiological characteristics of field grown plants. Thus, for example, we achieved a very large radish productivity when we sharply changed its photomorphogenesis (Tikhomirov et al., 1976). This is true for increasing cucumber productivity too. However, if we accept this concept, we must know where and how we should deviate from natural conditions to increase productivity of plants grown in controlled environments. So I have the following suggestions:

1) As a temporary measure the draft guideline distributed by the organizing committee might be recommended for usage for plants grown in controlled environments;

2) Research work should be expanded to identify the spectrum of PAR radiation for each plant species which provides the maximum crop value.

If these suggestions are taken into consideration, my colleagues from Russia and I are ready to discuss a program of research and take part in its conduct.

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SHORT REPORT

OPTIMIZATION OF LAMP SPECTRUM FOR VEGETABLE GROWTH*

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An increase in the demand for and production of vegetables in the winter, mainly in northern and Siberian regions, inevitably leads to mass building of structures for growing plants under completely artificial conditions. It is required to create an industrial lighting technology whose main parameters (spectrum, irradiance, photoperiod) should be assigned carefully and should uniquely determine, along with other important characteristics of the artificial climate, the productivity of the plant-production facility.

The most widespread crops grown in our country under indoor conditions are cucumber and tomato plants, which account for more than 98% of the area of greenhouses. These plants are good prospects for growing completely under intense artificial lighting conditions (photocultures). Optimization of the main parameters of optical radiation when growing these plants is the most important task of achieving their profitable production.

At present considerable experience has been gained in studying the dependence of productivity of cucumber and tomato communities on irradiation conditions. Fundamental studies of the Agrophysical Research Institute of the Russian Academy of Sciences, Timiryazev Institute of Plant Physiology of the Russian Academy of Sciences, Timiryazev Agricultural Academy, and other institutes create a good basis for a detailed study of the given problem. Commercial sources of radiation substantially differing in spectral characteristics in the region of photosynthetically active radiation (PAR) were used in the studies (Table 1).

TABLE 1 Spectral Characteristics of Light Sources.

Light source	Approximate ratio of radiant fluxes in three PAR ranges, %		
	400-500 nm	500-600 nm	600-700 nm
Incandescent lamp	14	34	52
DKsT lamp	35	31.5	33.5
DRV750 lamp	25.5	46	28.5
DRLF400 lamp	26	56	18
DNaT400 lamp	7	56	37
DRI2000-6 lamp	39	43	18

One of the first studies of a cucumber variety "Klinskie" photoculture is reported in (Moshkov, 1966) and it is noted that the use of type DRL400 lamps with PAR irradiance 80-120 W/m^2 produced good results.

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In experiments with cucumber variety "Dyadya Stepa" three types of lamps with a different spectrum were used: DRLF400, DRV750, and DR12000-6 (Sharupich, 1982). Unfortunately, each type was used in its "own" range of PAR, the boundaries of which were selected with consideration of the energy efficiency in the PAR region and unit power of the lamp. With irradiation of the plants by a spectrum with a small share of radiation in the red region (DRLF400) and with variation of irradiance E_{PAR} within 35-100 W/m^2, the productivity of the community did not exceed 17 kg/m^2. In experiments with DRV750 lamps (increased share of radiation in the red part) with an increase of E_{PAR} from 35 to 200 W/m^2, maximum productivity increased to 23 kg/m^2. Finally, for E_{PAR}=300-400 W/m^2 (DRI2000-6), productivity of the community increased to 30 kg/m^2. The author (Sharupich, 1982) concluded that the range E_{PAR} = 80-150 W/m^2 is preferable for a cucumber culture, and an evaluation of the favorable spectrum is possible only at the qualitative level.

Detailed studies of potential productivity of tomatoes under photoculture conditions were carried out by the author (Moshkov, 1966) and were continued by his successors. The main sources of radiation in the experiments were 300-W metallized incandescent lamps, the spectrum of these sources was most suitable for intense growing of tomatoes under artificial conditions. A tomato variety Pushkinskii yield, of about 22 kg/m^2 was obtained with E_{PAR} of about 250-300 W/m^2 under conditions with water screens.

In the next study (Ermakov, 1987), 1000-W halogen lamps (HLs) and 400-W high-pressure sodium lamps (HPSLs) were used and the conclusion about the special significance of the long-wave part of PAR for the vital activity of tomato plants was confirmed.

It should be noted that the spectrum of type DKsTV6000 lamps having close to equi-energy in the PAR region, was used in photobiological studies of the Timiryazev Agricultural Academy (Leman, 1976), and also was quite effective for tomato photoculture. To develop well-founded requirements imposed on the spectrum when growing tomato and cucumber plants under intense photoculture conditions, it is necessary to conduct experiments with broad variation in the spectrum within the PAR. Such experiments were conducted by the Institute of Biophysics, Siberian Branch, Russian Academy of Sciences (IBF SO RAN) jointly with the All-Union Lighting Research and Development Institute (VNISI) in 1986-1989.

Using the method of Tikhomirov, (1983) and a series of selective metal halide lamps (MHLs), the PAR region was divided into three spectral ranges: 400-500 nm ("blue"), 500-600 nm ("green"), and 600-700 nm ("red"). The spectra of these lamps with filters are shown in Figure 1. The required spectral distribution and level of irradiance were achieved by combining lamps in a multilamp lighting fixture. Cucumber variety "Moskovskii Teplichnyi" and tomato variety "Starfire" were grown in 1 m^2 chambers with adjustable temperature and humidity characteristics until the final tomato crop was obtained. The environmental parameters (except the varied spectrum) were maintained at optimal levels: humidity 60-70% (cucumbers) and 60-70% (tomatoes), air temperature during irradiation 25 ± 1 °C (cucumbers) and 28 ± 1 °C (tomatoes), night temperature 20 ± 1 °C (cucumbers) and 25 ± 1 °C (tomatoes), photoperiod 14 hr (cucumbers) and 16 hr (tomatoes).

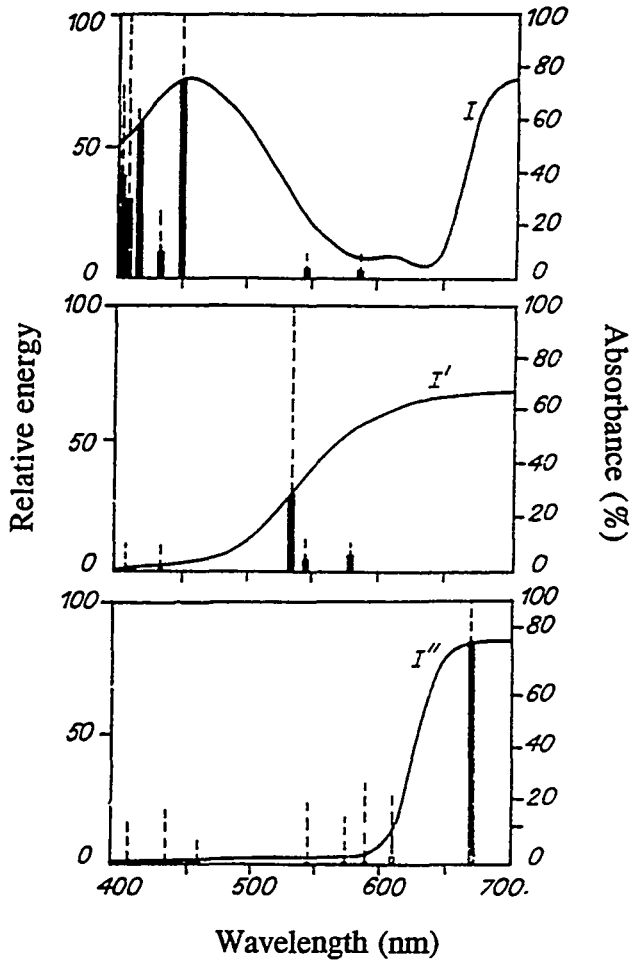


Fig. 1. Spectra of lamps and absorbance of filters utilized for irradiation of plants. Spectral emissions of lamps shown by vertical lines for a) blue mercury-gallium-indium lamps, b) green mercury-thallium lamps, c) red mercury-thallium lamps based on relative energy emission of the strongest waveband. Dashed vertical lines are the relative energy without filters and solid vertical lines are the relative energy with filters. Absorbance of specific filters(T,%) utilized with each lamp is shown by the solid line curve.

In each experiment PAR was maintained at the level 100 $\pm$ 10 W/m^2. By means of a planer water screen, and when necessary glass heat-protecting filters, the share of IR radiation was established at a level of about 25% of the radiation in the PAR region. The spectral distribution of irradiance was checked by a portable PDSF spectrophotometer.

Sixteen experiments with cucumbers and seven with tomatoes were carried out with various spectral combinations. The results of the experiments (nine characteristic experiments were selected for cucumbers) are given in Tables 2 and 3.

TABLE 2 Productivity of Cucumber Variety "Moskovskii Teplichnyi" with Variation of the Spectrum in the PAR Region.

Ratio of irradiance in three PAR ranges, (%)			Fruit yield (kg/m^2)	Period of growth (days)	Average daily fruit yield, (g/m^2)
E_b (400-500m)	E_g (500-600m)	E_r (600-700m)			
40	20	40	20.8±1.6	80	260.0±20.0
60	20	20	16.1±1.3	90	178.8±14.4
20	60	20	17.5±1.2	80	218.3±15.0
40	40	20	18.2±1.6	85	214.2±18.8
34	33	33	22.5±1.9	75	200.0±29.3
15	35	50	22.1±1.5	70	322.8±21.9
25	35	40	25.2±1.5	75	336.0±20.0
15	45	40	27.4±1.7	70	391.4±24.3
20	40	40	27.5±1.3	70	392.9±22.9

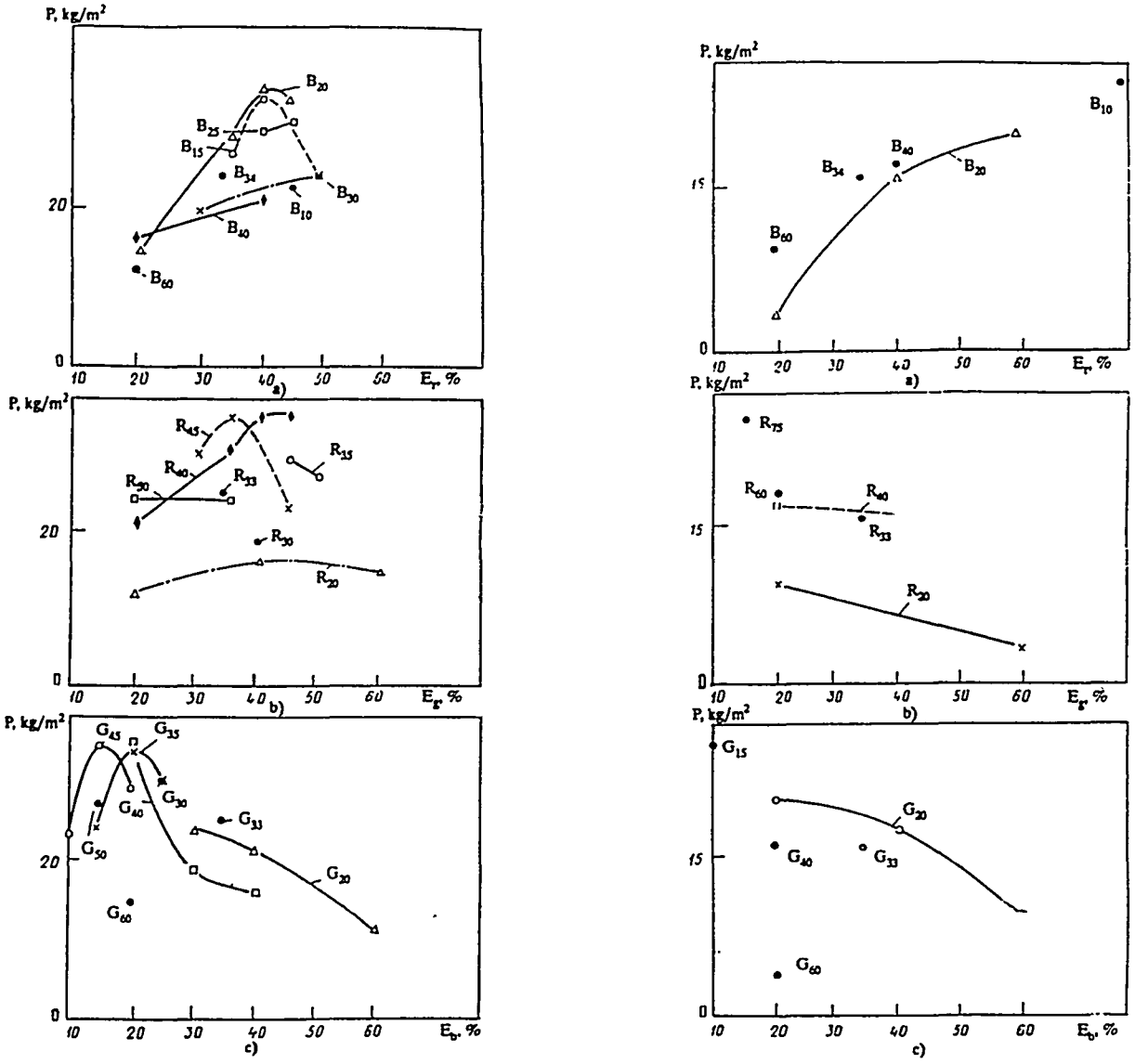
TABLE 3 Productivity of Tomato Variety "Starfire" with Variation of the Spectrum in the PAR Region.

Ratio of irradiances in three PAR ranges, %			Fruit yield (kg/m^2)	Period of growth (days)	Average daily fruit yield, (g/m^2)
E_b (400-500m)	E_g (500-600m)	E_r (600-700m)			
60	20	20	13.2±0.9	130	101.5±7.0
20	60	20	11.1±0.7	120	92.5±5.8
20	20	60	16.9±1.2	100	169.0±12.0
40	20	20	15.7±1.0	120	131.0±8.0
20	40	40	15.5±0.9	110	141.0±8.0
34	33	33	15.4±1.1	110	140.0±10.0
10	15	75	18.5±1.2	100	185.0±12.0

Assuming total productivity of the crop P, kg/m^2, is a function of the share of irradiance in each of the three spectral ranges (E_b, E_g, E_r) of the total E_{PAR} and taking into account the equation of the relation existing for these variables, we obtain a system of equations.

$$P - f(E_b, E_g, E_r);$$
$$E_b + E_g + E_r = 100\%$$

We reduce the problem to three-dimensions and, drawing sections along one of the variables in accordance with its values realized in the experiments, we represent the results obtained in the form of Figure 2. For each of the vegetables we obtained six families of curves, but we have limited ourselves here to three characteristic relations (the results of all 16 experiments with cucumbers were taken into account).



Cucumber Tomato

Fig. 2. Dependence of productivity of cucumbers and tomatoes on share of radiation of one of the three spectral ranges (E_b, E_g, or E_r) with total irradiance E_{PAR} = 100W/m^2:1) P = $f(E_r)$, E_b is a parameter (B_{25}, for example, means that the share E_b = 25%; b) P = $f(E_g)$, E_r is a parameter; c) P = $f(E_b)$, E_g is a parameter.

Before the main series of experiments on the cucumbers, an attempt was made to evaluate the photophysiological significance of each of the three PAR ranges. It was found that for irradiance E_{PAR} = 50 W/m^2 cucumbers, unlike many other plant species, are not formed either with only blue or green rays, and even with a high level E_{PAR} = 100 W/m^2 an extremely low yield was obtained only in blue rays.

The character of the dependence of the productivity of cucumbers on an increase of the share of radiation in the green and red ranges of PAR is about the same. There are fairly distinct optima of productivity for E_g = E_r = 35-45% of the total level. With an increase of the share of radiation in any of the indicated ranges above 45% (and corresponding decrease of the share of radiation in the other range), the productivity of the plants decreases markedly. The presence of blue radiation in the spectrum is necessary, but in a small dose. The dependence of productivity on the share of blue radiation reaches a maximum when E_b = 15-20%. It is interesting to note that with a decrease of the share of green radiation, the position of the maximum of the productivity curve shifts toward E_b.

Thus with respect to a cucumber photoculture, we need speak about the preference of a "balance" of radiation in ranges 500-600 and 600-700 nm with the small addition of radiation in the range 400-500 nm. The best results for commercial technology are obtained with a spectral ratio E_b:E_g:E_r = 15-20%:35-45%:40-45% (USSR, 1991).

As follows from the results of experiments on cucumbers (see Table 2), optimization of the spectrum creates additional possibilities for reducing the cost of production due to a noticeable reduction of the period of growth. Substantially different conclusions about preferable spectra follow from an analysis of the results of experiments on tomatoes (see Fig. 2 and Table 3). The qualitative and quantitative effect of each of the three PAR ranges on the formation of the tomato crop is displayed rather clearly, despite the smaller number of experiments with a fixed spectrum than for cucumbers. We note the most important significance of radiation is the region 600-700 nm to acheive a high productivity of the tomato community. With a change in the share of E_r over 20-75%, the tomato yield can differ by almost 1.7 times; the maximum level of productivity in the experiments was achieved for E_r = 75%, although there are signs of saturation of the dependence already for E_r = 60-65%. Radiation in ranges 400-500 and 500-600 nm, conversely, is needed in insignificant shares, satisfying evidently, photomorphogenetic processes in plants. Thus, already for E_b = E_g = 15-20% against the background of a high share of red radiation, a drop of tomato productivity is observed. For E_r = 35-40% an increase of radiation in the green region weakly affects productivity, an increase of the share of red radiation for E_r = 20-40% can lead even to an increase of yield. However, all these effects are observed against the background of a low level of tomato productivity.

The requirements imposed on preferable spectral characteristics for tomato photocultures formulated on the basis of the studies are: E_b:E_g:E_r = 10-20%:15-20%:60-75%.*

The requirements imposed on the spectrum for growing tomatoes and cucumbers can be regarded as optimal.

*A team of authors of IBF SO RAN and VNISI applied for a patent on a method of growing tomatoes under artificial conditions and a favorable decision was obtained.

The experimental data permit us to make an estimate of the correspondence of the spectral requirements in the PAR region to the spectrum of certain commercial light sources to the productivity of tomatoes and cucumbers. The data are given in Table 4, where the level of maximum productivity corresponds to the experimental results with the recommended optimal spectral ratios. Lower productivity values were obtained with the use of combinations close or corresponding to the PAR spectrum of commercial lamps (DRLF, DNaT, DRI, etc.).

TABLE 4. Calculation of the PAR efficiency of some types of light sources for cucumber and tomato culture. Productivity estimated based on maximum productivity determined in previous experiments of Tables 2 and 3.

	Productivity (% of maximum)	
Lamp Type	Cucumbers	Tomatoes
DksT	81	95
Incandescent	78	84
DNaT	70	83
DRI	66	70
DRLF	64	60

As is seen, not one of the commercial light sources can be recommended for efficient use in commercial technology of cucumber culture, and the least suitable for this purpose are DRLF400 lamps; the spectrum of lamps with a high radiation efficiency in the PAR region (DNaT400 and DRI2000-6) are almost equal to the spectrum of DRLF400 lamps. We note that the requirements imposed on the "ideal" spectrum for growing cucumbers can be rather simply realized by selecting the appropriate filling of the MHLs. Work is presently underway to create such lamps.

Type DRLF400 lamps were also least acceptable for irradiating tomatoes. The creation of a special grow light on the basis of MHLs with a spectrum close to that in the PAR region of incandescent lamps (ILs) is a technically more complex problem. However, as the results of our experiments, confirming the conclusions of (Sharupich, 1982), showed, under conditions of an intense tomato culture, the use of HPSLs provides a sufficiently high level of productivity. For large conveyor-type plant production facilities, it would be expedient to create 700- or 1000-W HPSLs.

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EFFECTS OF RADIATION QUALITY, INTENSITY, AND DURATION ON PHOTOSYNTHESIS AND GROWTH

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THE RELATIONSHIP BETWEEN RADIATION ABSORPTION, PHOTOSYNTHESIS, AND PLANT GROWTH

Importance of Radiation Absorption

Increases in plant dry mass are not always associated with increases in photosynthetic rate, particularly when increased internode elongation increases plant height or diameter. Photosynthetic efficiency is rigorously defined as the amount of CO_2 fixed per absorbed photon, a ratio known as quantum yield. Longer internodes typically increase the interception and absorption of photons, causing increased plant growth (CO_2 fixed or dry mass gain) without an increase in quantum yield (photosynthesis). An increase in the physical process of radiation interception is often incorrectly interpreted as an increase in the biochemical process of photosynthesis.

Plant scientists continue to grossly underestimate the magnitude and importance of side lighting in single-plant studies. The reflective walls of growth chambers mean that side light intensity is only slightly less than that from the top. If a single, spaced plant is considered to be spherical rather than circular, the surface area for radiation interception changes from πr^2 to $4\pi r^2$, a 400% increase. Even if only the top half of the sphere is exposed to light, the surface area and thus light absorption are still twice that of a circle. In many studies, plant surface area and radiation absorption should be analyzed as a cylinder determined by plant height and width, rather than as a circle determined by width only.

Side lighting means that tall plants intercept more photons and will have a higher growth rate than short plants, *even when the irradiance level is identical at the top of the plants.* It is important to distinguish between radiation absorption and photosynthesis because the increases in growth or width caused by increased side lighting do not occur in plant communities where plants form a closed canopy and mutual shading eliminates side lighting.

In our studies with wheat canopies, elevated CO_2 increased photosynthesis, which increased tillering (branching) and lateral spread at the edges of the plant canopy. Precise measurements of the canopy-absorbing area showed that *half* of the CO_2 effect was caused by increased radiation absorption. The direct CO_2 effect on photosynthesis was only about 50% of what we originally measured.

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*Research reported in this paper was supported by the National Aeronautics and Space Administration cooperative agreement 2-139, and by the Utah Agricultural Experiment Station. This is Journal paper number 4665.

Small increases in lateral spread cause surprisingly large increases in radiation absorption. Figure 1 shows how a 10% increase in lateral spread of a wheat canopy resulted in a 24% increase in plant surface area causing a similar increase in growth rate and a corresponding overestimation of the effect of CO_2 on plant growth per unit surface area.

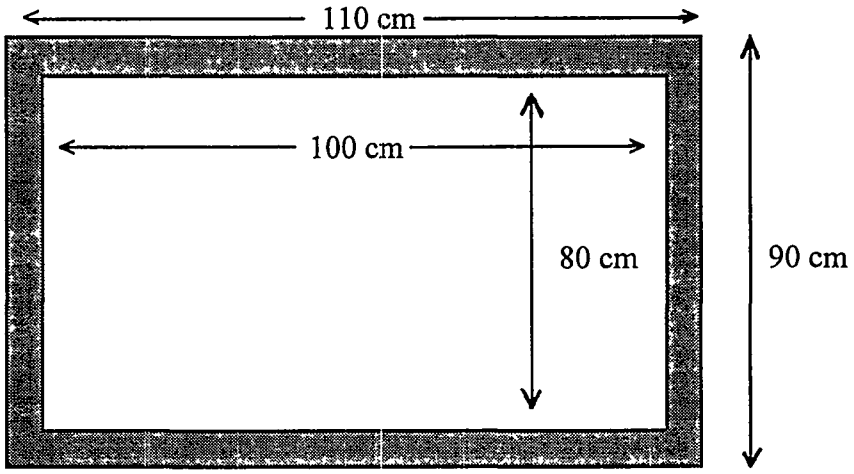

Fig. 1. The effect of a 10% increase in lateral spread (5 cm on all sides) on surface area of a plant canopy. The planted surface area was 0.8 m^2. The actual plant growth area was 0.99 m^2, resulting in a 24% increase in final/initial surface area. Small increases at the perimeter cause large increases in surface area.

Single-Leaf Maximum Quantum Yield and Whole-Canopy Actual Quantum Yield

Photosynthetic efficiency is routinely measured by determining the maximum quantum yield of single leaves, which occurs only at low PPF (less than 200 μmol m^{-2} s^{-1}) and is measured at the initial slope of the PPF response curve. It is often useful to determine the average daily quantum yield of whole plants at much higher PPF levels, which requires determining the number of photons absorbed by a whole plant. This is difficult because it requires measuring and integrating the incident, transmitted, and reflected photons on all sides of the plant. However, these measurements are often made in plant canopies where the edge effects are small or can be eliminated by artificial shading (Gallo and Daughtry, 1986).

We have used fiberglass window screen for artificial shading to simulate the effect of additional plants and to minimize edge effects. The screen is hung over a wire that is stretched around the perimeter of the canopy at the top edge. The wire and screen are raised daily as the canopy grows. The window screen extends from the top to the bottom of the canopy. The goal is to create the same vertical radiation attenuation at the edge of the canopy as the center. The data in Table 1 indicate that 3 layers of window screen may be necessary to create a similar radiation attenuation at the edges.

TABLE 1 A comparison of the radiation attenuation from two or three layers of window screen for artificial shading at the edge of a dense wheat canopy.

cm from top of canopy	center of tub	(edge) 3 layers of windowscreen	(edge) layers of windowscreen
0	1100	1100	1100
6	750	750	750
10	265	225	225
17	50	35	100
36	0	0	20

Values are for PPF in $\mu mol\ m^{-2}\ s^{-1}$

Whole-canopy quantum yield

We calculated average daily canopy quantum yield. This involved integrating net photosynthesis during the light period and was based on the assumption that dark respiration occurs at the same rate in the light and the dark (McCree, 1986). Dark respiration may be slightly lower in the light because ATP can be supplied in leaves by photophosphorylation, or slightly higher because the energy demand for translocation and active uptake are increased. Net photosynthesis plus dark respiration equals gross photosynthesis in $\mu mol\ m^{-2}\ s^{-1}$ of CO_2. Gross photosynthesis divided by absorbed photons ($\mu mol\ m^{-2}\ s^{-1}$) is canopy quantum yield (Bugbee and Monje, 1992; Monje, 1993; Monje and Bugbee, 1994).

DEFINING GROWTH AND DEVELOPMENT

I define plant growth as an increase in dry mass and define plant development as a change in plant shape. These are important distinctions when describing the effect of radiation on internode elongation. An increase in stem elongation is not necessarily an increase in growth. Some radiation environments increase plant height with no change in dry mass, e.g. far-red light can cause rapid stem elongation with no change in photosynthesis or dry mass.

PHOTOSYNTHETIC RATE IS SURPRISINGLY LITTLE AFFECTED BY LIGHT QUALITY FROM STANDARD LAMPS

The effect of radiation quality on photosynthesis has fascinated physiologists for over a hundred years. Early studies were done on photosynthetic bacteria and algae and we have long known that green light is less useful than other colors. McCree (1972a, 1972b) made comprehensive studies of photosynthesis in single leaves and described an average relative quantum efficiency curve (Figure 2), which was replicated by Inada (1976, 1978a, 1978b) and extended by Sager et al. (1982, 1988). However, the most common method of measuring photosynthetically active

radiation gives equal value to all photons with wavelengths between 400 and 700 nm and is referred to as Photosynthetic Photon Flux (PPF). Because blue and green photons result in about 25% less photosynthesis than red photons, a PPF sensor overestimates the photosynthetic value of the blue photons from a source, for example, metal halide lamps. However, a PPF sensor does not respond to ultraviolet or far-red radiation and these wavelengths drive some photosynthesis. A lamp with significant amounts of UV and far-red radiation could thus have a *higher* photosyn-thetic rate than predicted by a PPF sensor.

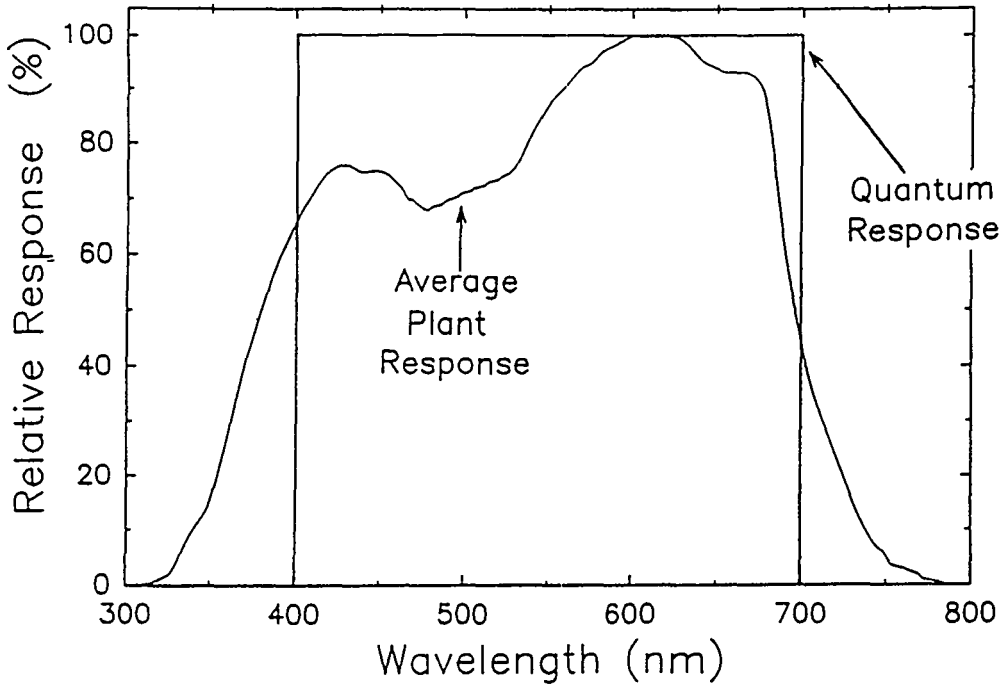

Fig. 2. The quantum (PPF) response when all photons are weighted equally between 400 and 700 nm: and the relative quantum efficiency curve as determined by the average plant response for photosynthesis (from McCree. 1972a). The quantum response overestimates the photosynthetic value of photons between 400 and about 550 nm, but underestimates the photosynthetic value of photons below 400 and above 700 nm.

Differences between the Quantum and the Actual Plant Response for Common Radiation sources

Because the spectral output for electric lamps is reasonably constant, the ratio of the constant photon response (quantum or PPF response) to actual plant response can be calculated from the average quantum efficiency curve (from McCree, 1972a). This ratio is shown in Table 2. The differences among lamp types are surprisingly small. Similar calculations have been described previously (McCree. 1981).

An additional source of error is that all sensors that integrate photosynthetic radiation are imperfect. Barnes et al. (1993) analyzed the errors associated with commercial sensors designed to integrate photosynthetic radiation over a range of wavelengths.

The ratio in Table 2 some lamp types is not intuitively obvious so it is useful to plot the spectral output from the lamps (Figure 3) and plot this output with the average plant response curve (Figure 4).

TABLE 2. The spectral efficiency of six electric lamps and sunlight.

Lamp type		Ratio
Low Pressure Sodium	(LPS)	.99
High Pressure Sodium	(HPS)	.95
Incandescent	(INC)	.95
Metal Halide	(MH)	.90
Cool White Fluorescent	(CWF)	.89
Red Light-Emitting Diode	(LED)	.89
Solar on a clear day		.88

Spectral efficiency is defined as the ratio of the lamp spectral output multiplied by McCree's quantum efficiency weighting factors, divided by the number of photons between 400 and 700 nm. Examples are given in Figure 4. The ratio for solar radiation is not a constant (see Figure 3). The LED had a peak output of 660 nm. LED's with peak outputs at shorter wavelengths wouldhave greater spectral efficiency, e.g. a peak output at 610 nm would result in an efficiency close to 1.0.

PLANT GROWTH IN SOME SPECIES IS SURPRISINGLY LITTLE AFFECTED BY LIGHT QUALITY

Although photosynthesis may not be affected by light quality in short-term studies, the spectral quality from some lamps decreases chlorophyll concentration and alters phytochrome status, which can be detrimental to plant growth in long-term studies. The monochromatic radiation from low-pressure sodium lamps can significantly reduce chlorophyll and plant growth in several dicotyledonous species, for example.

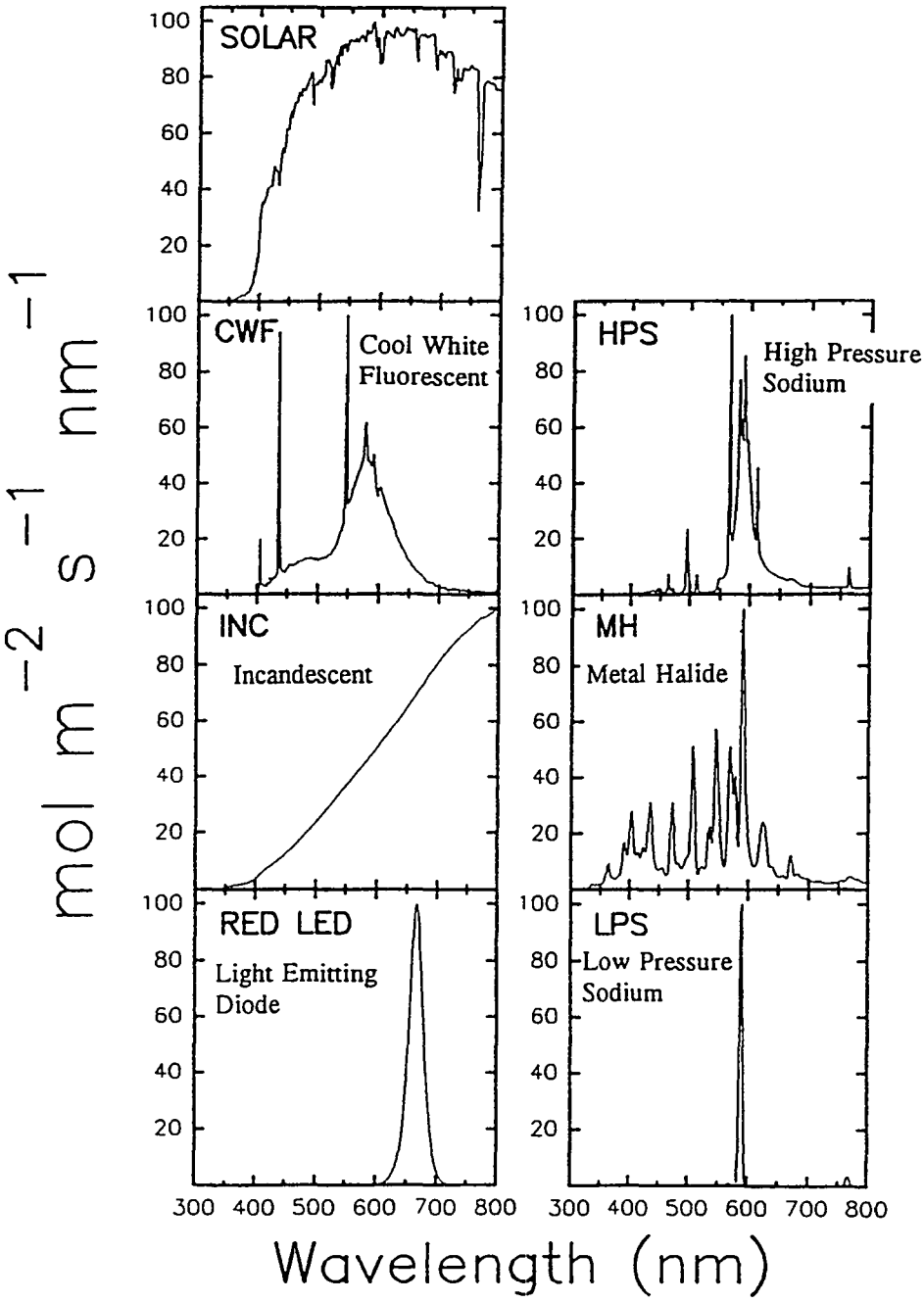

Fig. 3. The spectral characteristics of the seven radiation sources discussed in Table 2. Data are normalized to a peak value of 100 to facilitate comparisons and plotted on a photon flux basis, which is a better predictor of plant response than is energy flux (adapted from Barnes et al., 1993). The solar curve was measured at noon on a sunny ay in Logan, UT. Increasing diffuse radiation (from clouds or low sun angles) shifts the peak to shorter wave-lengths and would tend to decrease the ratio for solar shown in Table 2.

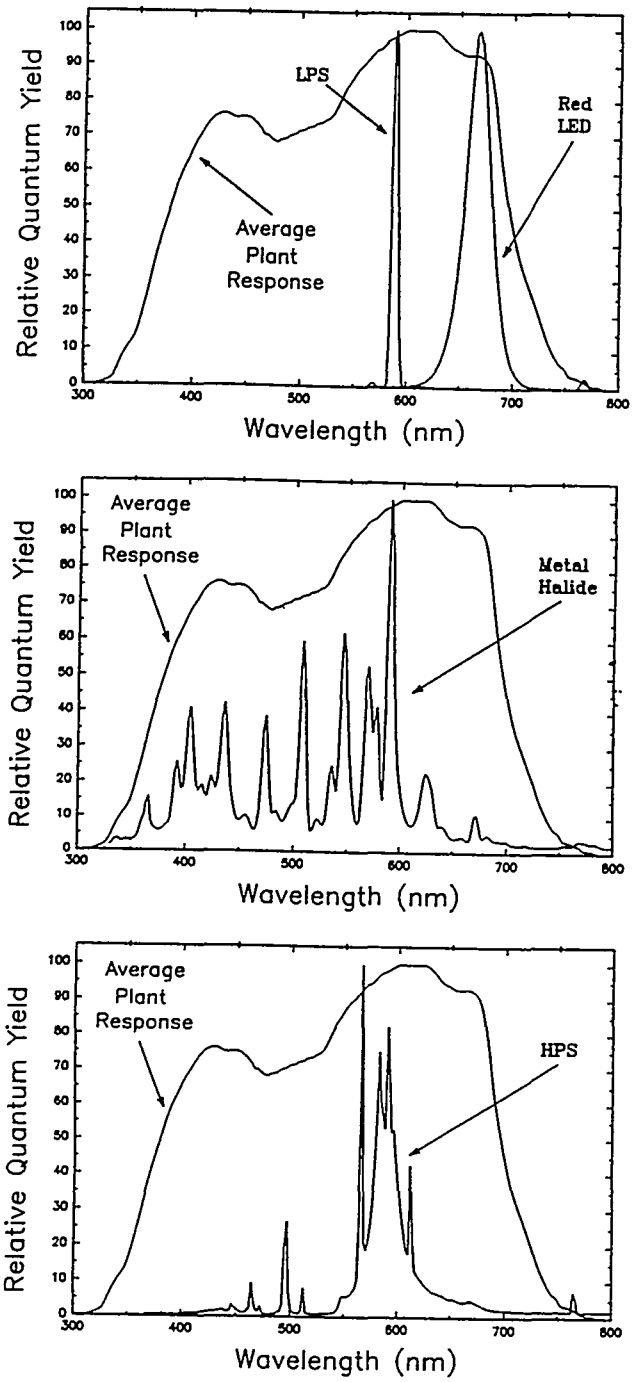

Fig. 4. A comparison of the spectral output from low pressure sodium (LPS), red LED's, metal halide (MH), and high pressure sodium (HPS) lamps to the average quantum efficiency curve. Monochromatic, LPS lamps are near the peak quantum yield (a ratio of 0.99). Some output of red LED's exceeds 680 nm where the plant response drops sharply. The ratio for MH lamps (0.90) is reduced because they emit blue photons but this reduction is offset some because they emit photons in the UV region, which are not measured by PPF sensors. HPS lamps have a relatively high ratio (0.95) because most of their output is near the peak quantum yield.

Effect of spectral quality of wheat growth and yield

Not all species are sensitive to spectral quality, however. Low-pressure sodium lamps did not

decrease the growth and yield of wheat compared to HPS and MH lamps (Table 3), a finding we recently confirmed. The plants under the low pressure sodium lamps of course did not look green, but the apparent difference in green color disappeared when the plants were removed and placed together in full spectrum light. Studies with wheat grown under red LED's also indicate that chlorophyll synthesis, photosynthesis, growth, and yield of wheat (*Triticum aestivum*) are insensitive to spectral quality.

TABLE 3. The effect of radiation source on growth and yield of wheat grown under three radiation sources. (adapted from Guerra et al., 1985).

Lamp Type	Total Biomass ($g\ m^{-2}$)	Grain Yield ($g\ m^{-2}$)
Low Pressure Sodium	171	61.7
High Pressure Sodium	159	58.8
Metal Halide	162	62.4
$\alpha = 0.05$	n.s.	n.s.

Effect of HPS and MH lamps on soybean growth and yield

Soybean leaves grown under HPS lamps are visually chlorotic and have reduced chlorophyll concentrations compared with plants grown under MH lamps. However, most plant leaves have excess chlorophyll, and small reductions do not necessarily decrease photosynthetic rates. Three recent studies in our laboratory confirm the reduction in chlorophyll under HPS lamps, but indicate that this reduction does not reduce growth or yield (Table 4). In fact, growth and yield were slightly better under HPS lamps. There was greater petiole elongation in plants grown under HPS lamps, but we lowered the plants as they grew taller to maintain a constant PPF at the top of the canopy. Lateral spread was prevented by enclosing the plants with a double layer of window screen around the perimeter of the stand. The reduced chlorophyll concentration may have increased PPF transmittance and allowed more PPF to penetrate to lower leaves in the canopy, thereby increasing canopy photosynthesis.

TABLE 4. The effect of lamp type on the seed yield of soybean canopies.

	PPF ($\mu mol\ m^{-2}s^{-1}$)		
Lamp type	400	600	800
Metal Halide	90	91	83
High Pressure Sodium	100	100.	100

The data are normalized to 100% in each study. In spite of reduced chlorophyll concentrations, soybean canopies grown under HPS lamps had slightly increased yields.

RADIATION INTENSITY: INSTANTANEOUS VS. INTEGRATED DAILY PHOTOSYNTHETIC PHOTON FLUX

Daily plant growth is closely related to the daily integrated PPF (mol m^{-2} d^{-1}). Leaf emergence rates are determined by daily integrated PPF (Volk and Bugbee, 1991; Faust and Heins, 1993), and physiological and anatomical characteristics of leaves appear to be determined by the integrated rather than the instantaneous PPF. When Chabot, Jurik, and Chabot (1979) examined combinations of photoperiod and instantaneous PPF; maximum photosynthetic rate, specific leaf mass, and leaf anatomy were all determined by the integrated daily PPF; instantaneous PPF had little effect.

One of the objectives of the workshop that resulted in these proceedings was to establish guidelines for radiation intensity in controlled environments. The use of high intensity discharge lamps (HPS and MH lamps) means that full summer sunlight (50 to 60 mol m^{-2} d^{-1}) can easily be obtained in growth chambers. Although the instantaneous value of summer sunlight is about 2000 μmol m^{-2} s^{-1}, it is not always necessary to obtain this PPF level in growth chambers because the photoperiod can be extended to achieve integrated PPF levels similar to the field. A PPF of only 800 μmol m^{-2} s^{-1} during a 16-h photoperiod results in an integrated PPF of 46.1 mol m^{-2} d^{-1}, which is close to average field values for June and July in much of the northern hemisphere. Some short-day plants require a 12-h photoperiod, which decreases the integrated daily PPF in both field and controlled environments. Geographic locations and seasons (equinoxes) with 12-h photoperiods have lower daily PPF levels (35 to 40 mol m^{-2} d^{-1}), so high instantaneous PPF levels may still not be required in growth chambers. A PPF of 800 μmol m^{-2} s^{-1} with a 12-h photoperiod results in 34.6 mol m^{-2} d^{-1}.

THE PPF RESPONSE OF SINGLE LEAVES AND CANOPIES

Light response curves for single leaves are well characterized and some workers have suggested that PPF levels that saturate single-leaf photosynthesis are adequate for controlled environment studies. However, canopy photosynthesis saturates at much higher PPF levels than single leaves and PPF levels higher than 1000 μmol m^{-2} s^{-1} would be beneficial in some studies. We have found that the photosynthetic response of wheat canopies is linear up to full sunlight (2000 μmol m^{-2} s^{-1}; Meek, 1990; Figure 5).

Canopy photosynthetic efficiency at a PPF of 100 mol m^{-2} d^{-1}

The data in Figure 5 (previous page) are based on short-term (about 1-h) measurements at each PPF level, and these high photosynthetic rates may not be sustained over longer time intervals. However, our studies indicate that high photosynthetic rates are sustained in wheat canopies over a 20-h photoperiod at twice the integrated daily PPF of full summer sunlight (Figure 6).

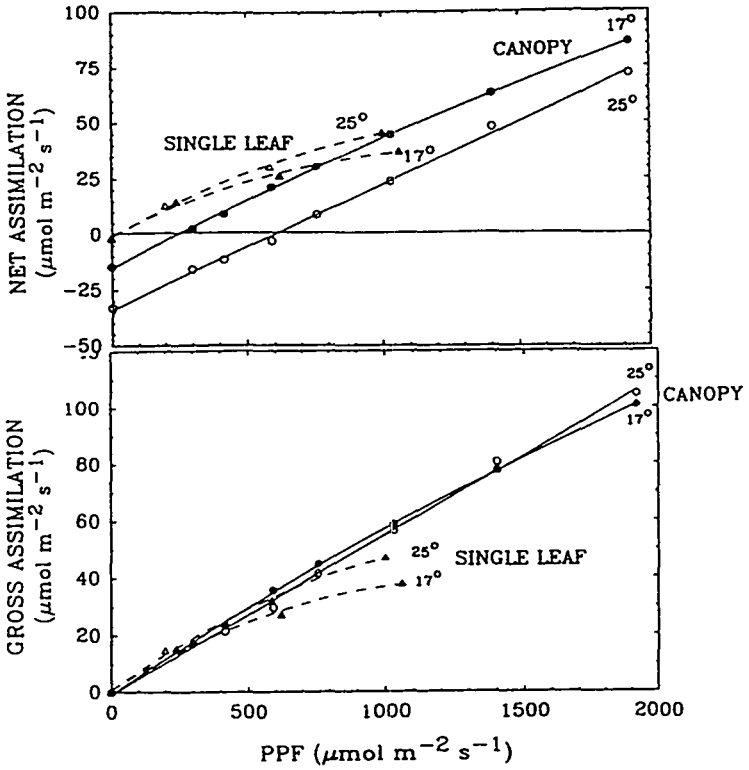

Fig. 5. The photosynthetic response of component wheat leaves and of the intact wheat canopy. The leaves light saturate at a PPF of about 1000 μmol m^{-2} s^{-1}, but canopy photosyn-thetic rate is linear, even up to the equivalent of full sunlight (2000 μmol m^{-2} s^{-1}). The canopy was grown at a constant 21 °C with elevated CO_2 (1200 μmol mol^{-1}). The photosynthetic rate of the single leaves is expressed on a leaf-surface-area basis, and the canopy photosynthetic rate is expressed on a ground or horizontal-surface-area basis. The leaf area index of the canopy exceeded 10, which results in a high dark respiration rate, a high light compensation point, and a linear response to increasing PPF.

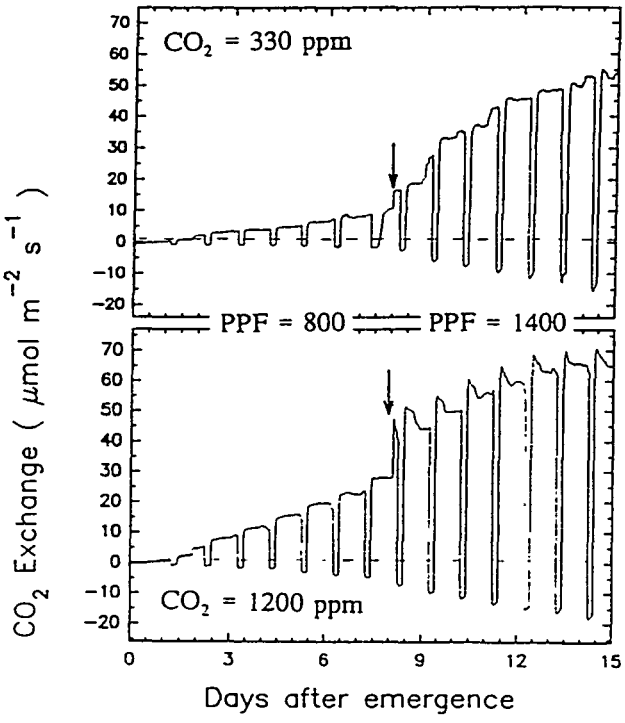

Fig. 6. The photosynthetic rate of wheat canopies grown at two CO_2 levels (ambient: 330 and saturating: 1200 μmol mol^{-1}). The arrow indicates a change in the PPF from 800 to 1400 μmol

m^{-2} s^{-1}. The photoperiod was 20-h. There was no evidence for feedback inhibition of photosynthesis, as indicated by a decreasing photosynthetic rate during the photoperiod, in any of the conditions except at the highest PPF level coupled with elevated CO_2. The magnitude of feedback inhibition gradually decreased in the days following the increase in PPF. Within about 6 days after the PPF was increased, the decrease in photosynthesis was less than 5% of the rate at the start of the light period. The daily integrated PPF at 1400 μmol m^{-2} s^{-1} was 100.8 mol m^{-2} d^{-1}, or about twice full summer sunlight. Plants were grown at a constant 23 °C day/night temperature. Data are from Monje (1993).

CONCLUSIONS

Differences in radiation quality from the six most common electric lamps have little effect on photosynthetic rate. Radiation quality primarily alters growth because of changes in branching or internode elongation, which change radiation absorption. Growth and yield in wheat appear to be insensitive to radiation quality. Growth and yield in soybeans can be slightly increased under high pressure sodium lamps compared to metal halide lamps, in spite of greatly reduced chlorophyll concentrations under HPS lamps. Daily integrated photosynthetic photon flux (mol m^{-2} d^{-1}) most directly determines leaf anatomy and growth. Photosynthetic photon flux levels of 800 μmol m^{-2} s^{-1} are adequate to simulate field daily-integrated PPF levels for both short and long day plants, but plant canopies can benefit from much higher PPF levels.

Acknowledgements

I greatly appreciate the review comments of Frank Salisbury and Tracy Dougher. The insightful editorial assistance of Kurt Gutknecht is also appreciated.

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SHORT REPORT

LIGHT PERIOD REGULATION OF CARBOHYDRATE PARTITIONING

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We have shown that the photosynthetic period is important in regulating carbon partitioning. Even when the same amount of carbon is fixed over a 24h period considerably more is translocated out of the leaf under the longer photosynthetic period. This is extremely important when parts of the plant other than the leaves are to be sold. It is also important to notice the amount of carbon respired in the short photosynthetic period. The light period effect on carbohydrate fixation, dark respiration and translocation is shown in the following table.

Length of light period (h)	Photosyn. rate (g CH_2O m^{-2} h^{-1})	Total CH_2O fixed during light period (g m^{-2})	Total CH_2O respired during dark period (g m^{-2})	Total CH_2O translocated during light period (g m^{-2})	Total CH_2O translocated over 25 h (g m^{-2})
8	0.74b	5.95a	1.56b	1.29b	3.46a
16	0.37a	5.87a	0.55a	3.32a	4.88b

Values in column followed by the same letter are not significantly different at $P \leq 0.05$ using F-test.

Experimental Conditions:

Incandescent and cool white flourescent lamps (plants were grown for 38 days under 12 hr photoperiod at 150 μmol $m^{-2}s^{-1}$. At 38 days the plants were separated into 2 groups. One group received an 8 hr photoperiod at 300 μmol $m^{-2}s^{-1}$ and a second group received a 16 hr photoperiod at 150 μmol $m^{-2}s^{-1}$)

Temperature: Day = 26° C
Night = 23° C

Humidity: 70-80%

CO_2: 350-400 ppm

Plants were grown in 10 cm pots in a peat: vermiculite: perlite mix (40:40:20 by volume)
Plants were irrigated twice weekly with half-strength Hoagland solution

Reference:

Lobendra, S. & H.W. Janes, 1992. Light Duration Effects on Carbon Partitioning and Translocation in Tomato. Scientia Horticultura 52: 19-25.

SHORT REPORT

LEAF ABSORBANCE AND PHOTOSYNTHESIS

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The absorption spectrum of a leaf is often thought to contain some clues to the photosynthetic action spectrum of chlorophyll. Of course, absorption of photons is needed for photosynthesis, but the reverse, photosynthesis when there is absorption, is not necessarily true. As a check on the existence of absorption limits we measured spectra for a few different leaves.

Two techniques for measuring absorption have been used, *viz.* the separate determination of the diffuse reflectance and the diffuse transmittance with the leaf at a port of an integrating sphere and the direct determination of the non-absorbed fraction with the leaf in the sphere. In a cross-check both methods yielded the same results for the absorption spectrum.

The spectrum of a Fuchsia leaf (fig. 1), covering the short-wave region from 350 to 2500 nm, shows a high absorption in UV, blue and red, the well known dip in the green and a steep fall-off at 700 nm. Absorption drops to virtually zero in the near infrared, with subsequent absorptions, corresponding to the water absorption bands. In more detailed spectra, taken at 5 nm intervals with a 5 nm bandwidth, differences in chlorophyll content show in the different depths of the dip around 550 nm and in a small shift of the absorption edge at 700 nm. From figure 2, showing spectra for Geranium (*Pelargonium zonale*) and Hibiscus (with a higher chlorophyll content) it is clear, that the upper limit for photosynthesis can not be much above 700 nm. No evidence, however is to be seen of a lower limit for photosynthesis and in fact, some experiments down to 300 nm still did not show a decrease of the absorption although it is well recognized that no photosynthesis results with 300 nm wavelengths.

Fuchsia leaf

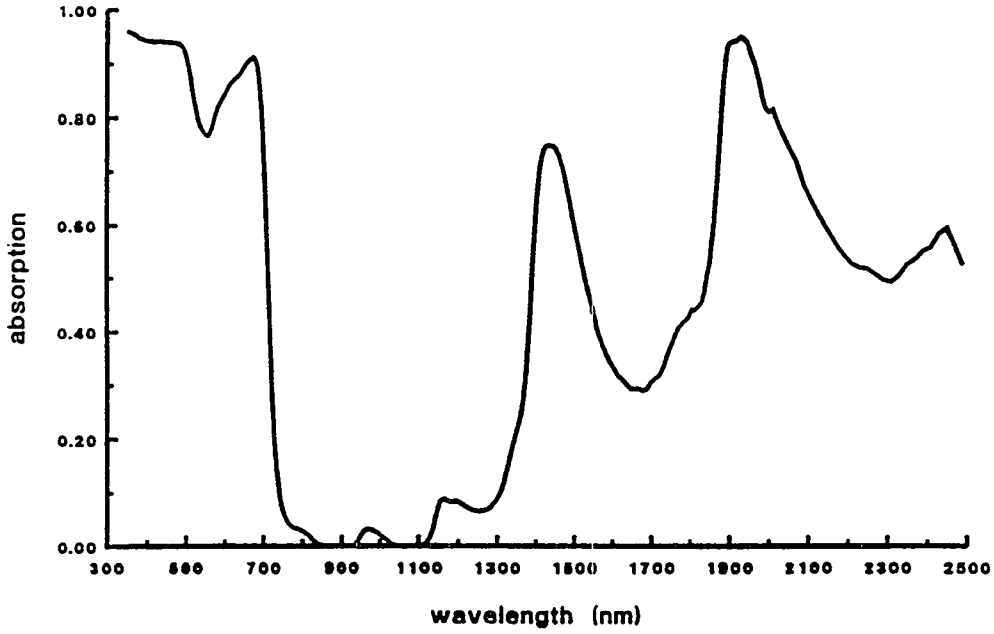
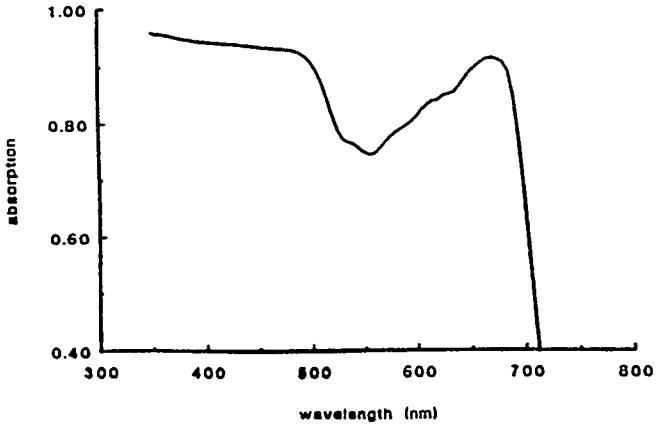


Fig. 1. Shortwave abosrption spectrum of a Fuchsia leaf

Geranium leaf



Hibiscus leaf

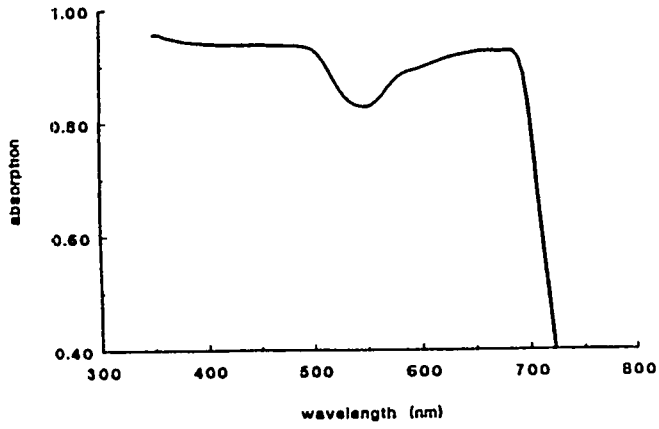


Fig. 2. Detailed absorption spectra of leaves of Geranium and Hibiscus

PLANT REQUIREMENTS

NON-PHOTOSYNTHETIC (PHYTOCHROME)

PHYTOCHROME-MEDIATED RESPONSES
IMPLICATIONS FOR CONTROLLED ENVIRONMENT RESEARCH FACILITIES

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Light is undoubtedly the most important environmental variable for plant growth and development; plants not only use radiant energy in photosynthesis, they also respond to the quantity, quality, direction and timing of incident radiation through photomorphogenic responses that can have huge effects on the rate of growth and the pattern of development. It is surprising, therefore, that the manufacturers and suppliers of controlled environment facilities have been singularly uninventive in the design of the lighting assemblies they provide. The consumer has one choice only - a lighting assembly that provides irradiance levels usually only a fraction of sunlight, and a control system that is limited to regulating the timing of the on-off switch. The reasons for these limitations are partly technological, but in the main they result from ignorance on the part of both the consumer and the manufacturer. A specific and powerful example of this ignorance relates to the importance of the so-called far-red wavelengths (FR = 700-800 nm). Because the human eye can hardly detect wavelengths above 700 nm, and photosynthesis also cuts off at *ca.* 700 nm, the majority of plant and crop physiologists are still almost completely unaware that FR radiation can have massive effects on growth rate and development. In consequence, most growth cabinets have light sources based on fluorescent tubes, and provide very little FR apart from that emitted by a token number of small incandescent bulbs. Larger growth facilities often use broader spectrum light sources, but growth facilities that provide the capability to vary the FR incident upon the plants are about as abundant as seals in the Sahara. This article sets the background of the significance of FR radiation in the natural environment and its importance for plant growth and development in the hope that it might inform intelligently those concerned with improving the design of plant growth facilities.

The Natural Radiation Environment

The daylight spectrum. The light environment experienced by plants in nature is obviously complex, but a number of generalisations can usefully be made. Solar radiation outside the atmosphere is distributed according to Planck's radiation distribution law, with the sun behaving as a blackbody emitter with an apparent surface temperature approximating 5800° K. From Wien's simplifications of Planck's radiation formulae, the wavelength of maximum quantum emission is ca 620 nm, whereas in energy terms it is ca 500 nm; radiant emission falls off sharply at lower wavelengths and more gradually at higher wavelengths. This means that about 55% of the radiation incident on the earth's surface falls within the 380-800 nm range of photochemical activity - which is fortunate, because photochemistry drives the energetic reactions of the biosphere via photosynthesis. Atmospheric components including ozone, oxygen, water vapour and carbon dioxide selectively absorb narrow wavelength bands, resulting in the typical radiation distribution of daylight at the earth's surface seen in Figure 1. This radiation distribution is remarkably constant, being affected little by clouds and other climatic conditions (Holmes and Smith, 1977a). Pathlength through the atmosphere is important, of course, and as pathlength

increases with the sun's approach to the horizon at dusk (or dawn), refraction and Rayleigh scattering (inversely proportional to the fourth power of the wavelength) gives dawn/dusk radiation distributions with relatively elevated levels of blue light, and slightly increased levels of FR compared to daylight.

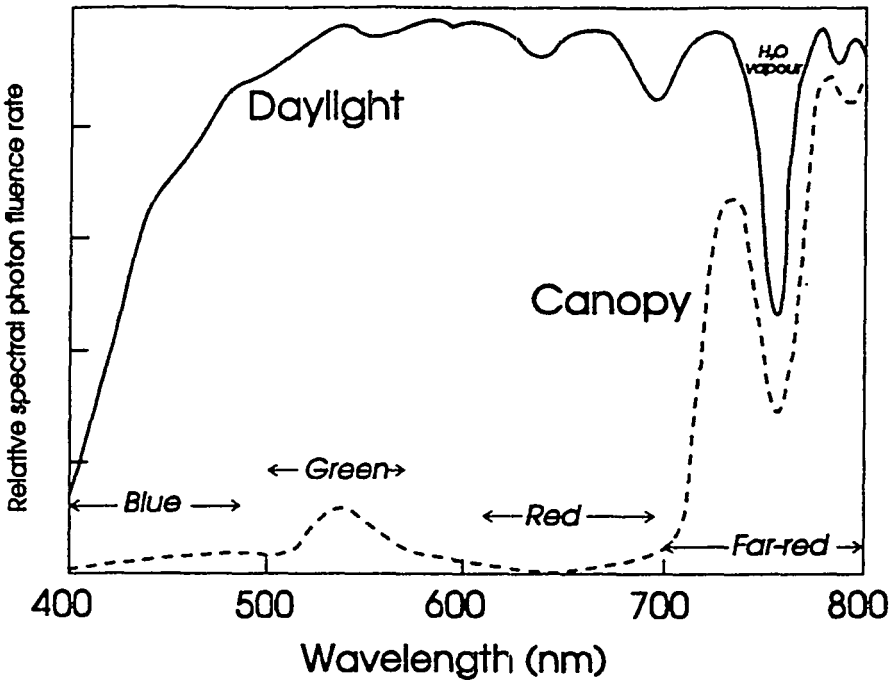


Fig. 1. The spectral distribution of daylight at the earth's surface (solid line) and under a dense vegetation canopy (dotted lines).

Underwater light. The underwater light environment is of major importance, since more than half of plant life is underwater. Refraction at the air-water discontinuity leads to the incident light from above being concentrated into a cone of half-angle 48.6°; consequently, a sensor facing upwards below, but near to the surface inevitably receives a proportion of upwelling radiation reflected back down from the surface. More important phenomena, as far as radiation distribution is concerned, are scattering and absorption by water itself, and by dissolved molecules or suspended particles. Rayleigh scattering results in the selective attenuation of the blue region of the spectrum of downwelling radiation. Water has strong absorption bands at *ca.* 730 nm and in the near infra-red, and therefore the FR is also selectively attenuated. Thus, in clear water, downwelling radiation is effectively "compressed" with increasing depth into a decreasingly narrow band of wavelengths, usually peaking at or around 500 nm. Absorption and scattering by algae, or by organic debris, causes the spectral distribution of radiation in turbid waters to be very variable.

The light environment within vegetation canopies. Ecologically, the most important fluctuations in radiation distribution occur when radiation interacts with vegetation. The photosynthetic

pigments, the chlorophylls and carotenoids, absorb radiation over almost the whole of the visible spectrum (i.e. 400-700 nm). A small fraction of the "green" radiation is either transmitted or reflected, which is why leaves are green to our eyes. What is not so immediately obvious is that vegetation hardly absorbs any radiation between 700 and 800 nm. Thus, virtually all the incoming FR is either transmitted or reflected; i.e. the FR is scattered either through the leaf, or from the surface of the leaf. Since our visual systems are very insensitive to radiation beyond ca 700 nm, we fail to recognise that leaves should look far-red, rather than green! Figure 1 shows a typical daylight spectrum within a dense vegetation canopy, and demonstrates the marked depletion of red (i.e., R, 600-700 nm) and the relative enhancement of FR radiation within canopies.

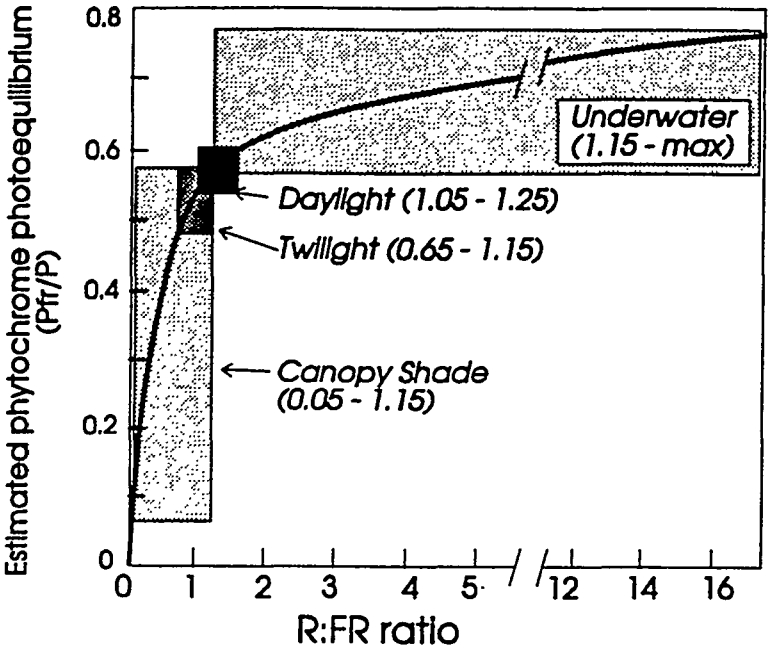


Fig. 2. The relationship between R:FR ratio and phytochrome photoequilibrium (Pfr/P). The shaded areas indicate the ranges of R:FR that are found under ecologically important conditions. Modified from Smith (1982).

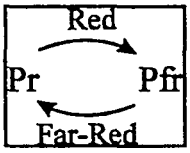
The extent to which R is depleted and FR relatively enhanced by vegetation varies, of course, with the density of the canopy and the depth of the sensor within that canopy, and direct relationships with leaf area index have been established (Holmes and Smith, 1977b). A more subtle effect of vegetation on the relative amounts of R and FR radiation depends on the direction of propagation of the radiation being measured, or perceived. Unfiltered solar radiation is propagated downwards and is highly directional; i.e., only slightly scattered. After interaction with the leaves of a vegetation canopy, multiple scattering occurs, causing the radiation to be propagated more randomly. This means that radiation propagated more-or-less horizontally within a canopy will already have interacted with vegetation and will consequently be depleted in R and relatively enriched in FR, compared to radiation within a canopy that is propagated more-or-less vertically downwards (Smith, Casal and Jackson 1990). This point has a far-reaching significance, as will become evident later.

The biological significance of the variations in the relative amounts of R and FR radiation in the

natural environment is that they provide signals of vital ecological importance. Plants have evolved a sophisticated battery of photoreceptors that enable them to sense environmental variations in R and FR and to use the information so obtained to direct appropriate alterations in metabolism, growth and development. Perception of environmental R and FR allows plants to detect the presence of neighbours, to gauge their competitive threat, and to react to actual or incipient shade by appropriate redirection of growth and development. The photoreceptors responsible for the perception of R and FR are the phytochromes.

The Phytochromes - Sensors of the Natural Radiation Environment

The Phytochrome family. The phytochromes are a family of photochromic photoreceptors each member of which consists of an apoprotein bearing a linear tetrapyrrole chromophore. Each phytochrome is capable of existing in two stable forms: Pr, which absorbs maximally at *ca.* 660 nm, and Pfr, which absorbs maximally at *ca.* 730 nm. Upon the absorption of radiation, Pr is photoconverted to Pfr, and Pfr photoconverted to Pr, according to the following scheme:



The absorption spectra of the Pr and Pfr forms of phytochrome isolated from etiolated oats show widely overlapping bands of absorption below *ca.* 730 nm, so that in broad-band radiation (such as daylight) both forms are continually photoexcited, resulting in a steady state photoequilibrium (defined as Pfr/P, where P = Pr+Pfr), in which the proportions of the total phytochrome present as Pr and Pfr are functions of the radiation distribution and of the absorption cross sections of Pr and Pfr. Since the absorption maxima are in the R and the FR, it is these wavelengths that are most important in achieving equilibrium. For this reason Smith and Holmes (1977) proposed that daylight spectra could be usefully characterised and simplified by measuring the ratio of radiation in two 10 nm wavebands centred on the absorption maxima of Pr and Pfr. Thus, the parameter R:FR, which is the ratio of the photon flux density in the 655-665 nm waveband, to that in the 725-735 nm waveband, has become the standard way of characterising daylight for photomorphogenic purposes.

There are known to be at least five members of the phytochrome family (i.e., phytochrome A to phytochrome E) in higher plants, as judged by Southern analysis of *Arabidopsis* genomic DNA (Sharrock and Quail 1989). Evidence from physiological studies of normal, mutant and transgenic *phy* gene overexpressers indicates that each member of the family probably has a distinct eco-physiological function, although functional overlap may occur under certain circumstances (Smith and Whitelam 1990). On this basis, the phytochromes represent a battery of photosensors that enable plants to obtain ecologically significant information from the light environment.

R:FR Ratio and Pfr/P. The benefit of using R:FR as a simplified parameter of the spectral distribution of natural radiation lies in the fact that R:FR can be readily transformed into a

measure of the relative proportions of Pr and Pfr present at photoequilibrium. Figure 2 shows the hyperbolic relationship that exists between R:FR (as defined above) and Pfr/P (Smith and Holmes, 1977). Using this relationship, any measured value of R:FR can be transformed to a value which represents the Pfr/P to be expected in the outer epidermis of the irradiated tissue (ignoring any light reflected or scattered back from within that tissue); the transformation is made simply by reading Pfr/P from the curve for any measured value of R:FR. The actual direct measurement of Pfr/P in light-grown plants yet eludes the advance of analytical technology, mainly because there is very little phytochrome present and its absorption is overwhelmed by that of chlorophyll. The parameter arrived at by transforming R:FR is not necessarily an accurate measure of the real Pfr/P in the tissue; it is merely a physiologically-relevant way of expressing the relative amounts of R and FR in the incident radiation. Reading Pfr/P from the curve in Figure 2 is inadvisable for artificial sources in which either the R or FR is filtered out, or for sources in which blue light (which is capable of photoconverting Pr and Pfr) predominates. Under these circumstances it is advisable to integrate the spectral photon irradiances for the 400-800 nm waveband with the extinction coefficients of Pr and Pfr and the quantum efficiencies of the Pr Pfr and Pfr Pr phototransformations. In other words, the influence of light over the whole wavelength region absorbed by phytochrome on the photoconversion of Pr to Pfr, and *vice versa*, can be calculated, resulting in a more meaningful value for Pfr/P than can be derived from R:FR. Simple computer protocols exist for this transformation.

The relationship between R:FR and Pfr/P in Figure 2 reveals three important points. First, because R:FR during the day is very constant and unaffected by weather conditions, it provides the plant with a norm against which fluctuations in R:FR due to other environmental conditions may be compared. Secondly, underwater, R:FR increases very sharply with depth of immersion, but because the underwater values of R:FR are on the asymptote of the relationship between R:FR and Pfr/P, it is clear that phytochrome would be an insensitive detector of depth underwater. Thirdly, and most importantly, small reductions in R:FR caused by vegetation shade, or the proximity of neighbours, cause relatively large reductions in Pfr/P. Thus, because shade R:FR values lie on the steep part of the hyperbolic curve, the phytochromes in principle have the capacity to be very sensitive detectors of shade.

The Phytochrome-Mediated Shade Avoidance Syndrome

The nature of shade avoidance reactions. The acclimative responses of herbaceous plants to shade from other vegetation can be viewed in terms of two extreme strategies (Grime 1979). One strategy, that of *shade tolerance*, involves relatively slow growth rates, the conservation of energy and resources, perennation usually by vegetative processes, and the development of photosynthetic structures that are especially efficient at low light levels. The opposite extreme is *shade avoidance*, a syndrome of growth and developmental changes in which extension growth is favoured at the expense of leaf and storage organ development. As the name suggests, if successful, shade avoidance has the overall effect of projecting the photosynthetic structures (usually leaves) into those parts of the environmental mosaic in which the resource of light is plentiful. Shade avoiders tend to be photosynthetically inefficient at low light levels, but have the capacity rapidly to direct growth potential from leaf development to shoot extension upon the first detection of incipient shading. Shade avoidance is an effective strategy for life in an

herbaceous community, but has limitations for herbs growing on the floor of a dense forest. The two strategies, avoidance and tolerance, are not necessarily mutually exclusive, since some plants display intermediate strategies and appear to be able to adapt to life either in open or shaded habitats, whilst other plants can exhibit shade avoidance and shade tolerance at different points in their life cycle.

Phytochrome-mediation of shade avoidance. When shade avoiding species are grown in white light to which various amounts of FR have been added, developmental responses essentially similar to those seen in natural canopy shade result (Morgan and Smith 1978, 1979; Smith 1982; Smith and Morgan, 1983; Casal and Smith 1989). Figure 3a shows the relationship between extension growth and the predicted Pfr/P for seedlings of the shade avoiding weed *Chenopodium album* grown in cabinets in which the PAR was held uniform but the R:FR was decreased by supplementation with varying flux densities of FR. This figure presents the most striking effect of supplemental FR, which is the enhanced elongation growth at low R:FR, but all the other components of the shade avoidance syndrome can be induced by such decreases in R:FR. For example, growth in WL+FR causes a major redistribution of assimilates from leaf expansion and storage organ accumulation to stem and petiole growth (Keiller and Smith 1988). It also strongly accelerates flowering (Robson, Whitelam and Smith, 1993), a phenomenon as yet little studied but potentially of considerable importance.

Thus, the induction of the shade avoidance syndrome requires the perception of the spectral changes associated with shade, rather than the changes in total light quantity. Furthermore, the linear relationship between extension rate and calculated phytochrome photoequilibrium (Figure 3a) has been shown to obtain for a wide range of species (Morgan and Smith 1979), providing convincing evidence that the perception of shade and the induction of shade avoidance responses is phytochrome-mediated. In particular, the magnitude of extension growth responses to added FR is related to the life style of the plant; i.e., shade avoiders respond strongly, whilst shade tolerators respond weakly (Figure 3b) (Morgan and Smith 1979).

Two further important characteristics of R:FR perception are its rapidity and its compensation for changes in irradiance. Using position-sensitive transducers to enable the continuous monitoring of stem extension rate, changes in extension rate caused by FR radiation applied to the growing internode via fibre-optic probes can be detected within minutes (Morgan, O'Brien and Smith 1980; Child and Smith, 1987). Furthermore, within wide limits, the extension rate is determined by the R:FR at the internode and is independent of the flux density of white light presented from above (Child and Smith 1987). These results indicate that the perception of R:FR is precisely quantitative and is compensated for variations in total irradiance. This means that, in principle, phytochrome-mediated R:FR perception should not only be able to operate at the light levels that exist within dense canopies, but should also function at the high irradiances present in sparse stands of plants that are not sufficiently close to cast actual shade. That R:FR perception does indeed occur at very high flux densitys was shown by Smith (1990) who observed strong accelerations of extension rate in mustard seedlings when exposed to high levels of FR added to a background white light in excess of 1500 μmol m^{-2} s^{-1}.

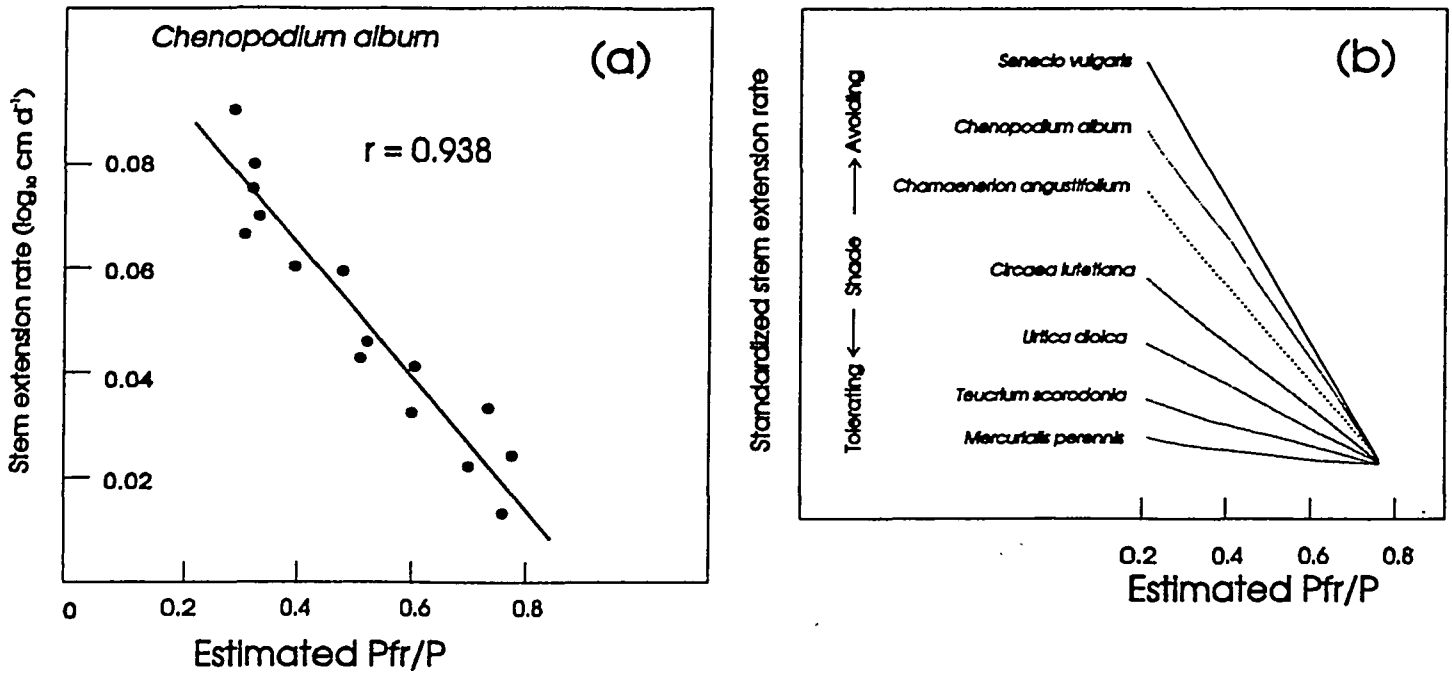


Fig. 3. The linear relationship between Pfr/P (estimated from the incident radiation spectrum) and the rate of stem extension growth. (a), data for *Chenopodium album*; (b), normalised data from a range of shade-avoiding and shade-tolerating plants. Modified from Smith (1982).

Neighbour detection and proximity perception. This latter point leads to the expectation that plants should be able to detect the FR reflected from neighbours before actual shading occurs, thereby providing for anticipation of competition for light. That this occurs in nature was suggested by Kasperbauer *et al.* (1984) in studies of soybeans grown in either north-south or east-west rows. R:FR near the top of the north-south rows of plants was lower on the west side in the morning, and on the east in the evening; indicating that the adjacent rows act as FR reflectors when the sun is low in the sky. The fact that mustard plants growing under background white light in growth cabinets react very rapidly to FR directed horizontally at the growing internodes, also indicates that plants can detect horizontally-propagated FR whilst being exposed to high R:FR light from above. Ballaré *et al.* (1987, 1990) have demonstrated direct effects of reflected FR on plant growth in the field using seedlings of *Datura ferox*, a strongly shade-avoiding herb, grown in the field close to grass screens that were either green, or bleached by being sprayed with a herbicide. The plants adjacent to unbleached, green hedges grew significantly faster than those near to the bleached hedges. *Datura ferox* seedlings, when inserted into a sparse canopy of similar seedlings not dense enough to cast actual shade, grew faster than in the open. If their growing internodes were surrounded by transparent collars containing dilute copper sulphate solution (which absorbs FR), there was no increase in growth. Thus, phytochrome-mediated R:FR perception is sufficiently sensitive to allow the detection of reflected light from neighbouring vegetation. Smith *et al.* (1990) measured the reflection signals from stands of tobacco, and also measured actual Pfr/P in samples of purified oat phytochrome exposed to the radiation reflected from the tobacco stands. These data showed that, in principle,

neighbour detection could operate over substantial distances, and that the signals progressively increased with proximity to the neighbours. In nature, therefore, plants are able to detect the FR reflected from neighbours even though the FR flux is a tiny fraction of that of the vertically propagated, high R:FR daylight. It seems that simple geometry may be responsible for this apparent paradox, as the most sensitive regions are the growing internodes which, for most shade avoiding species, are held erect, thereby receiving very little downwardly propagated radiation. On this basis, phytochrome-mediated R:FR perception provides plants with the capacity for proximity perception; in other words, plants not only can detect their neighbours, they can effectively perceive how far away they are, and therefore are able to gauge the competitive threat posed.

In summary, plants are exceptionally sensitive to the relative amounts of R and FR they receive. In nature, the shade avoidance syndrome provides plants with the capacity to adapt rapidly to the competitive threat posed by neighbours. In the controlled environment, manipulation of the R:FR ratio can give the experimenter, or the grower, impressive control over the pattern of development and the rate of growth.

Implications for the Design of Plant Growth Facilities

There are, of course, alternative ways of varying R:FR in controlled environments; one can add FR to a constant R, one can add R to a constant FR, or one can vary both R and FR simultaneously. The latter is what happens in the natural environment, but in our hands the objective has been to dissociate the phytochrome-mediated responses to varying R:FR, from any effects that might be a result of changes in photosynthetic rates caused by reduced levels of photosynthetically active radiation. Ideally, we would like to have growth facilities in which photosynthetic rate could be held uniform at high levels, whilst simultaneously varying the proportions of Pr and Pfr; for this reason we have concentrated on designing cabinets that provide a constant, uniform background of white light (and therefore constant R) whilst varying R:FR by adding FR. This approach inevitably carries a number of technical problems.

At present, no sources are available at an affordable cost that provide high irradiance FR without also emitting large amounts of longer wavelength infra red. The simplest way of producing FR is to filter the radiation emitted by incandescent sources, but these have maximum emissions at ca 900 nm or higher, and put out a great deal of radiation in the longer wave infra red. Consequently, using such sources inevitably means that one has to remove a large amount of radiant heat. Because of the technical problem of dealing with this heat, until recently we have been forced to use cabinets in which the background WL was of relatively low irradiance. In our latest designs, we have developed cabinets in which high irradiance broad-band WL can be supplied from above, with high irradiance FR being provided horizontally from sources mounted in the side walls; these cabinets were built as a direct response to the realisation of the importance of horizontally-propagated radiation.

Removal of radiant heat can only be achieved by absorption of the heat, followed by some

form of heat exchange. Our approach has been to use so-called "water windows", in which flowing water, cooled by passage through a heat exchanger, absorbs the radiant heat emitted by the incandescent lamps used to provide the FR. Following radiant heat absorption, the FR is selected by the use of Perspex (Plexiglass) filters. The design and construction of effective water-windows is by no means a trivial exercise, and when a window fails, the close proximity of gallons of water to high voltage circuitry can yield impressive pyrotechnic displays. Nevertheless, with appropriate fail-safe devices and controls, water windows can be reliable and safe, although the cost would be prohibitive for standard growth cabinets. With this approach we have been able to develop cabinets in which upwards of 500 mol m^{-2} s^{-1} FR can be added to background WL of between 150 mol m^{-2} s^{-1} PAR (old designs) and 400 mol m^{-2} s^{-1} PAR (new design). In the latest side-wall FR cabinets, we can provide 500 mol m^{-2} s^{-1} FR from the side and up to 900 mol m^{-2} s^{-1} PAR from above. The latest cabinets were designed by us and constructed to an extremely high degree of excellence by Vindon Scientific Ltd., based near Oldham in the UK. Figure 4 shows the essential features of the latest set of Vindon cabinets, and the legend includes the contact person and the address of the company.

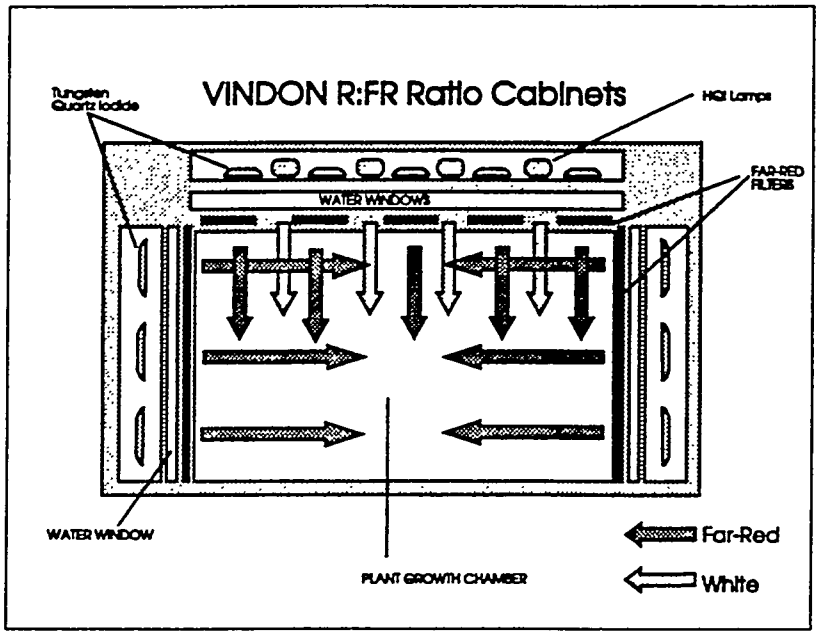


Fig. 4. A schematic diagram of a plant growth cabinet designed to provide high flux density white light from above which can be supplemented with high flux density FR radiation either from above, or from the sides. Removal of the FR filters from the upper lighting compartment provides a white light spectrum that simulates daylight reasonably well, provides a flux density of 900 mmol m^{-2} s^{-1} at 1 m from the compartment window, and has a R:FR ratio of ca 1.5. Radiant heat is removed by 'water windows', containing running water cooled by external refrigerating heat exchangers. The flux density of FR that may be supplied, either from above or the sides, is ca 500 mmol m^{-2} s^{-1}. This cabinet allows the possibility to grow plants in high flux density white light from above but to establish varying phytochrome

photoequilibria by supplementation with FR from the sides. (Further details of these cabinets may be obtained from the author, or from the manufacturer, by contacting Mr Alan Roylance, Vindon Scientific Ltd., Diggle, nr Oldham, Lancashire, UK).

Bringing water and electricity close together should, of course, be avoided. If other sources of high irradiance FR were to become available (i.e., discharge lamps, LEDs, micro-wave-driven sources, etc.) at a reasonable cost, then the design of cabinets that allow the simulation of natural R:FR ratios whilst simultaneously providing satisfactory photosynthetic rates would be simplified, and a major improvement in growth cabinet design could be contemplated. Both growers and experimenters would then be able to achieve much better control of the growth and development of their plants.

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HISTORY AND APPLICATIONS IN CONTROLLED ENVIRONMENTS

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INTRODUCTION

The widespread application of electric (often called artificial) light in greenhouses, growing rooms, and plant growth chambers would presuppose that the role of phytochrome would be considered in the selection and use of such lighting systems. Unfortunately this is not usually the case. Part of the problem is that many students, and indeed an unfortunate number of senior scientists, seem to regard phytochrome as a laboratory phenomenon without much application in the real world. They simply have not grasped the concept that phytochrome is functioning through all stages of plant development, wherever plants are grown. It is certainly true, as Meijer (1971) stated, that one cannot compare experimental results obtained under very strict laboratory conditions with plant irradiation in glasshouses and in growth rooms. For example, the action spectrum for flowering of the long-day plant, *Hyoscyamus niger*, (Parker et al., 1950) clearly shows that red radiation is the most efficient portion of the spectrum for promoting flower initiation, but in practical photoperiod control red or fluorescent lamps do not promote flowering nearly as well as the mixture of red and far-red in incandescent lamps. Nevertheless, much evidence exists that documents phytochrome control of plant growth and development in controlled environments and under natural conditions.

When Karl Norris developed the first practical portable spectroradiometer about 1962 some of the first measurements were to determine the red/far-red ratios under tree canopies (Downs and Hellmers, 1975). These measurements showed clearly the predominance of far-red in the understory and suggested that far-red was contributing to the elongation exhibited by many species growing in the shade, and possibly was a factor in the induction of light requirements in seeds. Subsequently we used Catalpa leaves as far-red filters to make light-insensitive lettuce seed light requiring. Much more detailed work, as reported in the preceding paper, has since been done on phytochrome effects in the natural environment, and it is encouraging to note that efforts are bring made to apply phytochrome research to horticulture (Decoteau, et al., 1993).

GREENHOUSES

As everyone interested in photoperiodism knows, L.H. Bailey (1891, 1892, 1893) used light from a Brush carbon-arc lamp to supplement natural light and extend the day in greenhouses. This was not; however, the first attempt to study the effects of electric light on plant growth.

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*The research reported in this publication was funded by the North Carolina Agricultural Research Service.

Carbon lamps* were used by Mangon (1861), and carbon arc lamps operated from steam or Otto gas engine driven Siemens, Grammes, or Alliance dynamos were used as early as 1853 and later by Siemens (1881), Deherain (1881), and Bonnier (1895). Prillieux (1869) investigated the effects of Drummond's lamp** and gas light used for ordinary lighting on plant growth. Later Welsbach mantle incandescent gas light lamps*** (Corbett, 1899), neon (Hostermann 1922; Roodenburg, 1933), incandescent-filament lamps (Rane, 1894; Tjebbes and Uphof, 1921; Harrington, 1926; Truffaut and Thurneyssen, 1929), and quartz mercury lamps like the Cooper-Hewitt Uviarc were used for greenhouse supplementary light. Several early researchers noted the elongating effects of the greenhouse supplementary light, especially when incandescent-carbon or incandescent-filament lamps were used (Bonnier, 1895; Massart, 1920; Ramaley, 1931). Use of the term supplementary light (to supply what is lacking) is somewhat confusing, because in many cases the supplementary light was used continuously, throughout the night (Hostermann, 1922; Harrington, 1926), or only during the dark period (Cathey and Campbell, 1975), rather than as a supplement to natural light. In these studies, at least some of the growth effects reported are surely due to a response to the extremely long photoperiods, to end-of-day photomorphogenic effects, and to root zone warming rather than to additional photosynthesis.

Using artificial light, usually from incandescent-filament lamps, for deliberate photoperiod control was initiated by Garner and Allard (1920) and was soon followed by many others. As photoperiod control became a production tool for floriculture and plant breeding, the more efficient fluorescent lamps were installed in a number of commercial greenhouses, often with unfortunate results; specifically failure or delay of flowering in long-day plants. Borthwick and Parker (1952) investigated this problem by comparing several kinds of fluorescent lamps, including special phosphor lamps, to incandescent lamps for efficiency in extending the greenhouse day to promote flowering of long-day plants. Annual beet and sugar beet flowered poorly or not at all under daylength extensions with any kind of fluorescent lamp, but flowered promptly when incandescent-filament light was used (Table 1). Although Odén, et al. (1932), Rasumov (1933), and Wenger (1934) had noted that the long wavelengths of light were necessary, or at least promotive, to normal flower stalk development, red radiation was considered the principal part of the spectrum controlling flowering. The action spectrum data probably influenced Borthwick and Parker (1952) to suggest that the much greater responsiveness of plants to light from incandescent-filament than from fluorescent lamps was because the incandescent emitted a much greater percentage of red radiation than the fluorescent lamps. A few years later, of course, it was firmly established that the far-red emittion, or the lack thereof, had a strong influence on the response of plants to photoperiod control lighting.

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*This was probably the Robert's lamp introduced in 1852 in which a graphite rod was heated to incandescence in a vacuum or later in a nitrogen atmosphere.

**Drummond's lamp, invented in 1826, heated a button of calcium oxide to incandescence. The resulting light was usually projected as a beam.

***Patented in 1886, Welsbach mantle lamps were made with a cotton wick impregnated with thorium oxide and a small amount of cerium oxide.

TABLE 1. Effect of light source on flowering of beets. (Borthwick and Parker, 1955)

Photoperiod Control Light Source	Annual Beets Seed Stalks (per lot of 20)	Sugar Beets Flower Stalks (per lot of 12)
Incandescent	19	11
Fluorescent		
Warm White	3	0
Soft White	1	0
Cool White	1	0
Daylight	2	0
Agricultural*	4	0

* Agricultural lamps emitted more red than the white lamps.

Many subsequent studies of photoperiodism compared daylength extensions obtained with fluorescent or incandescent light. Compared to fluorescent, the incandescent extension induced increased stem length in evergreen and deciduous tree species as well as herbaceous species such as tomato and soybean, promoted heading in millet, barley, and wheat, induced earlier flowering in *Hyoscyamus niger*, Petunia, dill, and other long-day species (Downs, et al., 1958; Downs and Hellmers, 1975; Vince-Prue, 1975), and produced greater pod set in *H. niger* (Table 2). Bulbing of onions was promoted by incandescent photoperiod control lighting and failed to occur when fluorescent was used (Woodbury and Ridley, 1969). Fluorescent photoperiod lighting failed to inhibit flowering of red-insensitive soybean varieties (Table 3), and when using photoperiod light to make a 13.5 h day for the most normal rate of reproduction in Ransom soybeans, incandescent lamps resulted in more pods than fluorescent lamps (Table 4).

TABLE 2. Reproduction of *Hyoscyamus niger* as affected by the source of light used to extend an 8-hour day in the greenhouse to 16 hrs.

Photo-period (h)	Light Source	Duration (d)	Stem Length (cm)	Time to Anthesis (d)	Fruit Set (%)
8	none	61	0.2	Vegetative	0
16	Incandescent	52*	42	27	66
16	Fluorescent	61*	34	36	12

* Anthesis plus 25 days

TABLE 3. Growth and reproduction of Blackhawk soybeans after 60 days under short days with various daylength extensions using incandescent or fluorescent light.

Light Regime	Stem Length (cm)	Days to Anthesis	Pods > 2 cm in Length	
			Number	Weight (mg)
9 h	37	28	27	745
20 h Incandescent	160	60	0	0
20 h Fluorescent	73	32	50	959
20 h Incandescent and Fluorescent	168	58	0	0

TABLE 4. Effect of the source of photoperiod control lighting on growth of Ransom soybeans in temperature-controlled greenhouses.

Light Source	Stem Length (cm)	Leaf Area (cm^2)	Fresh Weight (g)	Pod Number	Pod Weight (g)
Incandescent	68	4859	178.9	77	0.926
Fluorescent	42	2926	88.6	66	1.112

After the far-red reversibility of the red inhibition of hypocotyl growth in dark-grown seedlings was established (Downs, 1955), it was of interest to determine if this reversibility, and its confirmation of the activity of phytochrome, was also evident in internode growth of light-grown plants (Downs, et al., 1957). Irradiating bean plants for brief periods at the beginning of each dark period with far-red, so that the plants entered the dark period with phytochrome predominantly in the red-absorbing form, resulted in a large increase in internode length. The amount of elongation was proportional to the dark period remaining after the irradiation and was reversible by a subsequent exposure to red. Additional studies showed that what is now called 'end-of-day' far-red produced similar effects on most other bean varieties, sunflower, peanut, and morning glory. Also, end-of-day far-red promoted flowering of long-day plants, like dill, and short-day plants, such as millet (Downs, 1959) and milo (Lane, 1963), and had a marked effect on flowering of *H. niger* (Table 5). Extending the day with incandescent light is in effect providing end-of-day far-red, and the far-red effect becomes greater as the duration and irradiance of the incandescent light in increased.

TABLE 5. Effect of a long-day induction period with fluorescent light on promotion of flowering in *Hyoscyamus niger* by far-red at the close of 8-hour post-induction light periods.

10-day Pretreatment Photoperiod	Post-induction Far-red (mins)	Stem Length (mm)	Stage of Flowering
8 h	0	0	0.0
8 h	5	0	0.0
16 h	0	13	3.0
16 h	5	43	6.0

High intensity discharge lamps are now widely used in greenhouses to supplement the low natural light levels of winter (Templing and Verbruggen, 1975; Duke, et al., 1975). Some researchers also use HID lamps, especially high pressure sodium (HPS) lamps, for photoperiod control lighting to prevent dormancy and to promote flowering of long-day plants. HPS lamps, however, are reported to be much less efficient than incandescent lamps, requiring a 4 to 8 fold increase in irradiance to provide the same photoperiodic stimulus as the 1:1 red/far-red ratio* of incandescent lamps (Cathey and Campbell, 1964). In fact, the benefits of HPS supplemental light is enhanced by the addition of some incandescent lamps (Cathey and Campbell, 1977).

Today the incandescent lamp remains the chief source of light for photoperiod control because it is well established that a red/far-red ratio of 0.671** is more effective than the 7.6969 ratio from fluorescent or the 2.7 of HPS and 2.5 ratio of MH high intensity discharge lamps.

PLANT GROWTH CHAMBERS

Early attempts to use electric lamps as the sole source of light for plant growth chiefly used nitrogen-filled incandescent-filament lamps, the Mazda C lamp (Harvey, 1922; Maximov, 1925; Davis and Hoagland, 1928; Sande-Bakhuyzen, 1928; Redington, 1929; Truffaut and Thurneyssen, 1929; Stoughton, 1930; Arthur et al, 1930; Steinberg, 1931; Bracket and Johnston 1932; Johnston, 1932; Wilson, 1937; Wettstein and Pirschle, 1940), although some of these efforts utilized neon, low-pressure sodium, mercury tungsten, mercury arc, mercury vapor, or carbon-arc light, alone or in conjunction with incandescent lamps in order to increase the illuminance (Roodenburg, 1931; Johnston, 1938; Steward and Arthur, 1934; Weigel and Knoll, 1936; Pirschle and Wettstein, 1940; Ullrich, 1941; Aberg, 1941, 1943). Several of these examples where incandescent light was used noted excessive stem elongation. Roodenburg (1940) stated that near infra red produces a specific elongation effect and Aberg (1943) in noting the elongation that occurred, concluded that "*The infra-red rays of shorter*

*The red/far-red ratio of incandescent lamps is more nearly 0.67 than 1

**640-660/720-740 nm

wavelength that penetrate a layer of water 3 cm in thickness probably have a favorable effect on the internode elongation in the tomato plant."

In addition to the etiolation, a major problem with these early efforts was the low light level, equivalent to about 160 μmols m^{-2} s^{-1} and often less, generated by these lamps. In order to obtain a higher illuminance, Mitchell (1935) installed a new type, high intensity, carbon-arc lamp for respiration and photosynthesis studies. These lamps had been designed for use in hospital solaria to treat extrapulmonary tuberculosis patients. Gains made by the patients during summer exposure to sunlight were lost during winter months due to low light levels and cloudy days. Clinical sunlight, recommended at 140-160 mW m^{-2} between 290 and 310 nm, could be and was supplied by these carbon arc lamps (Grieder and Downes, 1932).

E.J. Kraus and Jack Mitchell left the University of Chicago about 1935 to join the Beltsville photoperiod project. Thus it was probably at their recommendation that the four temperature- and humidity-controlled plant growth chambers that were installed at Beltsville about 1937 were equipped with these carbon-arc lamps . Soybeans grown under the arc lamps consistently had a lower carbohydrate content than plants grown in the greenhouse. Parker and Borthwick (1949) concluded that the low carbohydrate level probably resulted from the small amount of red radiation emitted by the 'Sunshine' carbons in these carbon-arc lamps. So the following year they installed incandescent lamps that provided 8 to 10% of the illuminance of the arc lamp to provide additional red radiation. Soybeans grown under carbon-arc light plus incandescent revealed an increase in starch and sugars that could not be accounted for by the small increase in illuminance (Table 6). In retrospect it seems strange that Parker and Borthwick (1949) would attribute these gains to the increase in red due to the incandescent since a much larger increase in red obtained by using a different type carbon, .025 carbons, had very little effect. (Table 6).

TABLE 6. Carbohydrate composition of Biloxi soybeans grown for 4 weeks under a carbon-arc lamp utilizing different carbon types, with and without incandescent lamps. (Parker and Borthwick, 1949)

Carbon Type	Red %*	Reducing Sugars	Sucrose	Starch
		(mg per plant)		
Sunshine Carbons	42	32.5	6.6	39
Sunshine Carbons + Incand.	49	73.0	14.0	70
Sunshine Carbons + 025 Carbons	51	45	8.0	36

* 650 nm as percent of 450 nm radiation.

These carbon arc/incandescent lighted chambers were kept in almost continuous use for over 30 years, but operational and maintenance problems induced Parker and Borthwick (1950) in 1947 to begin planning a controlled-environment room lighted with fluorescent lamps. Several years earlier fluorescent lamps had been tested satisfactorily for plant growth (Naylor and Gerner, 1940; Hartmann and McKinnon, 1943; Hamner, 1944; Went, 1944), but the low illuminance available from these lamps was inadequate for controlled-environment rooms. The introduction of the 8 ft. slimline lamp following World War II seemed to provide a means of obtaining sufficient illumination for plant growth over relatively large areas, especially when the lamp current was increased from 200 to 300 mA. During the design phase of this room, Parker compared plant growth under slimline fluorescent with and without incandescent supplementary light. As with the carbon-arc lamp rooms, the avowed purpose of the incandescent lamps was to increase a possible deficiency of red radiation. The supplementary incandescent light resulted in an 18% increase in dry weight. Withrow and Withrow (1947) had reported that adding incandescent to fluorescent light increased yield, and later reports verified the increased growth due to added incandescent light (Dunn and Went, 1959; Helson, 1965; Deutch and Rasmussen, 1974; Cathey et al, 1978). Dunn and Went (1959) noted that the effect of adding 10% of the fluorescent illuminance with incandescent was no greater when added to red fluorescent than to blue fluorescent, concluding that *"while the most obvious explanation is that the effect is due to the infra red radiation of the incandescent lamps, it is unlikely that the far-red and infra red rays of the incandescent light was responsible* (for the increased growth) *since they would have been more effective when added to blue than to the red fluorescent light"*.

Parker planned additional experiments to evaluate the plant growth effectiveness of various kinds of fluorescent lamps, including experimental lamps with special phosphors like the Agricultural, and to examine other quantities of incandescent supplementary light. The results of these studies were never published, but when the fluorescent-lighted room was completed about 1950 it contained cool white fluorescent and incandescent lamps that provided about 10% of the illuminance of the fluorescent lamps. In order to facilitate future plant growth chamber construction, Joe Ditchman, a GE engineer assigned to biological lighting development, calculated that 10% of the illuminance of the slimline fluorescent lamps could be obtained by installing incandescent lamps at the rate of 30% of the fluorescent wattage. Due to lack of data on plant response to other levels of incandescent supplementary light, this value, 30% of the installed fluorescent watts, became a guideline for use in growth chamber design. The validity of this percentage, of course, was lost as designers increased the efficiency of the fluorescent lamp. For example about 1963, a chamber was constructed at Beltsville using 1500 mA, non-circular cross section, fluorescent lamps and, while the incandescent effect was still apparent at light levels as high as 500 μmols m^{-2} s^{-1} (Table 7), increasing the intensity of the main light source decreases the incandescent effect of the 'standard' incandescent installation. This fact was also noted by Meijer (1957) and Sanchez and Cogliatti (1975). Thus it is not surprising to find that increasing the percentage of incandescent watts increases the incandescent effect in chambers lighted with 1500 mA lamps (Krizek and Ormrod, 1980; Murakami, et al., 1991).

TABLE 7. Effect of radiation from incandescent lamps during the fluorescent light period on growth of Ransom soybeans after 32 days

Light Source	Main Axis		Branches	
	Length (cm)	Leaf Area (cm^2)	Number	Leaf Area (cm^2)
Fluorescent	77	1235	8	1993
Fluorescent plus Incandescent	93	1410	5	1622

In addition to increased plant weight (Rajan, et al., 1971; Deutch and Rasmussen, 1974; Hurd, 1974), the addition of incandescent light to the fluorescent system also resulted in increased flower weight and number of florets in Chrysanthemum, while reducing the number of days required to develop flower color (Hassan and Newton, 1975) and improved flowering of long-day plants (De Lint, 1958; Friend et al 1961; Dietzer et al, 1979). The incandescent light may also increase stem elongation, alter leaf area, and reduce branch and tiller development (Rajan, et al., 1971; Summerfield and Huxley, 1972; Proctor, 1973; Deutch and Rasmussen, 1974; Downs and Thomas, 1990; Casal, et al., 1985). Moreover, if the incandescent and fluorescent lamps are not turned off simultaneously a substantial, often undesirable, stem lengthening can occur (Table 8) that may not be recognized by many plant growth chamber users as an end-of-day far-red effect. With some plants incandescent light is essential for normal plant development (Friend, et al., 1961), but it is also clear that with other plants incandescent light is a major factor in the inability to simulate the field phenotype (Tanner and Hume, 1976).

TABLE 8. Effect of light quality for a 30 minute period after the close of the high-intensity light period on growth of tobacco seedlings.

Variety	Light Source	Stem Length (cm)	Fifth Leaf	
			Length (cm)	Width (cm)
Coker 319	Fluorescent	6.3	9.7	16.2
	Incandescent	13.7	10.0	19.7
NC2326	Fluorescent	5.7	9.0	15.8
	Incandescent	10.0	10.2	19.5

While fluorescent-lighted chambers have been constructed without incandescent supplemental light (Doorenbos, 1964), the advantages of using the incandescent to increase growth, accelerate flowering in long-day plants, control flowering in red-insensitive varieties, and

produce end-of-day far-red effects makes their addition in fluorescent-lighted plant growth chambers extremely useful and in some cases indispensable. For example tissue cultures of Loblolly pine fail to differentiate without incandescent light added to the fluorescent system.

In other cases where the incandescent supplemental light is a detriment to obtaining the growth or plant habit desired, the problem can be solved, in soybeans at least, by utilizing correct photoperiod regimes and/or using the incandescent lamps correctly (Downs and Thomas, 1990). In other examples of inadequate plant development, the incandescent lamps can be easily turned off.

HIGH INTENSITY DISCHARGE LAMPS

High intensity discharge lamps in the form of mercury or phosphor-coated mercury (sometimes called mercury-fluorescent) lamps were added to the fluorescent-incandescent system as early as 1955 (Oda, 1962). The development of similar systems by others soon followed (Leiser, et al., 1960; Yamamoto, 1970); each apparently without knowledge of the other installations. Chambers lighted solely with phosphor-coated mercury lamps also were constructed (Bretschneider-Hermann, 1964; Chandler, 1972; Smeets, 1978), but the low efficiency of these lamps limited their use. When the highly efficient metal halide lamps were introduced, plant growth chamber designers quickly incorporated them into new chambers (Nakamura, 1972; Kawarda and Shibata, 1972; Warrington, et al., 1976; Eguchi, 1986) and ultimately retrofitted them into older chambers (Downs, 1988). The further increase in light-producing efficiency achieved by the introduction of the high pressure sodium lamp about 1965 resulted in a number of trials with this light source (Downs and Hellmers, 1975). In our studies, HPS proved less than satisfactory as a sole source of light for field crop plants, but plants grew well when irradiated with a 1:1 mixture of mercury, or metal halide and HPS. In contrast to our earlier results, Smeets at Wageningen designed a 100 m^2 room with only HPS lamps that appears to provide satisfactory growth of several floricultural crops (personal observation).

Although HID lamps can provide the same irradiance as fluorescent lamps at a substantially reduced power requirement, the chief reason for using them seems to be to increase the PPFD above that normally available from fluorescent lamps. An exception is the work at the Climate Lab in New Zealand, which was primarily interested in obtaining a spectral distribution equivalent to sunlight including an appropriate red/far-red ratio (Warrington, et al., 1976; Warrington, et al., 1978), and was only secondarily interested in super high light levels. Today we see chambers being constructed with light levels equalling or exceeding peak solar radiation. The reason given for the high irradiance is usually that it is necessary for simulating field studies. It would seem that the R/FR ratio of natural light would also be a requirement for simulating field studies, but this subject is rarely encountered in arguments for artificially-produced solar irradiance levels. The spectral distributions of the tin chloride lamp, which was never produced commercially, and the Tungsram daylight metal halide containing dysporsium (Tischner and Vida, 1981) come very close to matching the natural light spectral distribution.

A question that arises frequently in the design of HID-lighted growth chambers is whether incandescent lamps should be added. Tibbitts, et al., (1987) reported that incandescent lamps had little to no effect on growth of mustard and wheat when they were added to high intensity

discharge lamps. However, there was a small but significant increase in soybean vegetative growth (Fig, 1), and Casal, et al. (1985) reported that incandescent light reduced tillering and advanced reproductive development in Lolium.

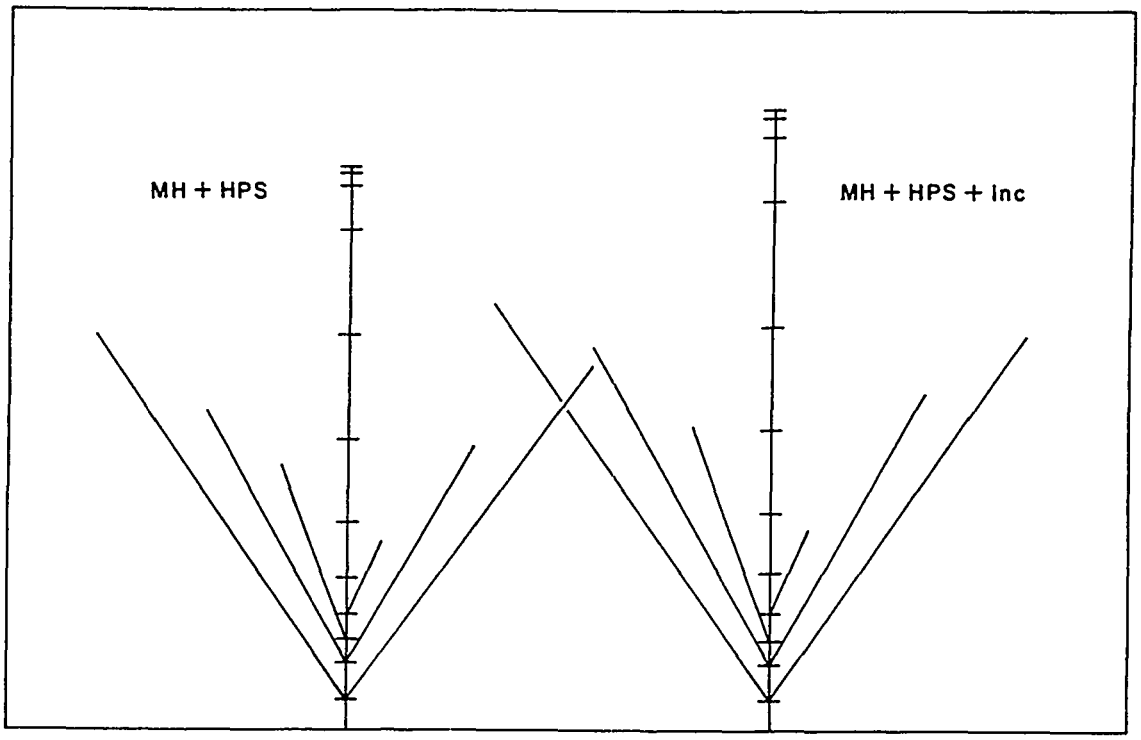

Fig. 1. Schematic of Ransom soybean growth after 30 days under a 1:1 ratio of high pressure sodium and metal halide lamps with and without incandescent.

We originally assumed that the lack of far-red effect when incandescent lamps were added to HID-lighted chambers was due to the higher HID irradiance. This is not a satisfactory explanation, however, since a marked far-red effect failed to be discernable at HID light levels comparable to fluorescent-lighted rooms (less than 500 μmols m^{-2} s^{-1}). Part of the problem seems to be that incandescent lamps provide red as well as far-red;and thus, the net increase in far-red relative to red is not as great as might be assumed. For example, the red/far-red ratio in a reach-in chamber lighted with 16, 115-W VHO fluorescent lamps was 6.684. Adding incandescent at an input wattage of 33% of the installed fluorescent watts reduced the R/FR ratio to 1.884. When we retrofitted this chamber with HID lamps the R/FR ratio was 2.526 with MH and 2.749 with a 1:1 mixture of MH and HPS lamps. Adding incandescent decreased the ratio to 1.7 and 2, respectively. These ratios are similar to those from fluorescent-incandescent systems but the far-red effect is much less.

In part, this lack of an incandescent effect can be alleviated by increasing the incandescent lamp wattage (Warrington, 1978) to equal that of the HID lamps. While a properly designed reflector and ventilation system can remove the thermal radiation from the HID lamps (Downs, 1989), the large amount of long wavelength radiation resulting from such a large wattage of

incandescent lamps makes a water filter essential. Unfortunately, the water filter is often not practical because it increases design costs and requires much more maintenance than the typical lamp loft barrier. The heat removal problem might be avoided by adding far-red without any increase in red radiation. In theory this could be done by using blue incandescent lamps which have a red/far-red ratio of 0.004 compared to the 0.671 of white incandescent ones, but in practice the far-red effect from blue incandescent lamps added to HID lamps is about the same as with white incandescent lamps.

Plants grown under HID lamps often produce abnormally short internodes, a fact observed by Warrington et al (1978), even when incandescent lamps were added. End-of-day exposures to incandescent lamps can be used as a tool to increase internode lengths to more acceptable values (Table 9). End-of-day irradiations with blue incandescent lamps, however, produce excessive elongation. (Table 10). Also, using the incandescent lamp for dark period interruptions, as an end-of-day treatment, or for daylength extensions can accelerate flowering of many long-day plants and control flowering of red-insensitive soybeans. The evidence seems to favor the addition of incandescent lamps to HID systems.

TABLE 9. Oregon 91 snapbeans grown under MH and HPS lamps with and without 30 min end-of-day incandescent irradiation.

Light Source	Stem Length (cm)	Branch Length (cm)	Leaf Area (cm^{-2})	Top Weight (g)
Incandescent	31.0	33	814	32.86
No Incandescent	11.4	19	626	25.78

TABLE 10. Seneca chief squash grown under MH and HPS lamps with 15 min. end-of-day exposures to white or blue incandescent lamps.

	Length				
Light Source	Hypocotyl (cm)	Stem (cm)	Petiole 1st Leaf	Leaf Area (cm^2)	Top Weight (g)
White Incandescent	1.6	2.7	12.8	514	26.53
Blue Incandescent	5.3	7.6	29.4	388	32.77

And thus, it is recommended that the design and construction of plant growth chambers continue to contain a provision for utilization of the incandescent lamp as part of the total irradiance system, to be implemented at the discretion of the investigator to meet the phytochrome requirements of the various biological organisms that may be grown in the chamber.

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PLANT PHOTOMORPHOGENESIS AND CANOPY GROWTH

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INTRODUCTION

An important motivation for studying photomorphogenesis is to understand the relationships among plant photophysiology in canopies, canopy productivity, and agronomic yield. This understanding is essential to optimize lighting systems used for plant farming in controlled environments (CE) and for the design of genetically engineered crop strains with altered photoresponses. This article provides an overview of some basic principles of plant photomorphogenesis in canopies and discusses their implications for (1) scaling up information on plant photophysiology from individual plants in CE to whole canopies in the field, and (2), designing lighting conditions to increase plant productivity in CE used for agronomic purposes [e.g. space farming in CE Life-Support-Systems (Bugbee and Salisbury 1989)]. We concentrate on the visible (λ between 400 and 700 nm) and far red (FR; $\lambda >$ 700 nm) spectral regions, since the ultraviolet (UV; 280 to 400 nm) is covered by other authors in this volume.

NEIGHBOR DETECTION IN PLANT COMMUNITIES

The spectral distribution of sunlight changes dramatically as the light beams interact with vegetation. Light is strongly scattered inside plant tissues, and leaf pigments absorb most of the UV and visible parts of the spectrum. In contrast, relatively few FR quanta are absorbed, and most of them exit plant organs in the form of scattered radiation. Therefore, within plant canopies the light climate is characterized by low levels of blue (B) and red (R) light (the visible wavelengths that are most absorbed by chlorphylls) and high levels of FR.

Changes in R:FR ratio are used by plants to monitor the proximity of neighboring individuals (for reviews, see Ballaré et al. 1992b, Sánchez et al. 1993, Ballaré 1994). R:FR sensing by phytochrome was originally proposed as a mechanism for the perception of leaf *shading* by seeds and plants occurring underneath vegetation canopies (Taylorson and Borthwick 1969). Thus, variations in R:FR caused by preferential absorption of R light by chlorphylls would shift the amount of phytochrome present as Pfr in plant tissues. This change in the amount of Pfr would provide a cellular signal that, being related to the degree of shading, could be used by plants in the understory to control developmental timing and morphogenesis. This idea has been supported by spectroradiometric studies in plant canopies (e.g. Kasperbauer 1971, Holmes and Smith 1977) and physiological experiments in CE (Taylorson and Borthwick 1969, Morgan and Smith 1978, Child and Smith 1987).

On the basis of field studies on the early development of seedling canopies, it was later

postulated that FR light, back-scattered by neighbors, may provide to each individual seedling an "early-warning signal" of impending competition, *before* the onset of severe shading among plants (Ballaré et al. 1987). Figure 1 shows how light scattering by plant tissues *increases* the fluence rate of FR received by vertically-oriented internodes as the leaf area index of a seedling canopy is increased, and how this spectral shift *precedes* variations in photosynthetically active radiation (PAR) at the leaf level. The ability of plants to remotely detect their neighbors using the R:FR spectral shift has now been demonstrated using a suite of experimental approaches, which involved manipulations of the light environment received by isolated plants growing under natural radiation (e.g. Ballaré et al., 1987, 1991a, Casal et al. 1987, Novoplansky et al. 1990), manipulations of the light environment in plant canopies (Casal et al. 1986, Ballaré et al. 1990), and the use of mutants deficient in R:FR sensing (Ballaré et al. 1992a, Casal and Kendrick 1993) .

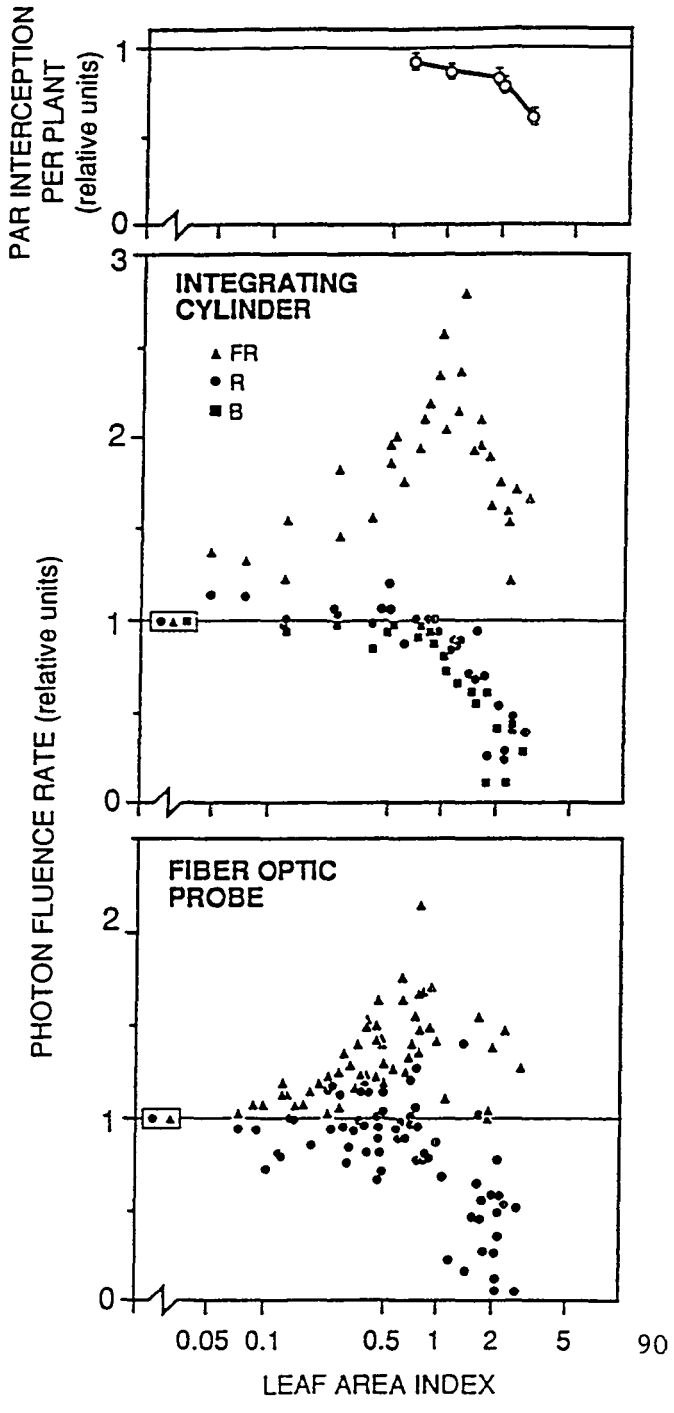

Fig. 1. Effects of increasing the leaf area index ($m^2_{leaf\ area}$ / $m^2_{soil\ area}$) in even-height canopies of dicotyledonous seedlings on light interception by leaves (top) and the light climate of the stems. The integrating cylinder collects sidelight received by the stem surface; the fiber optic probe collects light scattered within the stem tissue. All values are given relative to the measurements obtained for isolated plants or for leaf area index ≈ 0 (boxed symbols). *Abbreviations*: B, blue; FR, far-red; PAR, photosynthetically active radiation; R, red. (From Ballaré 1994; original data in Ballaré et al. 1991b.).

Changes in photon fluence rate can also convey information about the proximity of neighbors in plant canopies. For plants growing underneath other vegetation, a change in the leaf area index of the canopy will cause variations in irradiance that plants may use as an input signal for the systems that control shade acclimation at different levels, from chloroplast physiology to whole-shoot

allometry (e.g. Blackman and Wilson 1951, Björkman 1981). Moreover, changes in light fluence rate may also work as early proximity signals in even-height canopies of broadleaf seedlings (Ballaré et al. 1991a), because fluence rate sensed by vertically-oriented stems is more affected by changes in canopy density than the light climate of horizontal or diaphototropic leaves (Fig. 1).

Plants can "measure" fluence rate in two ways: (1) indirectly, by sensing changes in the availability of photosynthetic products (sugars), or (2) more directly, by sensing molecular signals closely related to the photoexcitation of the chloroplast photosystems or other photoreceptors (e.g. B-absorbing photoreceptors and phytochromes). Morphological responses to sucrose levels have been demonstrated (Montaldi 1969, Casal and Sánchez 1992) and changes in ATP and NADPH production (caused by variations of light intensity) may elicit changes in photosystem stoichiometry and organization, with consequences on photosynthetic capacity have been reported (Chow et al. 1990). Morphological responses to irradiance changes sensed by phytochrome (Ballaré et al. 1991a) and a B-absorbing photoreceptor (Britz 1990) have been extensively documented in studies with de-etiolated plants grown under high PAR. Experimental evidence supports the notion that plants growing in canopies use fluence rate signals perceived by these photoreceptors in the process of neighbor detection, and respond with morphological changes that presumably improve their light-harvesting ability in crowded populations (see below).

INFORMATION AND VEGETATIVE MORPHOLOGICAL DEVELOPMENT

Plants have evolved molecular mechanisms that use information about the canopy light environment, obtained through photoreceptors, to "decide" among alternative developmental programs. In this section we will briefly consider developmental photoresponses that involve changes in: (1) the rate of growth in height, and (2) the direction of vegetative spreading.

Reductions of R:FR promote stem elongation rate. This has been demonstrated for plants that received low levels of visible light (ca. $\leq$ 10 % of full sunlight, Kasperbauer 1971, Morgan and Smith 1978, Child and Smith 1987), and plants grown under natural radiation supplemented with FR provided by selectively-reflecting mirrors (Ballaré et al., 1987, 1991a). Manipulative experiments with even-height canopies of seedlings have shown that the reduction in R:FR of the scattered radiation that impinges laterally on the internodes (Fig. 1) can trigger an increase in elongation rate, even if most of the leaf area is exposed to full sunlight (Fig. 2; Ballaré et al. 1990). Although direct evidence is still lacking, most of the physiological data suggest that the decrease in fluence rate experienced by plant stems when the canopy begins to close (Fig. 1; leaf area index $\geq$ 1) does elicit an increase in elongation rate before shading at leaf level becomes significant (Ballaré et al., 1991a). The increase in elongation rate triggered by R:FR and fluence-rate signals is almost certainly beneficial for the individual plant, because, in a rapidly growing canopy, a small difference in height would imply an inordinately large difference in PAR harvesting (e.g. Ballaré et al., 1988).

As they grow in a heterogeneous canopy, plants can acquire information about the *spatial distribution* of their neighbors using fluence rate and R:FR signals perceived by phytochromes

and B-absorbing photoreceptors. Irradiance gradients elicit phototropic movements of plant leaves (Koller 1990) and stems (Iino 1990), which presumably increase the light harvesting capacity of plant shoots in horizontally patchy canopies. Novoplansky et al. (1990) suggested that seedlings of the plageotropic herb *Portulaca oleracea* use alterations in the R:FR ratio of

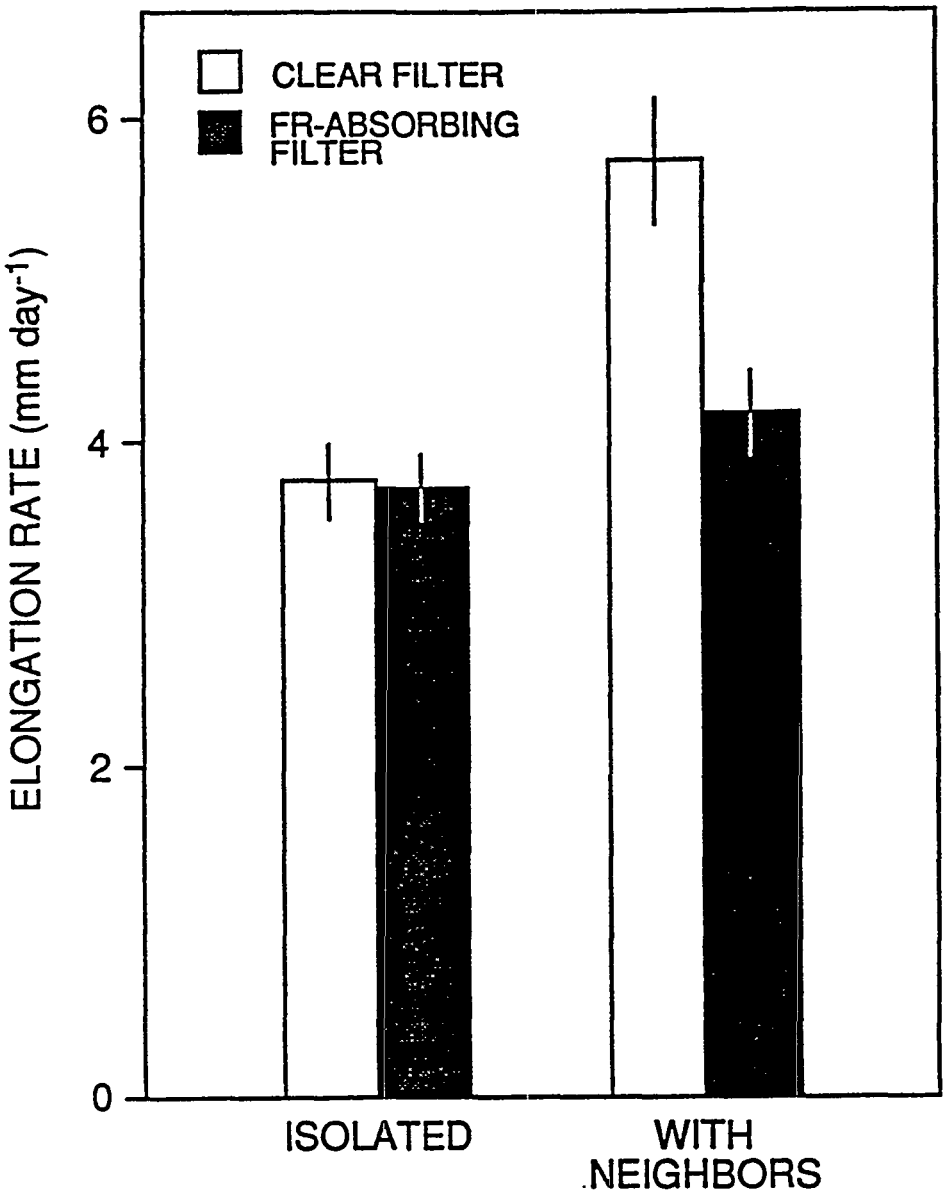

Fig. 2. Elongation responses of *Datura ferox* first internodes when seedlings were placed in the center of an even-height canopy of leaf area index ≈ 0.9 under natural radiation. During the experiment, which run for 3 days, the internodes were surrounded by annular cuvettes containing distilled water (clear filter) or a $CuSO_4$ solution that absorbed FR radiation and maintained the R:FR ratio at ca. 1.1 (FR-absorbing filter). (Adapted from Ballaré et al. 1990.).

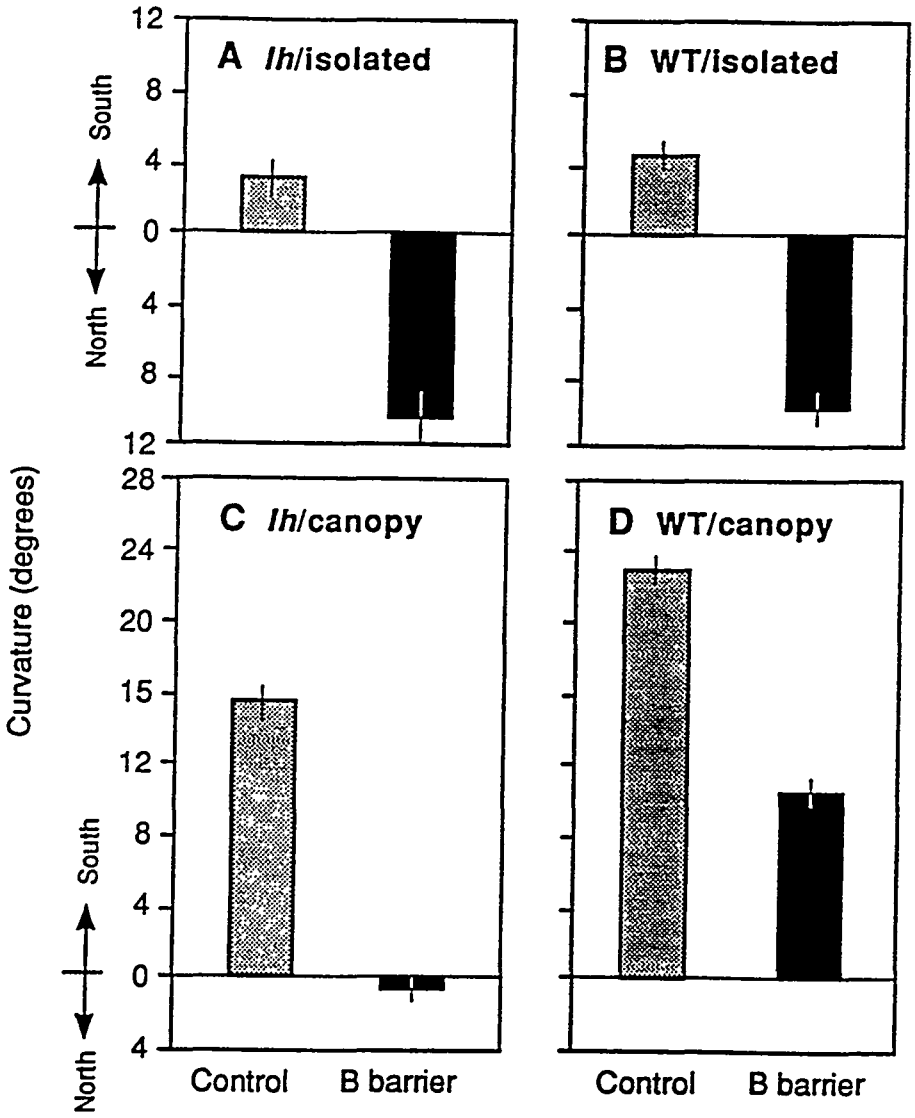

Fig. 3. Effects of the proximity of a green maize canopy and B-absorbing acetate filters (B barrier) on the orientation of the hypocotyls of WT and *lh*-mutant seedlings. Seedlings were grown in the field for 2 days at the center of a clear plot (isolated) or 8 cm to the south of the edge of a dense maize crop (canopy). Seedlings of the *lh*-mutant do not present phototropic responses to R:FR gradients, but display normal phototropism in response to B light. All the southward (i.e. "neighbor-avoiding") bending induced by the nearby maize canopy can be abolished by eliminating the B light irradiance gradient created by the presence of the canopy (cf. Control vs. B barrier in panel C). Compared with *lh* seedlings, WT seedlings display more intense bending in response to the proximity of the maize canopy, and a significant proportion of this bending cannot be accounted for by phototropic responses to B light gradients (cf. Control vs. B barrier in panel D). (From Ballaré et al. 1992a).

the scattered canopy light to effectively avoid their neighbors. Their manipulative physiological experiments under natural sunlight have supported this hypothesis. Ballaré et al. (1992a) have shown that cucumber plants use the phytochrome system and a B-absorbing photoreceptor to remotely detect their neighbors and to elicit stem bending responses toward canopy gaps (Fig. 3).

Apart from being able to use light signals in the control of vegetative morphogenesis, plants appear to have evolved mechanisms to relay information about the canopy light environment into systems that control reproductive allocation. The potential agronomic significance of this aspect of plant photomorphogenesis has been discussed (Ballaré et al. 1992b; Sánchez et al. 1993), and will not be covered in this article.

CONSEQUENCES AT THE POPULATION LEVEL

Very little is known about the consequences of the photomorphogenic behavior of individual plants at the *population-level* (e.g. Schmitt and Wulff 1993, Ballaré 1994). A common belief is that most plant responses to proximity signals (teleologically called "shade-avoidance responses") are selected through evolution because they confer an advantage to the individual plant, but that they would have normally a *negative* impact on canopy productivity or crop yield. On the basis of this idea, the need of eliminating these responses has been voiced by a number of authors. Two avenues have been proposed to accomplish this goal: (1) to artificially increase the R:FR ratio received by the canopy (in CE), and (2) to engineer photomorphogenically "blind" plant cultivars. In this section we will briefly discuss the likely implications of elongation and tropic photoresponses for *whole-canopy productivity.*

Exposure to low R:FR ratios normally results in plants having long internodes and low leaf-to-stem dry weight ratio (LSR) (e.g. Morgan and Smith 1978). One interpretation of the change in LSR is that the low R:FR triggers, through phytochrome, a *re-distribution* of C, away from the leaves and toward the stem. According to this view, stem growth responses to reduced R:FR may negatively affect canopy yield, by taking up C that would otherwise be allocated to leaves, the main light-harvesting organs. Most of the evidence obtained from experiments under relatively high irradiances is not consistent with this hypothesis. The most significant findings of these experiments are the following (Ballaré et al. 1991b). (1) The amount of C allocated to stem growth is, at least for young herbaceous plants, a relatively small percentage of the total C budget. (2) A localized reduction of R:FR at the stem level can increase internode elongation rate by a factor of two and dry mater accumulation in the stems by 40% *without* having any negative impact on leaf or root growth. In fact, total plant biomass can be increased by a localized R:FR treatment, presumably through a feedback control over photosynthesis. (3) If whole canopies are grown under extremely high R:FR ratios, which nearly eliminate elongation responses to neighbor proximity, stem dry matter accumulation is reduced, but without yielding any proportional increase in leaf or root growth (Fig. 4). In summary, the C saving benefits of abolishing stem growth responses to neighbor-proximity signals are likely to be very small or nil.

We have discussed in the preceding sections how sensing of radial R:FR gradients allows plants to monitor the spatial distribution of their immediate neighbors. This information, acquired through phytochrome, triggers phototropic responses that presumably optimize shoot geometry and spreading as a function of the spatial distribution of light gaps in the canopy. For instance, long-term experiments in the field have shown that wild-type cucumber plants are much more efficient at deploying leaf area into gaps than plants of an isogenic *lh* mutant that lack immunochemically-detectable phytochrome B. Shoot geometry and space occupation are mayor determinants of whole-plant C-assimilation (e.g. Küppers, 1994). Therefore, if we move up in scale one step, i.e. from single shoots to a shoot population, the inference would be that phototropic responses, triggered by R:FR gradients, are likely to be an important

component of the mechanisms that allow the growing canopy to efficiently "fill-up" the aboveground space. In other words, at each point in time during canopy development, phototropic responses of individual shoots would increase light interception per unit of canopy leaf area.

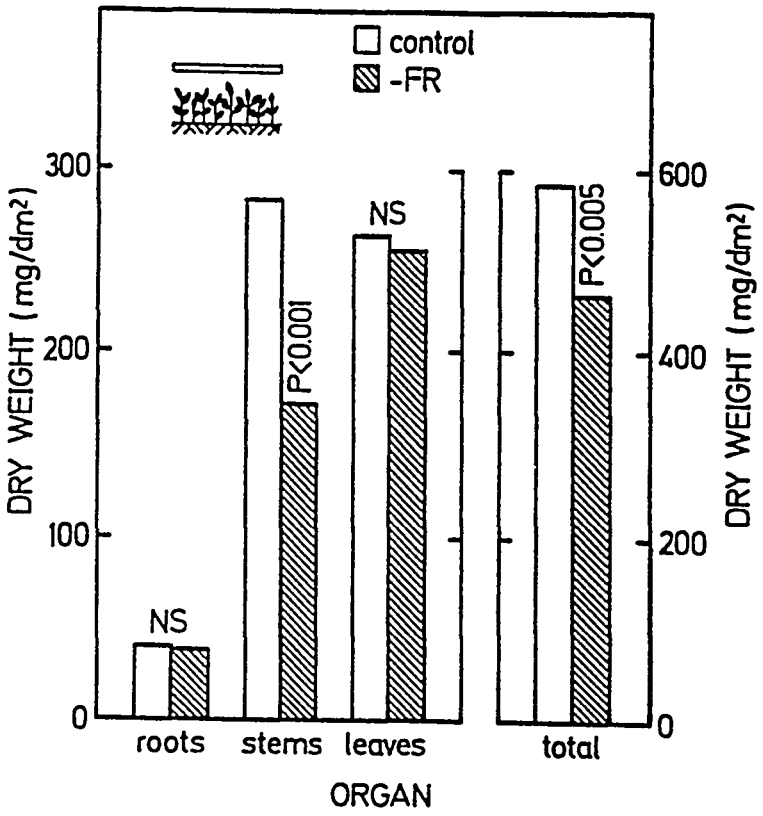

Fig. 4. Effect of filtering out the FR wave-band from the light received by canopies of amaranth (*Amaranthus quitensis*) on canopy growth and dry matter allocation. FR was filtered using cuvettes containing $CuSO_4$ solutions (see diagram upper left). This treatment increased the R:FR received at the top of the canopy from 1.1 (control; cuvettes filled with water) to 17.4 (-FR), and effectively reduced stem elongation. The bars indicate biomass present in the various organs after two weeks of treatment. The level of significance is indicated for each difference; NS = not significant (P>0.05). (Adapted from Ballaré et al 1991b).

Most studies on canopy photomorphogenesis have focused on the *average* response of the components of a population, not on the variability among individual plants. Yet information on the latter is important if the goal is to predict the population-level consequences of plant photophysiology. The development of *size* (dry weight) *inequalities* among neighbors is one of the best characterized population responses to increased plant density (number of plants per unit area) (Harper 1977, Weiner 1985). Because reproductive output and size are often positively correlated within plant populations (e.g. Thompson et al. 1991), understanding the determinants of size variability is of fundamental importance for ecologists (Weiner 1985, Weiner et al. 1990) and growers (Harper 1977, Benjamin and Hardwick, 1986). Transgenic tobacco plants that express an oat phytochrome gene (*phyA*) under control of the CaMV35S promoter and display altered photophysiology have been recently used to test the role of light

sensing in the genesis of size inequalities in plant populations (Ballaré et al. 1994). Compared with the isogenic wild-type, *phyA*-overexpressing plants showed dramatically reduced morphological responsivity to changes in the R:FR ratio of the incident light, and to the proximity of neighboring plants in spacing experiments. In transgenic canopies an increase in stand density caused the small plants of the population to be rapidly suppressed by their neighbors (Fig. 5). In wild-type canopies, plants responded to increased density with large morphological changes, and there appeared to be an inverse relationship between the magnitude of this morphological response and the ranking of the individual plant in the population size hierarchy (not shown). In these wild-type populations, size inequality increased only moderately with density within the time frame of the experiments (Fig. 5). These results suggest that, in crowded stands, the ability of individual plants to acquire information about their light environment via phytochrome plays a central role in driving architectural changes that, at the population level, delay the development of size differences between neighbors.

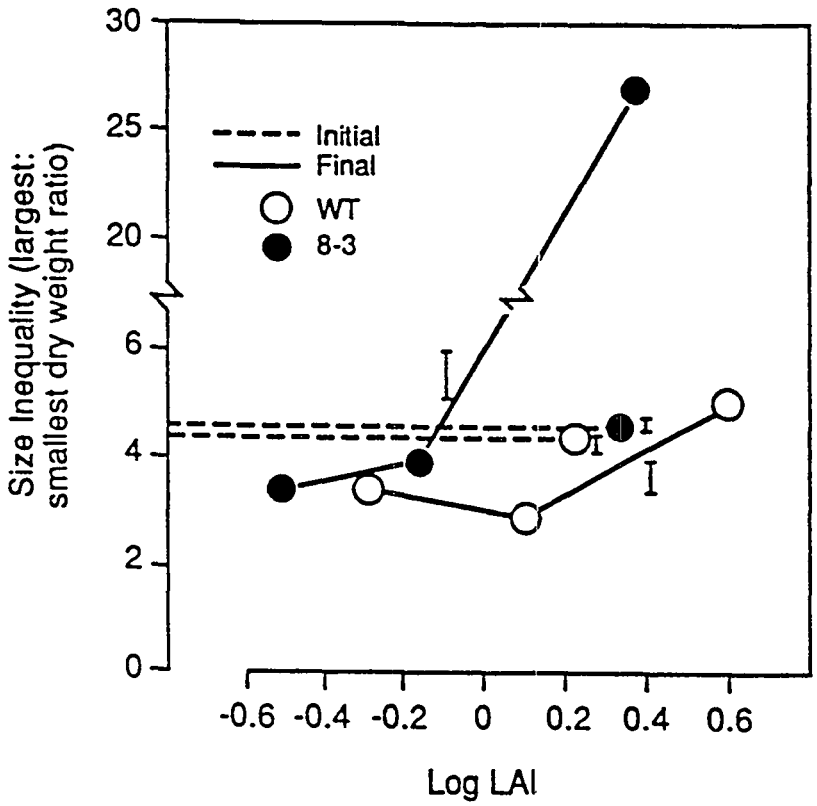

Fig. 5. Effects of increasing population density on the development of size inequalities among neighbors in monocultures of WT and 8-3 transgenic tobacco plants. Bars indicate $\pm$1 SE; n=5 (final) or n=15 (initial) replicate canopies. Dry weights were measured after 30 days of growth; data are plotted against the leaf area index (LAI) estimated for the 15th day. Initial inequality was within $\pm$ 15 % of the plotted average (dashed line) in all density treatments. (From Ballaré et al. 1994).

In summary, although very little is still known from studies under realistic levels of PAR, the evidence discussed in this section suggest that, contrary to the ideas currently on fashion, interfering with the normal traffic of light signals between neighboring plants (e.g. by using extremely high R:FR ratios), or with the plants' information-acquiring systems (e.g. by breeding photomorphogenically "blind" genotypes), is unlikely to result in an increase of canopy net *primary productivity*. The impact of such manipulations on harvestable yield is difficult to predict, mainly because of uncertainties regarding photomorphogenic controls of developmental timing (e.g. Mondal et al. 1986) and reproductive allocation (e.g. Heindl and Brun 1983). However, to the extent that size structuring compromises yield and yield uniformity, the available data suggest that elimination of plant photomorphogenic responses in canopies will result in reduced agronomic productivity.

IMPLICATIONS FOR LIGHTING IN CONTROLLED ENVIRONMENTS

Light conditions differ between controlled and natural environments in many regards, including: daily time course of irradiance changes, spatial distribution of the light field, total irradiance, and spectral balance. In this section we concentrate on the latter two aspects (total irradiance and spectral distribution). We will use some of the concepts developed earlier in this article to discuss how the use of unnatural irradiances and spectral distributions may affect (1) whole-canopy growth, and (2), the likelihood that results obtained in the CE may be properly extrapolated to the field situation.

Low Light Levels

Lighting fixtures in most CE, particularly in old designs, provide PAR irradiances that are between one twentieth to one half of the peak PAR in a clear summer day. This low PAR of course will limit canopy growth by limiting photosynthetic rates (e.g. Geiger, this volume). But in addition to the growth limitation, several aspects of plant morphogenesis are be altered by the use of low irradiances (e.g. Blackman and Wilson 1951). Of particular importance within the context of this article is the *interaction* between low PAR levels and proximity responses elicited by light signals. In the foregoing sections we have discussed evidence that changes in fluence rate may signal encroaching vegetation to plants growing in sparse canopies. Morphological responses to fluence rate, although readily observable under high light conditions (e.g. Ballaré et al. 1991a) have not been consistently detected in CE studies under low PAR (e.g. Child and Smith 1987). Of course there are many possible explanations for the differences between CE and field studies, and a complete treatment of this subject is far beyond the scope of this article. But, in principle at least, there are good reasons to suspect that the use of low background light levels in CE is in itself a major complicating factor in studies of photomorphogenic responses to total irradiance. In the same vein, the use of low PAR levels in CE might contribute to artificially *inflate* the opportunity cost of stem growth responses to low R:FR ratios. Thus, plants growing in the field might be able to compensate the increased C demand of rapidly elongating internodes with a slight increase in leaf photosynthesis, whereas plants that are already limited by light may be more likely to rely on re-distribution of their short supply of carbohydrates. Finally, under extremely low PAR levels, the extent of the response to R:FR may be affected, presumably as a consequence of assimilate limitations (Smith and Hayward 1985). Low light levels are also likely to

accentuate the development of size hierarchies within the population (i.e. increase the coefficient of variation of dry weight per plant) (Schmitt et al. 1986), with potential negative consequences for yield and yield uniformity.

High R:FR Ratios

Fluorescent tubes and high pressure sodium vapor lamps are popular PAR sources in CE, and both provide R:FR ratios several times higher than sunlight. Due to the spectral properties of Pr and Pfr, changes in R:FR above ca. 1.5 do not cause a proportional change in the phytochrome photoequilibrium (Smith and Holmes 1977). Therefore, the R:FR-based neighbor detection mechanism is likely to be distorted or disabled when canopies are grown under extremely high R:FR ratios. Some experimental evidence for this idea has been provided by studies with amaranth, in which $CuSO_4$ filters were used to increase the R:FR ratio of the light received by the canopies and reduce stem elongation. These studies have shown that very high R:FR ratios result in decreased (rather than increased) canopy net productivity. It is not clear whether this decrease is caused by (1) the elimination of an active sink of assimilates (i.e. the growing internodes), a change in the pattern of light penetration through the canopy (see below), or a combination of the two. In any case, these results appear to directly contradict the notion that canopy growth at high densities is limited by the diversion of photosynthate to "shade-avoidance" responses. Of course, the use of artificially high R:FR ratios may be a convenient way to obtain short-statured plants in CE, which may be desirable for many crops grown for horticultural or ornamental purposes (McMahon and Kelly 1990, Rajapakse and Kelly 1992).

Another predictable consequence of the use of extremely high R:FR ratios in CE is the elimination of phototropic responses triggered through phytochrome. Since these responses may play a role in the dynamics of gap-filling by the canopy, it is suggested that the increase in light interception over time (and therefore canopy growth) will be slowed under very high R:FR. Of course, the extent of this retardation would depend upon (1) the quantitative importance of phototropic responses in gap-filling by the shoot population, and (2), the extent to which phytochrome and B-absorbing photoreceptors play redundant roles in controlling phototropic responses in canopies.

Finally, very high R:FR, which disable the phytochrome-mediated mechanism of neighbor etection, will almost certainly result in increased size structuring in dense plant populations. From a plant grower stand-point the establishment of a strong size hierarchy in the population might have two negative consequences: reduced total yield at high densities and reduced yield uniformity.

ACKNOWLEDGEMENTS

Some of concepts stemmed from work supported by the Consejo Nacional de Investigaciones Científicas y Técnicas, the Antorchas Foundation (Argentina), and the Dept. of Forest Science, Oregon State University (USA). This support is gratefully acknowledged.

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PHYTOCHROME, PLANT GROWTH AND FLOWERING

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INTRODUCTION

Attempts to use artificially lit cabinets to grow plants identical to those growing in sunlight have provided compelling evidence of the importance of light quality for plant growth. Changing the balance of red (R) to far-red (FR) radiation, but with a fixed photosynthetic input can shift the phytochrome photoequilibrium in a plant and generate large differences in plant growth. With FR enrichment the plants elongate, and may produce more leaf area and dry matter (see Smith, 1994 these proceedings). Similar morphogenic responses are also obtained when light quality is altered only briefly (15-30 min) at the end-of-the-day (Ballare 1994; these proceedings). Conversely, for plants grown in natural conditions the response of plant form to selective spectral filtering has again shown that red and far-red wavebands are important as found by Kasperbauer and coworkers (Kasperbauer, 1992). Also, where photosynthetic photon flux densities (PPFD) of sunlight have been held constant, the removal of far-red alone alters plant growth (Mortensen and Stromme 1987; McMahon *et al.*, 1991). As shown in Table 1 for chrysanthemum, with FR depletion plants grown in sunlight are small, more branched and darker green. Here we examine the implications for plant growth and flowering when the far-red composition of incident radiation in plant growth chambers is manipulated.

TABLE 1. Influence of filtered sunlight on growth and flowering of chrysanthemum cv Yellow Mandalay in long days of summer. Adapted from McMahon *et al.* (1991).

Filter	R:FR	Pfr:Ptot	Plant Height (cm)	Leaf Chlorophyll (g cm^{-2})	Leaf Number	Visible Flowering (days)
Red	1.16	.71	30.3**	36.7	22	~ 52
Blue	0.99	.66	29.3	39.5	21.6	~ 52
Far-red	3.3	.79	16.9**	55.4**	17.1**	46-49
Control	1.16	.71	28.6	39.8	21.5	~ 52

Significant differences; * p = 0.05 or ** p = 0.01 *vs* control
R:FR ratio 655-665 nm *vs* 725-735 nm
Pfr:Ptot calculated over 350 to 850 nm

FAR-RED ENRICHMENT AND PLANT GROWTH IN ARTIFICIALLY LIT CHAMBERS

As with spectral filtering of sunlight, differences in the R:FR ratio of light in growth chambers can lead to large effects on growth (Figs 1, 2). Here PPFD was held constant across the two chambers (560 mols $m^{-2}s^{-1}$) and there were no major thermal differences, leaf temperatures across the chambers being within 1 to 2°C. Thus, the greater stem elongation with mixed metal halide/quartz halogen versus fluorescent lamps (Fig. 1) can be most simply explained as a phytochrome mediated response to FR enrichment. This FR-induced change was not driven by photosynthesis as stem elongation increased rapidly especially in sunflower (< 1 week, Fig. 1) and preceded by 1-2 weeks any increase in dry matter accumulation and leaf area production. To reiterate, there was firstly a change in plant form (Fig. 1), then later a change in dry weight indicating an initial photomorphogenically-driven increase in leaf area with subsequent photosynthetic increase, a conclusion suggested by Smith and coworkers from their studies over the last decade (see Smith 1994). On the other hand, photosynthetic capacity and/or leaf assimilate export could respond directly to FR enrichment. Chow, Anderson and coworkers have reported many FR effects on photosynthetic light harvesting pigment components particularly of young pea seedlings and these responses can result in slightly increased CO_2 exchange rates per unit leaf area (Chow *et al.*, 1990).

Surprisingly large effects on dry matter allocation to roots were observed as a consequence of FR enrichment (see Figure 2). Root growth has not always been measured in these types of experiment (e.g. Tibbitts *et al.*, 1983) but there could also be a trivial explanation for the data summarized in Figure 2. Greater dry matter allocation to the roots was evident only at the last (week 4) harvest. For tomato, for example, the root:shoot ratio doubled to 0.53 over the last week of growth in FR-enriched conditions whereas in the R-rich cabinet it remained at ca 0.3. However, this dry matter reallocation occurred when total dry matter was also increasing exponentially. Thus, the rapid increase in leaf assimilate supply may have temporarily exceeded stem demand leading to a shunting of assimilate to the roots and a transient shift in the root:shoot dry weight balance in FR-enriched conditions. Further studies are needed of responses of roots to FR-enriched conditions especially since our findings with tomato are the opposite of those noted earlier by Kasperbauer (1992) where only end-of-day light quality was altered.

Although sunflower and tomato grew optimally in FR-enriched conditions (Fig. 2) wheat was rather insensitive (Figs. 1,2) as also found for wheat by Tibbitts *et al.* (1983). The slower growth of the eucalypt (Fig. 1) may have masked positive responses. However, there was a significant reversal of response compared to other species in that FR-enrichment led to the formation of fewer leaves (61.2_3.5 *vs* 91.7_10.0) and branches (7.8_0.8 *vs* 13.2_1.5). This data for eucalypt requires confirmation but large differences in sensitivity to FR between species have been reported previously (Tibbitts *et al.*, 1983 and see references therein).

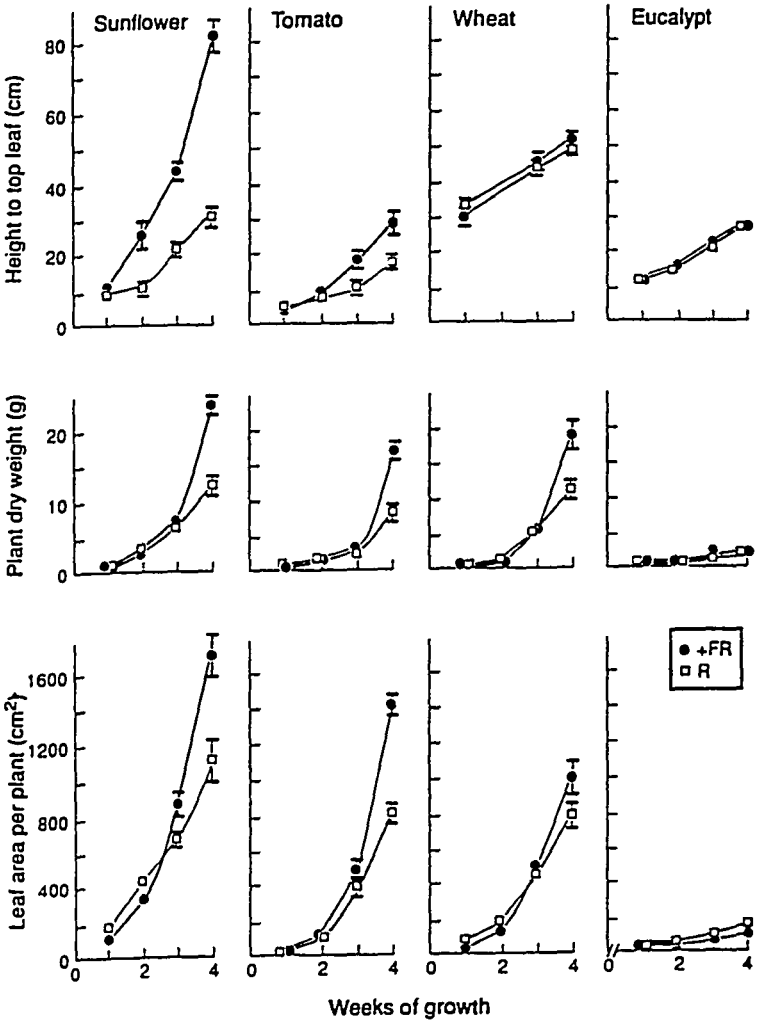

Fig. 1. Growth in height, plant dry weight and leaf area of 4 plant species over 4 weeks of exposure to FR-rich (●) or R-rich (□) lamps. Irradiance 560 mol $m^{-2}s^{-1}$ of photosynthetically active radiation (PAR). The ratios of R:FR (660:730 nm) were FR=1.53 R=5.08. Daylength was 12-h with a day:night temperature of 21:16°C.

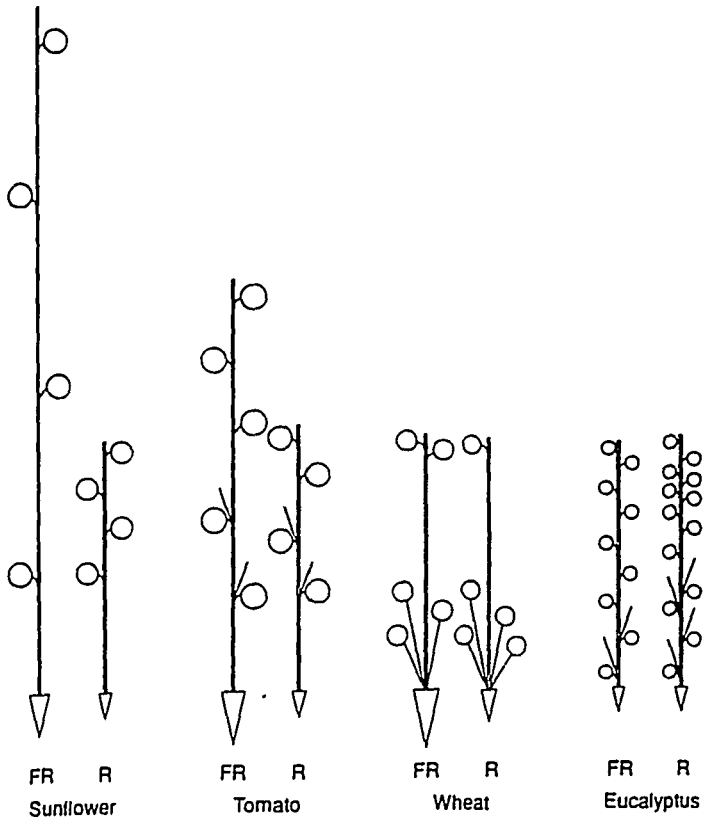

Fig. 2. Relative proportion of dryweight (R value set at 1) in root (▽) stem (length of uprights) and leaf (circles x 2) after 4 weeks growth in a FR- or R-rich cabinet. Conditions as in Fig. 1.

FLOWERING AND FAR-RED ENRICHMENT

Potential for change in time to flower with FR enrichment is one morphogenic response that has received little attention in the designing of lamp types for plant growth chambers. For short-day plants, red rather than far-red rich conditions favour flowering (see Salisbury, 1965) but in most published reports there have generally been confounding effects of daylength change and photosynthetic input. With equalization of photosynthetic inputs as in the study of McMahon *et al.* (1991) with the short-day plant chrysanthemum, there was actually a slight enhancement of flowering time for plants grown in long days with removal of far-red (see Table 1). However, the response to the presence or absence of far-red may also vary with the time of the day. For the short-day plant *Pharbitis nil* a FR interruption of as little as 90 min during continuous light can promote or inhibit flowering depending on its timing (Heide *et al.*, 1986). This FR response cycles with a period of about 12-h of a semidian rhythm (see Table 1).

By contrast with short-day plants, promotion of flowering by FR enrichment can be expected in long-day plants (see Vince-Prue, 1975; Deitzer, 1984). However, there are also very few comparisons of effects of luminaries on flowering of long-day plants when photosynthetic input has been fixed. In the studies of Tibbitts *et al.* (1983) mustard in 16-h long days reached anthesis about 2 to 3 d earlier (in a total of 25 to 29 d) when it was exposed to FR-rich lamps. Wheat was unaffected reaching anthesis at 57 d. However, an almost halving of days to flower (40 to 24 d) and of leaf number at flowering was found by Bagnall (1993) for the *fca* mutant of *Arabidopsis* (Landsberg strain) exposed to long days and ratios of R:FR ranging from 5.8 to 1.0.

The importance of FR-mediated effects of phytochrome on flowering in long-day plants is shown clearly by recent studies of Bagnall and coworkers (1994). They found that transgenic *Arabidopsis* plants constitutively overexpressing the far-red sensing phytochrome A gene flowered very early relative to the isogenic wild type (28 *vs* 64 d). Conversely, a mutant lacking phytochrome A is late to flower in FR-enriched conditions (Johnson *et al.*, 1994) involving low PPFD (10 mol $m^{-2}s^{-1}$) FR-rich tungsten daylength extensions.

A PHOTOSYNTHETIC ROLE IN FLOWERING

Although FR plays a central role in determining flowering time, photosynthetic input also influences expression of the long day response. *Lolium temulentum*, for example, flowers in response to a single long day and shows enhanced flowering the greater the photosynthetic irradiance. However, *Lolium* remains vegetative in short days independent of the irradiance of sunlight up to 1200 mol $m^{-2}s^{-1}$ (King and Evans, 1991). Photosynthesis alone is insufficient for flowering whereas a single non-photosynthetic long day given as a 16-h incandescent low-irradiance daylength extension is sufficient (Fig. 3) and less effective is an extension using a

fluorescent, FR-deficient lamp. For either lamp, in association with a long day, increasing their photosynthetic contribution gives parallel and linear increases in flowering response (Fig. 3). There is no evidence here of interaction between light quality - the phytochrome-mediated, response - and the photosynthetic response to this long day. Thus, photosynthesis in *Lolium* must be considered as beneficial but not sufficient for flowering. On the other hand, a more direct photosynthetic effect is evident in another long day plant, *Sinapis alba*. Its requirement for a single FR-rich long daylength extension can be bypassed by increasing photosynthesis for more than three short days although this effect involves four times the photosynthetic irradiance applied during a single photoinductive long day (Bodson *et al.*, 1977).

Since phytochrome and the photosynthetic pigments can act in concert to promote flowering of long-day plants, then, with increasing irradiance the photosynthetic contribution to flowering will range from nothing to apparently over-riding control by photosynthesis. As a consequence, action spectra could range from dominance by red wavelengths to a balance in the contribution by red and far-red and to the classic dominance by far-red wavelengths. The literature contains illustrations of all these combinations of wavelength and response of flowering to red and far-red. (Deitzer, 1984; Carr-Smith *et al.* 1989) and, clearly, some detailed reexamination of wavelength and irradiance interactions is required.

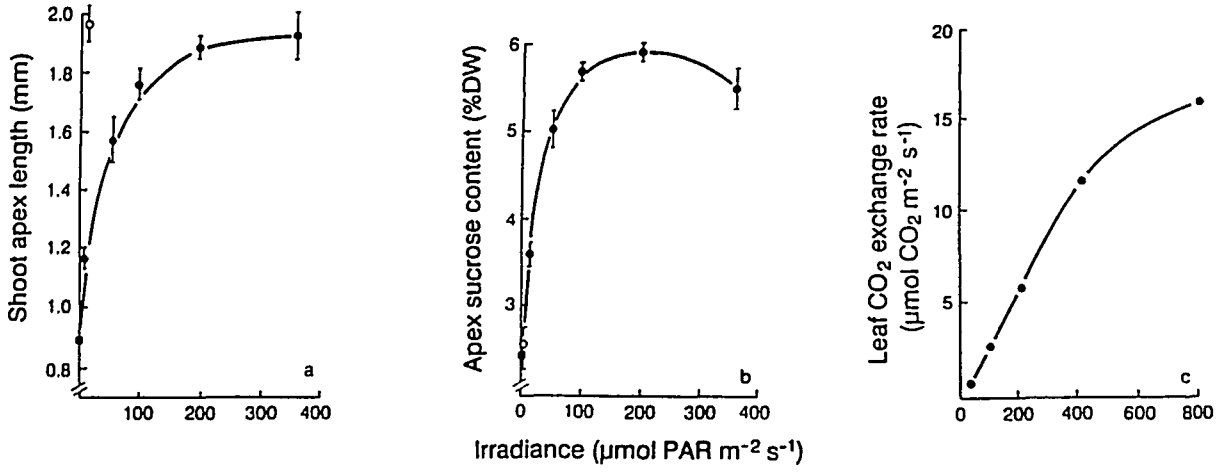

Fig. 3. Dependence on irradiance from fluorescent lamps during a single 16-h daylength extension of (a) flowering response in terms of shoot apex length after 3 weeks and (b) apex sucrose content at the end of the 16-h extension. Short day (■) and a low PPFD incandescent 16-h extension (o) are also included. Leaf CO_2 exchange (c) was determined during the main photoperiod. From King and Evans (1991).

OVERVIEW

As a broad generalization, far-red rich lamps are beneficial and sometimes essential, for plant growth and flowering in artificially lit chambers. Thus fluorescent and sodium lamps, being FR deficient may cause stunting and poor flowering. Brief end-of-day FR exposure may alleviate some of the stunting of growth but will probably have complex effects on flowering. A more beneficial approach appears to be continued FR enrichment over the whole photoperiod. A further complexity is that the need for FR input may vary cyclically over the day.

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PLANT REQUIREMENTS

NON-PHOTOSYNTHETIC (BLUE AND ULTRAVIOLET)

LIGHTING CONSIDERATIONS IN CONTROLLED ENVIRONMENTS FOR NONPHOTOSYNTHETIC PLANT RESPONSES TO BLUE AND ULTRAVIOLET RADIATION

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INTRODUCTION

This essay will consider both physical and photobiological aspects of controlled environment lighting in the spectral region beginning in the blue and taken to the normal limit of the solar spectrum in the ultraviolet. The primary emphasis is directed to questions of plant response to sunlight. Measurement and computations used in radiation dosimetry in this part of the spectrum are also briefly treated.

Because of interest in the ozone depletion problem, there has been some activity in plant UV-B research and there are several recent reviews available (Caldwell et al. 1989, Tevini and Teramura 1989, Teramura 1990, Tevini 1993, Caldwell and Flint 1994). Some aspects of growth chamber lighting as it relates to UV-B research were covered earlier (Caldwell and Flint 1990). Apart from work related to the blue/UV-A receptor (Senger 1984), less attention has been given to UV-A responses (Klein 1978, Caldwell 1984).

SOLAR UV AND BLUE RADIATION

The justification and interest in much of the plant research in controlled environments revolve around how plants may respond to solar radiation in nature. This is the emphasis of this essay. Some very different requirements may be in order for research probing the nature of chromophores, etc. However, these requirements can be very specific to particular research efforts and will not be considered.

In sunlight, blue and UV-A (320-400 nm)[1] radiation are tightly coupled and covary with changes in solar angle, atmospheric turbidity and cloudiness (Madronich 1993). The UV-B (280-320nm) is somewhat uncoupled from UV-A and blue light in that it is independently influenced by atmospheric ozone absorption. Even with the same total atmospheric ozone column thickness, as solar angle (and therefore atmospheric pathlength) varies, UV-B is affected to a greater degree than the longer wavelength radiation. Much interest of late has centered on the question of stratospheric ozone reduction and its influence on ground-level UV-B. However, even in the absence of ozone reduction, the normal latitudinal gradient in ozone column thickness and prevailing solar angles result in a much greater latitudinal gradient of UV-B (especially at the

[1]As originally defined (Coblentz, 1932), the UV spectrum is: UV-A 315 to 400 nm, UV-B 280 to 315 nm, and UV-C <280 nm. However, the division between UV-A and UV-B is often taken as 320 nm.

shorter wavelengths) than in UV-A and visible radiation (e.g., Caldwell et al. 1980, Madronich 1993).

Within the UV-B waveband, the spectral distribution is also greatly influenced by changes in atmospheric ozone column thickness and solar angle (Fig. 1).

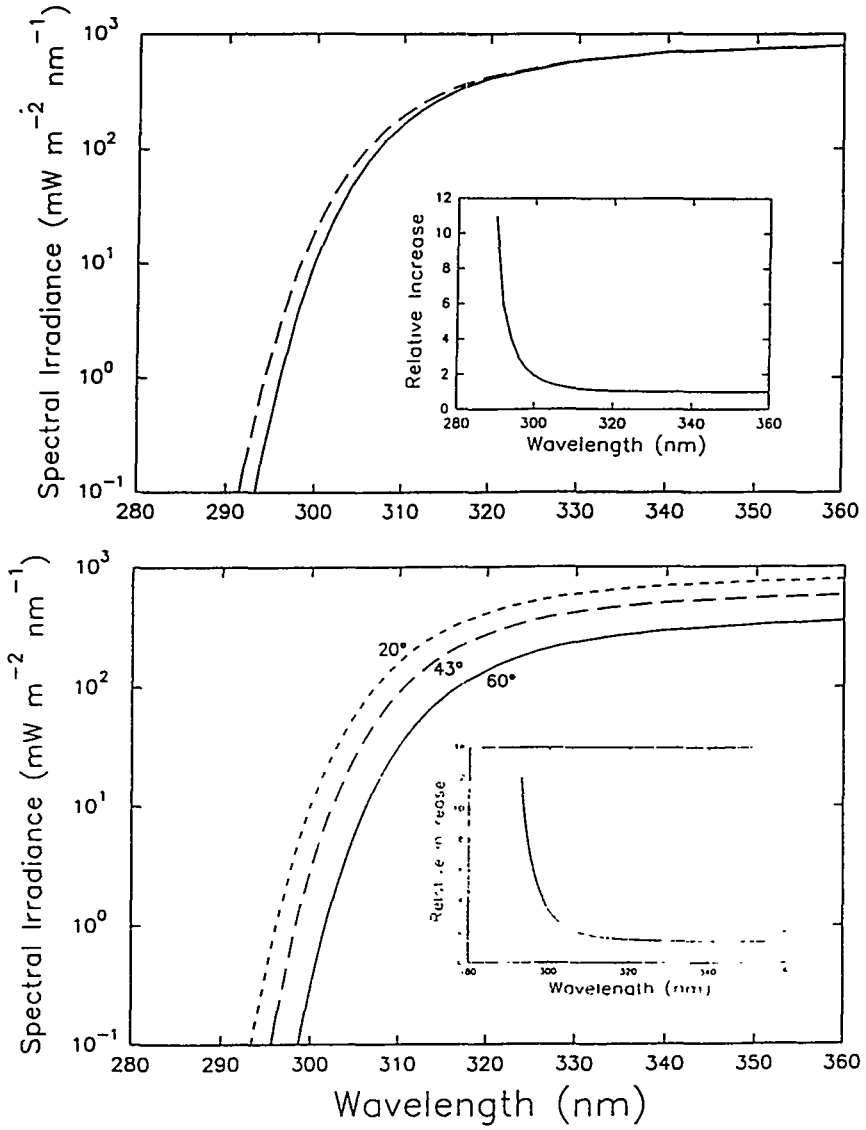

Fig. 1. (upper) Solar spectral irradiance (direct beam + diffuse) at noon at a temperate latitude (40°) location in summer with normal (continuous line) and a 20% reduction of the ozone column (dashed line). In the inset is the factor for relative increase of spectral irradiance at each wavelength due to the ozone column reduction. (lower) Solar spectral irradiance at a temperate latitude (40°) location in summer at different solar angles (20°, 43° and 60° from the zenith). In the inset is the factor for relative increase of spectral irradiance when the solar zenith angle changes from 43° to 20°.

These large alterations of spectral distribution within the UV-B are the result of the absorption cross section (absorption coefficient) of ozone. The abrupt decrease of spectral irradiance as a

function of decreasing wavelength has not, to our knowledge, been satisfactorily achieved without using ozone itself as a filter. [Tevini et al. (1990) have achieved this by using ozone to filter natural sunlight in the field. However, the size of the useable plant experimentation space is very limited.] To mimic the change in spectral flux density during the day in controlled environments (as occurs with solar angle changes) would be technically challenging and very costly -- a cost of dubious value for most research goals. Given the unpractical nature of trying to trying simulate solar spectral irradiance, some compromises are normally taken as will be discussed later.

SOME PHOTOBIOLOGICAL CONSIDERATIONS

Ultraviolet and blue radiation can elicit many photobiological reactions in plants, some of which have been rather well studied (e.g., the blue/UV-A receptor phenomena -- Senger 1984). Other responses are less well understood in terms of chromophores and other photobiological characteristics. Nevertheless, action spectra and/or suspected chromophore absorption spectra are often used conceptually in dosimetry and prescribing requirements for radiation. This is analogous with what has been done in illumination technology and in considering visible radiation for photosynthesis. For example, the standard photopic relative luminous efficiency or "standard eye" curve is used a weighting factor in all photometric units (such as luminous flux, candela or lux). Basically, this involves a dimensionless factor at each wavelength that weights the radiation according to the ability of the human eye to see this wavelength of radiation. When the weighted spectral irradiance is integrated with respect to wavelength, a single value of luminous flux is obtained. This has served well in lighting engineering since light from various sources can be compared with respect to human ability to utilize the light such as in reading. In a similar vein, a standard to represent photosynthetically active radiation has been widely adopted, namely the total photon flux density in the waveband 400-700 nm. The introduction of an integrating dosimeter for total photon flux in this waveband by Biggs et al. (1971) was a very useful contribution for plant scientists. With this "quantum sensor", one can easily measure what is commonly termed "photosynthetically active radiation -- PAR" or "photosynthetic photon flux -- PPF". An error analysis by McCree (1981) shows that the errors involved in using the quantum sensor with sunlight and various lamps are small. Also, he showed that the discrepancy between the true photosynthetic action spectrum and the quantum sensor spectral sensitivity approximating total photon flux, though appreciable in the blue part of the spectrum, is usually not serious for the types of dosimetry normally conducted. Thus, with relative impunity, the plant scientist can make his/her measurements and be primarily concerned with other aspects of the research.

Analogous approaches have been used in the UV-B and dosimeters have been devised for obtaining a weighted integrated measure of "effective" UV-B -- the weighting function usually is that describing sunburning of human skin (e.g., Berger 1976, Diffey 1986). We are not aware of this approach with dosimeters incorporating biological weighting factors being taken in the UV-A. There are several difficulties with this approach in the spectral region spanning the blue to UV-B -- some which are related to the manner in which solar radiation behaves and some to the many potential chromophores that may be important in this part of the spectrum. This diversity is indicated in Fig. 2.

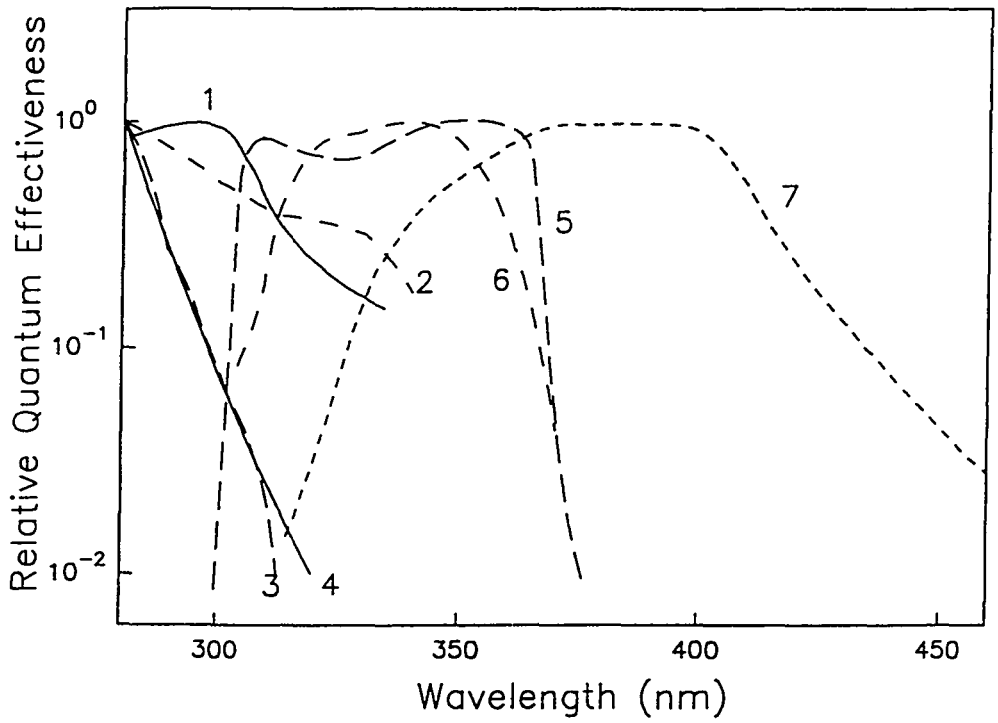

Fig. 2. Action spectra for various plant or microbial photobiological reactions in response to UV-B and UV-A radiation: (1) flavonoid pigment induction in cell cultures of parsley (Wellmann 1983); (2) photosystem II activity inhibition of isolated spinach thylakoids (Bornman et al. 1984); (3) DNA-dimer formation in intact alfalfa seedlings (Quaite et al. 1992); (4) inhibition of net photosynthesis in intact dock (*Rumex patientia*) leaves (Caldwell et al. 1986); (5) growth delay allowing more effective repair of UV damage (called photoprotection) in *E. coli* (Kubitschek and Peak 1980) (6) carotenoid protection of UV damage in *Sarcina lutea* (Webb 1977); (7) photoreactivation of UV damage to DNA (dimer formation) in *E. coli* (Jagger et al. 1969) .

This collection is certainly not comprehensive, but should convey the diverse characteristics of these spectra. Of course, a plant response may involve coaction of two or more chromophores.

In addition to the diversity of chromophores, the nature of solar radiation also complicates representation of plant-effective radiation, especially in the UV-B. In the UV-A and visible spectrum, spectral irradiance does not undergo large changes as a function of wavelength. However, in the UV-B, attenuation by ozone comes into play and spectral irradiance drops by orders of magnitude with decreasing wavelength -- more than 4 orders of magnitude within 25 nm (Fig. 1). When weighting functions (derived from action spectra or suspected chromophore absorption spectra) are applied to the spectral irradiance, small differences in the weighting functions can result in very large differences in the "effective" radiation (Caldwell et al. 1986, Madronich 1993). Thus, a situation quite different from evaluating PPF in the visible spectrum exists. Since simulating the solar spectrum in controlled environments is, for the most part, never achieved, one is forced to compare the "effective" radiation in sunlight with the "effective" radiation derived from the lamp systems no matter how the effective radiation is defined (i.e., which weighting function is employed). This may not always be apparent to the reader of such research reports, but is a necessary component of evaluating the radiation environment of the

plants. Depending on the weighting functions used, large discrepancies can arise. This is discussed in detail elsewhere (Caldwell et al. 1986). In principle, these discrepancies would be much less of problem in the UV-A and blue part of the spectrum. However, there has been little attention to analogous dosimetry at these longer wavelengths.

DOSIMETRY

As mentioned above, a few UV-B dosimeters have been devised. Even if these dosimeters function flawlessly, the quantity obtained is confined to the built-in weighting function and this cannot be easily extrapolated to UV-B weighted with other biological weighting functions. Alternatively, one can measure the spectral irradiance, wavelength by wavelength. This is certainly the most desirable since the spectral irradiance can be convoluted with any desired weighting function. However, an instrument that can measure satisfactorily in the solar UV-B spectrum involves much more demanding (and expensive) characteristics than is required in the visible spectrum. The primary reason for this is the orders-of-magnitude change in flux in this part of the spectrum (Kostkowski et al. 1982, Diffey 1986). This essay is not an appropriate place for a discussion of spectroradiometer measurements and characteristics, but the reader should at least be warned of the difficulties.

There are also geometrical considerations. Unlike solar visible radiation which is dominated by the direct beam component, the proportion of global solar UV radiation in the diffuse component is much greater and this proportion increases with decreasing wavelength. At the shorter (and generally most biologically effective) UV-B wavelengths, most of the radiation is in the diffuse component. Certainly the geometrical representation of radiation in controlled environments seldom approaches that of solar radiation in nature and it would probably not be a wise investment to attempt this for most problems. Nevertheless, the assumptions made and the geometrical characteristics of the radiation sensors (cosine law adherence, etc.) further complicate the comparison of sunlight with controlled environment lighting.

INTERACTIONS OF DIFFERENT SPECTRAL COMPONENTS

The use of biological weighting functions (whether built into dosimeters or used in computations of effective radiation from spectral irradiance determinations) carries the assumption that the plant response represented by the weighting function also applies with polychromatic radiation. The weighting functions are derived from action spectra (usually obtained with monochromatic radiation) or suspected chromophore absorption spectra (necessarily derived from monochromatic radiation). Whether the aggregated monochromatic radiation responses, i.e., the integral of weighted spectral irradiance, adequately represents responses in polychromatic radiation has seldom been tested. Nevertheless, this is the common assumption.

Some of the action spectra in the UV-A and blue light represented in Figure 2 are specifically for secondary processes that modify primary responses to UV-B -- usually mitigating the damage. Even if all the primary UV-B and secondary UV-A and blue light driven processes were perfectly understood, the question is whether their aggregated responses interact in a simply additive fashion. Or, would synergistic responses occur? A mechanistic understanding of these interactions eludes us thus far. Therefore, one must rely on empirical clues. For example, a few

experiments have been performed to test how visible and UV-A radiation affect UV-B sensitivity.

Experiments specifically designed to investigate the influence of PPF level on UV-B sensitivity showed that UV-B effects were less pronounced if plants were under higher PPF (Teramura 1980, Teramura et al. 1980, Warner and Caldwell 1983, Mirecki and Teramura 1984, Latimer and Mitchell 1987, Cen and Bornman 1990, Kramer et al. 1991, Kumagai and Sato 1992). More recently a field study using a combination of UV-emitting lamps and filters indicated that both high PPF and UV-A flux had mitigating effects on UV-B reduction of plant growth (Caldwell et al. 1994). However, the mitigating effects of UV-A and PPF did not act in a simple additive manner nor in a fashion that could be predicted from combinations of the action spectra represented in Figure 2. Although they did not specifically test the effect of different levels of UV-A and PPF on UV-B sensitivity, Middleton and Teramura (1993a) showed that UV-A could exert both positive and negative effects on plant growth and some physiological characteristics in a greenhouse study. Fernbach and Mohr (1990) demonstrated coaction of UV-A/blue light receptor and phytochrome and they also showed UV-A to be important in modifying UV-B sensitivity (Fernbach and Mohr 1992).

SPECTRAL BALANCE IN GROWTH CHAMBERS AND GREENHOUSES

The ratio UV-B:UV-A:PPF in sunlight is approximately 1:23:270 when taken on a total photon flux basis in each waveband (without weighting) (Caldwell et al. 1994). This is seldom replicated in controlled environments (Fig. 3).

To provide some perspective on how the average daily UV-B and PPF employed in greenhouse and growth chamber experiments relate to such values measured in the field, a brief survey is given in Figure 4.

Forty papers describing growth chamber UV-B experiments published between 1990 and October, 1993 were examined for ratios of UV-B:PPF employed in the experiments. Of these only 14 reported enough information to determine the daily UV-B and PPF used. Since some of these papers included multiple treatments, there is a total of 20 data points in Figure 4. Similarly, for greenhouse experiments during the same period, only 6 (out of 27) reported integrated daily PPF and the daily UV-B used. Again because of multiple treatments, ten data points are available. (We feel simply reporting the maximum midday values of PPF in greenhouse experiments does not provide a useful indication of the daily average values.) Even though maximum PPF in growth chambers may not be particularly great, in some experiments with sufficiently long daylengths, the integrated total-day UV-B:PPF ratio was close to that of the natural environment. However, in most of these experiments the UV-B:PPF ratios were far from those experienced by plants in the field.

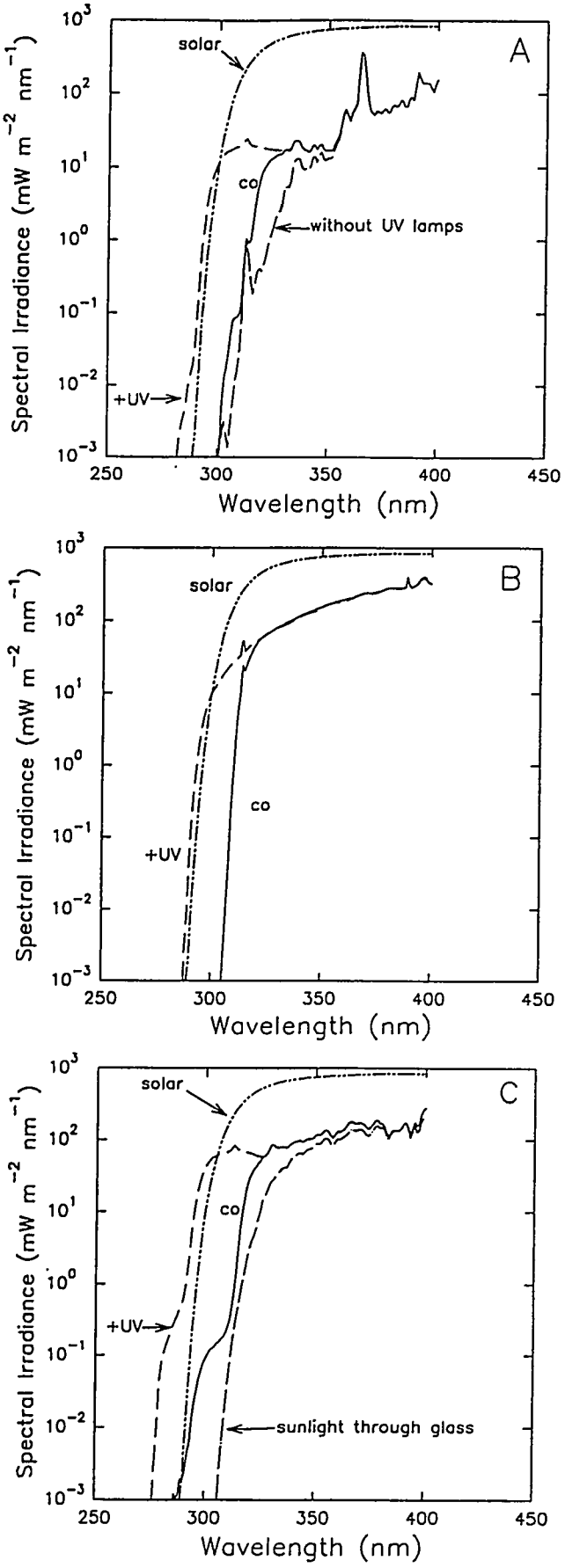

Fig. 3. Spectral irradiance in two types of growth chambers and in a greenhouse where different UV-B experiments were conducted. **A.** A chamber equipped with a combination of metal halide and high pressure sodium lamps combined with the normal filtered UV-B fluorescent lamps used in UV-B plant experiments: (**solar**) solar radiation at noon at midlatitude in the summer; (**+UV**) chamber lighting combined with UV-B fluorescent bulbs filtered with cellulose acetate plastic film; (**co**) the same, but with the UV-B bulbs filtered with polyester film (often used as a control); (**without UV lamps**) the chamber lighting without UV-B bulbs. **B.** A chamber with 6000-W xenon short arc lighting: (**solar**) solar radiation as in A.; (**+UV**) the xenon lamp filtered with cellulose acetate film; (**co**) the xenon lamp filtered with polyester film. **C.** Spectral irradiance in a glasshouse with the filtered UV-B fluorescent bulbs as in A: (**solar**) solar radiation as in A, outside the glasshouse; (**+UV**) UV-B fluorescent lamps filtered by cellulose acetate plastic film with background high pressure sodium lamps and sunlight coming into the glasshouse; (**co**) UV-B bulbs filtered by polyester film with background high pressure sodium lamps and sunlight coming into the glasshouse; (**sunlight through glass**) background winter sunlight coming into the glasshouse without other lamps.

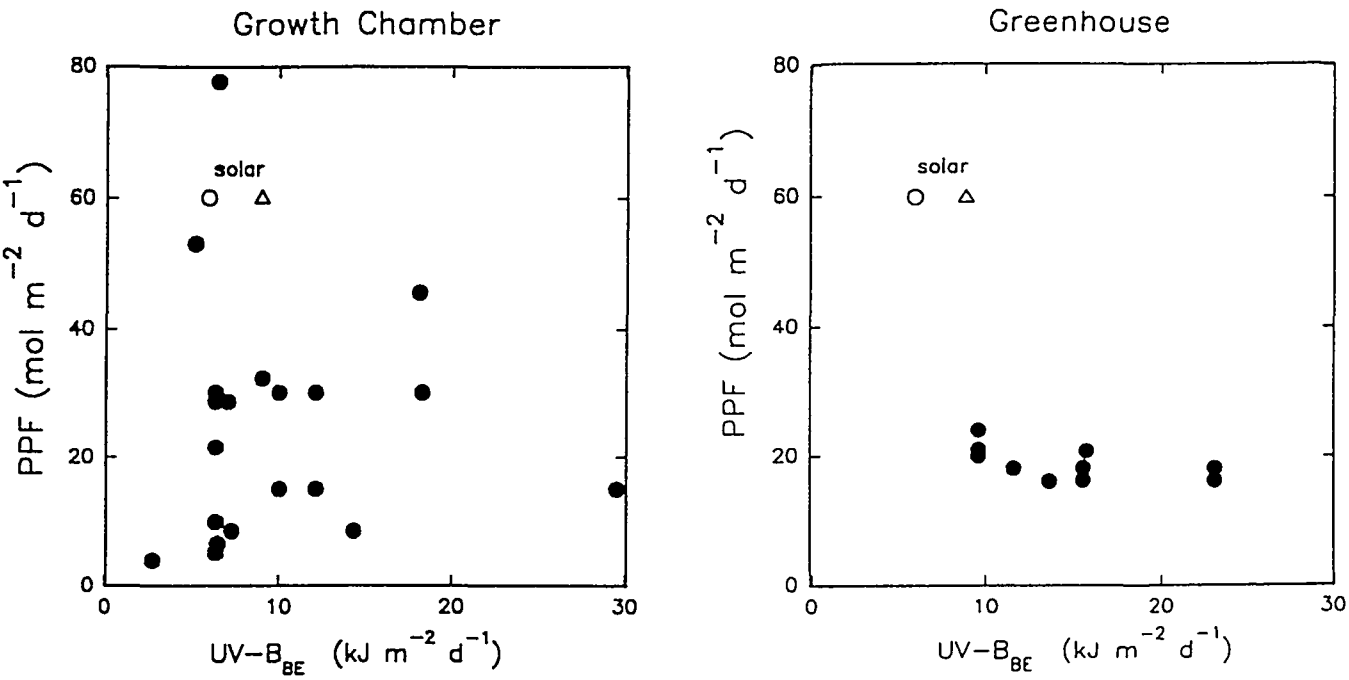

Fig. 4. Average daily integrated biologically effective UV-B using the generalized plant action spectrum weighting function (Caldwell 1971) normalized to 300 nm (UV-B_{BE}) and total photon flux in the 400-700 nm waveband (PPF) employed in growth chamber and greenhouse experiments (●). For comparison, measured solar UV-B_{BE} and PPF on a clear day (3 August 1993) at 1450 m elev. and 41°N latitude (○) and the corresponding value computed (using the measured values as a basis) for a 20% reduction of the ozone column (△). From Caldwell and Flint (in press).

Usually the UV-A is not reported in greenhouse and growth chamber experiments. However, since a portion of the UV-A is removed by greenhouse glass and the lamps in many growth chambers do not emit a large flux of UV-A (Fig. 3), fluxes of UV-A comparable to those in sunlight are not generally anticipated (Middleton and Teramura 1993b). The levels of UV-B and PPF in Figure 4 and the generally low UV-A in greenhouse and growth chamber experiments leads us to suggest that many such experiments may have substantially exaggerated plant sensitivity to UV-B. However, if the research interest does not relate to UV-B effects, but rather specific responses to UV-A or blue light, different criteria should be considered and the UV-B:UV-A:PPF ratio may be of less interest.

CONCLUSIONS AND COMPROMISES

It would be quite desirable to replicate the solar radiation, both in flux density and spectral distribution, in controlled experiments. Assumptions regarding appropriate weighting functions,

etc. would be obviated and a greater realism in experiments could be realized. However, duplicating the sun with artificial lighting, especially in the UV-B, is not presently attainable and may only be realized in the future with inordinate expense. A less ideal, but more practical, solution will usually be a compromise. For example, rather than trying to achieve the perfect spectral shape of sunlight, a more achievable goal would be to maintain the ratio of UV-B:UV-A:PPF similar to that in solar radiation. Increased duration of irradiation in growth chambers may have to compensate for not achieving peak midday solar flux densities. Of course, the degree to which different compromises are acceptable depends on the particular research interests. In any case, investment of resources and time in good dosimetry is of prime importance. Most lamps and many types of filters undergo ageing and lamp output is often temperature dependent. Thus, frequent measurements need to be conducted. In greenhouse environments, the solar radiation background continually changes while supplemental lamps in use may change relatively less. Thus, rather than simply representing peak values or midday averages, irradiation in different spectral bands should be reported in mean daily integrals. Use of weighting functions can seldom be avoided, at least for work in the UV-B. However, it is important to appreciate the assumptions and limitations involved in their use.

ACKNOWLEDGEMENTS

Portions of this essay stem from work supported by the Cooperative State Research Service, U.S. Department of Agriculture under Agreement No. 92-37100-7630 and the Andrew W. Mellon Foundation.

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UV-A/BLUE-LIGHT RESPONSES IN ALGAE

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INTRODUCTION

All life on earth depends on light. A variety of photoreceptors capture the light for a wide range of reactions. Photosynthetic organisms absorb the light necessary for energy transformation and charge separation facilitating photosynthesis. In addition to the bulk pigments there are a great diversity of photoreceptors present in minute concentrations that control development, metabolism and orientation of plants und microorganisms. (Shropshire and Mohr 1983, Senger 1987a, Kendrick and Kronenberg 1994). Based on its spectral absorbance, the well-studied phytochrome system acts in the RL region as well as in the UV-A/BL region where the above mentioned reactions are mediated by a variety of photoreceptors whose natures are largely unknown.

Phyllogenetically the UV-A/BL photoreceptors seem to be more ancient pigments that eventually were replaced by the phytochrome system. However, there are many reports that suggest a coaction between the UV-A/BL receptors and the phytochrome system. In several cases the UV-A/BL activation is the prerequisite for the phytochrome reaction (for a review see Mohr 1994). Historically it was the German botanist Julius Sachs who first discovered in 1864 that phototropism in plants was due to BL reactions. It took over 70 years until Bünning (1937) and Galston and Baker (1949) rediscovered the BL response. Since then, an ever-increasing attention has been paid to this effect.

Two international conferences in 1979 and 1983 have been entirely dedicated to the BL phenomenon (Senger 1980 and 1984). In this contribution, the general aspect of UV-A/BL responses and especially the responsiveness of algae will be covered. There are numerous review articles covering the various aspects of UV-A/BL action and the photoreceptors involved (Senger and Briggs 1981, Kowallik 1982, Richter 1984, Senger 1987a, Senger and Lipson 1987, Galland and Senger 1988a and 1988b, Galland and Senger 1991, Galland 1992, Gualtieri 1993, Kaufman 1993, Senger and Schmidt 1994).

GENERAL ASPECTS OF UV-A/BLUE-LIGHT EFFECTS

The best, and easiest, approach to study UV-A/BL effects is action spectroscopy. Action spectra calculated from fluence-rate response curves for an array of wavelengths provide both absorption

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Abbreviations: ALA = 5-aminolevulinic acid; BL = blue light; Chl = chlorophyll; LHC = light-harvesting complex; LIAC = light-induced absorbance change; RL = red light;

characteristics of photoreceptors involved and thresholds of the given responses (Schäfer and Fukshansky 1984, Galland 1987). Out of numerous effects, we present a selection of action spectra that document that UV-A/BL responses can be observed in higher plants, ferns, mosses, algae, fungi and cyanobacteria (Fig. 1). The variety in the shape of the action spectra indicates that UV-A and BL must excite a number of different photoreceptors. Nevertheless, it is obvious that peaks around 370, 450 and 480 nm are typical. Documentation in the UV region, especially below 350 nm, is still insufficient, because in many laboratories light sources and filters to produce the desired wavelength are not available.

Photomorphogenic responses are observed throughout the entire spectral region; ranging form UV-B to far-red light (Fig. 2). Therefore, the coaction between photoreceptors has to be expected in plants growing under a natural light regime. Indeed, coactions between UV-B and UV-A on the one hand (Fernbach and Mohr 1992, Caldwell et al. 1994) and UV-A/BL and phytochrome on the other hand (Mohr 1980 and 1994) have been reported. The obvious variety in UV-A/BL effects is accompanied by an even wider range of intensities evoking these effects (Fig. 3). This range covers at least 12 orders of magnitude and thus, in the natural environment, weak moon light, as well as strong sun-light, can trigger UV-A/BL responses.

Although action spectroscopy is a straight forward approach to identify photoreceptors regulating photobiological responses, several points have to be considered if conclusions are to be drawn with respect to the behavior of a plant in its natural environment. Under daylight conditions, both the fluence rates and the spectral composition of solar light change due to a number of factors such as solar angle (time of day, season), atmospheric turbidity, scattering, cloudiness, the ozone concentration, the plant canopy and, in the case of aquatic plants, the absorption characteristics of their aquatic environment (Caldwell 1981, Jeffrey 1981, Smith 1981). Furthermore, distinct wavelengths of the solar spectrum are absorbed by different photoreceptors simultaneously. Thus, the final response of a plant to the light environment is the sum of reactions influenced by the factors listed above and can hardly be mimicked in the laboratory.

The Nature of UV-A/Blue-light Receptors

Non-photosynthetic responses of plants to light are regulated via a variety of photoreceptors encompassing UV/BL receptors (Dörnemann and Senger 1984, Galland and Senger 1991, Senger and Schmidt 1994), phytochrome (Pratt et al. 1990, Quail 1991, Furuya 1993), rhodopsin (Foster et al. 1984, Hegemann et al. 1991, Gualtieri 1993) and phycochromes (Bogorad 1975, Björn and Björn 1976). Phytochrome has been well characterized on the protein and gene level. The present knowledge about UV-A/BL receptors, by contrast, still derives from physiological investigations on UV-A/BL responses, analyses of photoreceptor mutants, chemical analyses of pigments, characterization of the optical properties of putative chromophores, in particular light-induced absorbance changes (LIACs), and the elucidation of the signal transduction chain (Galland and Senger 1988a and 1988b, Galland 1992, Liscum and Hangarter 1991, Kaldenhoff et al. 1993, Kaufman 1993, Palmer et al. 1993a and 1993b).

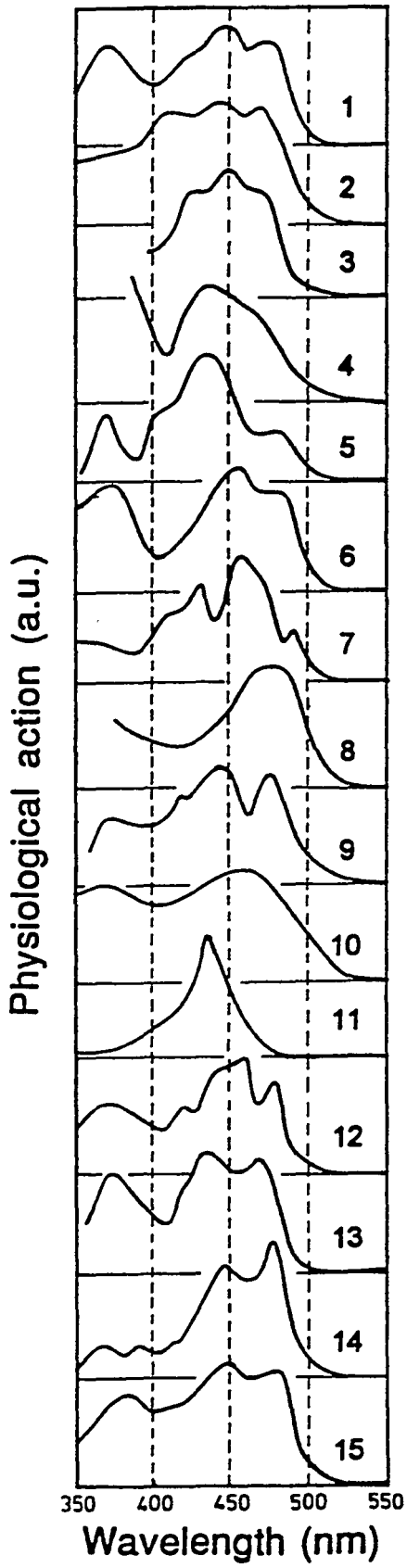

Fig. 1. Action spectra displaying the widespread distribution of UV-A/BL-regulated physiological processes among plants and fungi. (1) Phototropism of *Avena sativa* coleoptile, 10° and (2) 0° (Shropshire Jr. and Withrow 1958); (3) light-induced absorbance change (LIAC) in *Brassica oleracea var. botrytis* (Widell et al. 1983); (4) photoinactivation of indole acetic acid in *Pisum sativum* (Galston and Baker 1949); (5) germination of spores of the fern *Pteris vittata* (Sugai et al. 1984); (6) chloroplast rearrangement in the moss *Funaria hygrometrica* (Zurzycki 1967); (7) hair whorl formation of *Acetabularia mediterranea* (Schmid 1984); (8) cortical fibre reticulation in *Vaucheria sessilis* (Blatt and Briggs 1980); (9) formation of 5-aminolevulinic acid in *Chlorella protothecoides* (Oh-hama and Senger 1978); (10) carbohydrate decrease in *Chlorella vulgaris* (Kowallik and Schänzle 1980); (11) DNA-photoreactivation in *Anacystis nidulans* (Saito and Werbin 1970); (12) perithecial formation in the fungus *Gelasinospora reticulispora* (Inoue and Watanabe 1984); (13) photoreactivation of nitrate reductase in *Neurospora crassa* (Roldan and Butler 1980); (14) carotenogenesis in *Neurospora crassa* (DeFabo et al. 1976); (15) phototropism in *Phycomyces blakesleeanus* (Lipson et al. 1984).The physiological action is given in arbitrary units (a.u.).

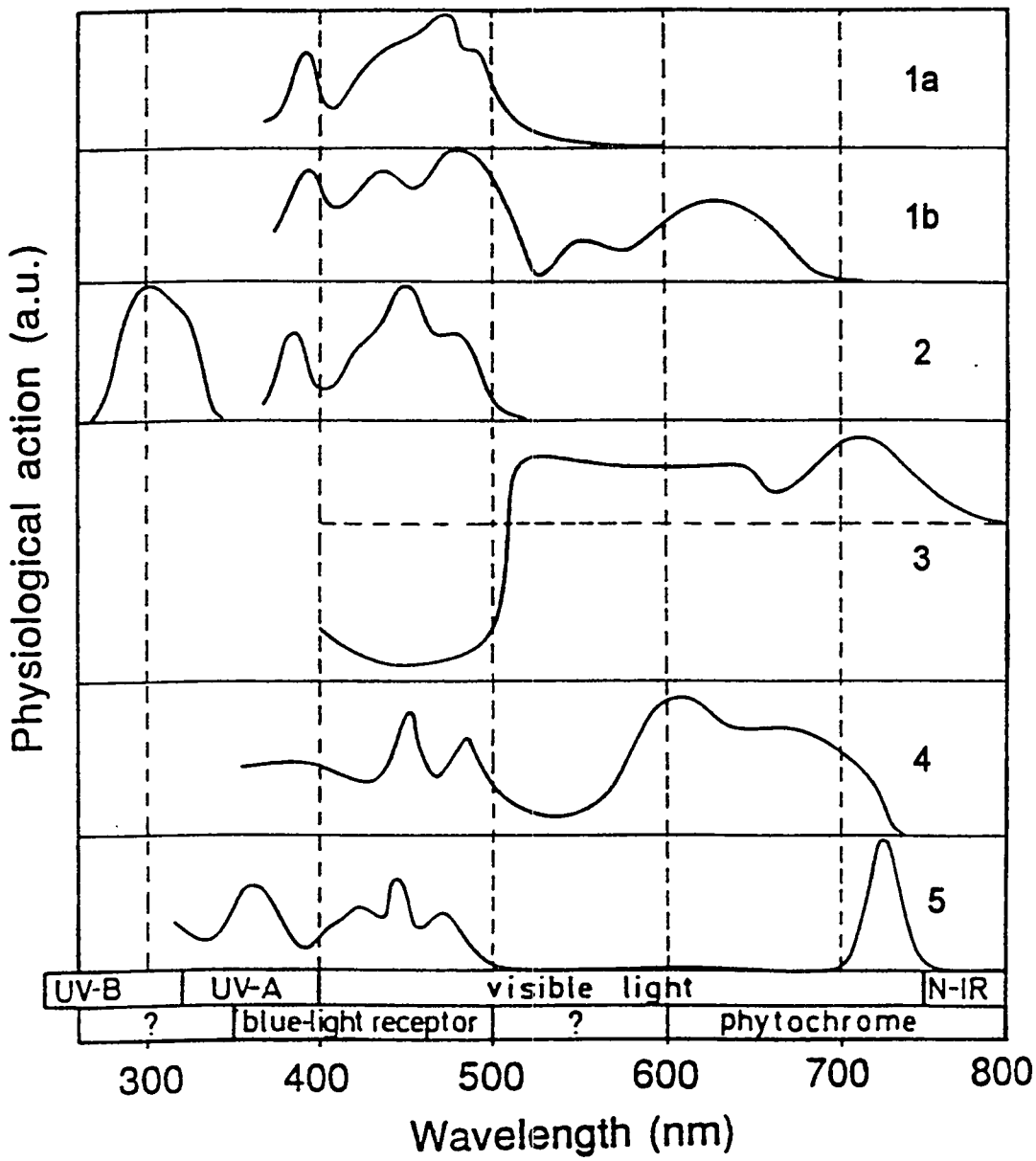

Fig. 2. Action spectra of physiological responses (in arbitrary units, a.u.) depending on the excitation of different photoreceptors. (1a) Chlorophyll accumulation in dark-grown *Scenedesmus* (Brinkmann and Senger 1978a) and (1b) after 2 h preillumination with BL (Brinkmann and Senger 1978b); (2) induction of conidiation in *Alternaria* by UV-B light and its reversion by BL (Kumagai 1983); (3) morphogenetic index L/W (ratio length to width of fern protonema) in *Dryopteris filix-mas* (Mohr 1956); (4) light-induced sensitization to geotropic stimulus in maize roots (Klemmer and Schneider 1979); (5) high-irradiance response (HIR) of light-inhibition of hypocotyl elongation in *Lactuca sativa* (Hartmann 1967).

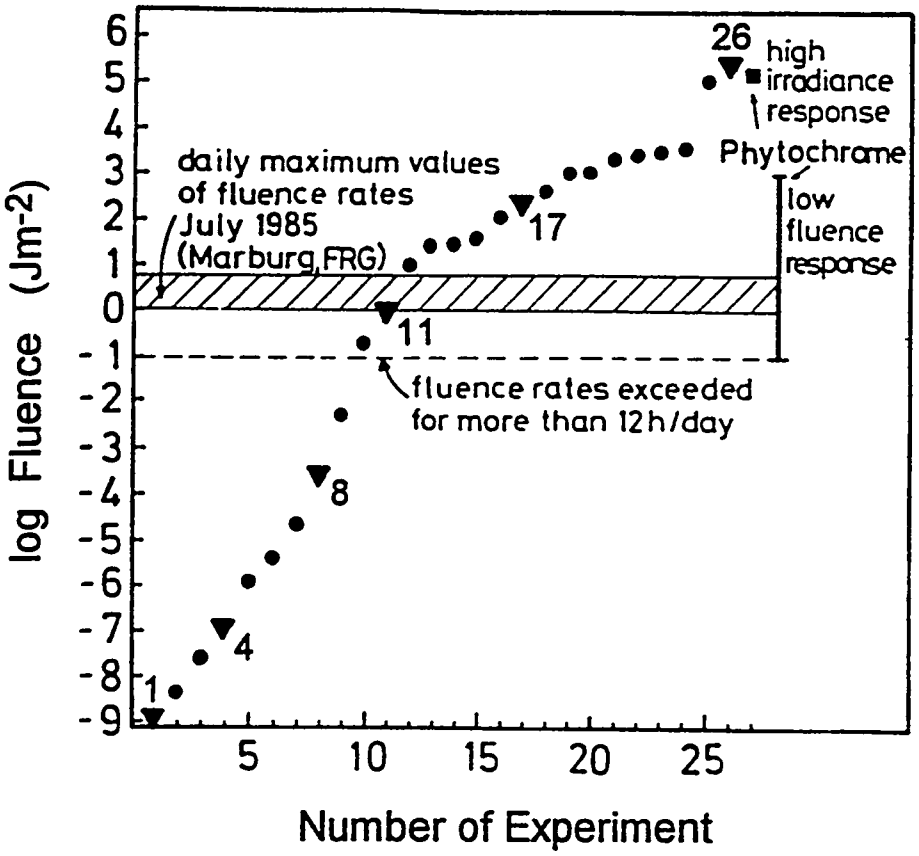

Fig. 3. Range of fluences inducing UV-B-, UV-A- and BL-controlled reactions. Closed triangles indicate the following experiments: (1) phototropism of *Phycomyces*; (4) oxgen uptake of *Chlorella*; (8) anthocyan synthesis in *Sorghum*; (11) inhibition of spore germination in *Pteris vittata*; (17) light-induced absorbance change (LIAC) in membrane fractions of corn and *Neurospora*; (26) adaptation of the photosynthetic apparatus in *Scenedesmus*. A description of the entire set of experiments is provided by Senger and Schmidt (1994)

According to the action spectra of UV-A/BL responses and physico-chemical properties of the putative pigments, pterins (Galland and Senger 1988a) and flavins (Galland and Senger 1991) as well as carotenoids (Zeiger et al. 1993, Zeiger 1994), are favoured to be the chromophores of the UV-A/BL receptors. Analysis of photoreceptor mutants of the fungus *Phycomyces* (Hohl et al. 1992a and 1992b) and investigations on the alga *Euglena* (Brodhuhn and Häder 1990, Schmidt et al. 1990, Sineshchekov et al. 1994) provide evidence for the involvement of pterins and flavins in controlling phototropism and phototaxis, respectively. Reduced Flavin ($FADH^-$) and methenyltetrahydrofolate have already been shown to constitute the chromophores of some DNA photo-

lyases (reviewed by Kim and Sancar 1993). Recently, an interesting contribution was provided by Ahmad and Cashmore (1993), who showed that a protein homologous to the DNA photolyase exists in *Arabidopsis*. However, the association of the native protein with chromophore(s) and photoreceptor function remain to be proven.

In general, three experimental approaches are advisable to elucidate the nature of the UV-A/BL receptors: generation and complementation of photoreceptor mutants (Adamse et al. 1988, Liscum et al. 1992, Chory 1991, 1992 and 1993), development of a LIAC-based purification procedure (Widell 1987, Galland 1992), and the indirect access via the immediate effectors, e.g. G poteins (Schäfer and Briggs 1986, Galland 1991, Terryn et al. 1993, Kaufman 1994).

GREEN ALGAL RESPONSES TO UV-A AND BLUE LIGHT

Since Kowallik (1965) introduced studies on the wavelength-dependent metabolism of *Chlorella* into the field of UV-A/BL research, green algae are among the best studied objects in this field (Senger 1987a). Research in our group has focussed on the unicellular green alga *Scenedesmus obliquus*, particularly on UV-A/BL control of chlorophyll biosynthesis (Oh-hama and Senger 1975, Senger 1987b, Dörnemann 1992), expression of the genes encoding the apoproteins of the light-harvesting complex of photosystem II (Hermsmeier et al. 1991 and 1992) and the development and light-adaptation of the photosynthetic apparatus (Senger and Bauer 1987, Humbeck et al. 1988).

Action spectra of chlorophyll accumulation, synthesis of 5-aminolevulinic acid, respiration, carbohydrate degradation, and accumulation of total cellular proteins (Fig. 4) display the important role of UV-A and BL in regulating fundamental cellular processes in *Scenedesmus*. The absorption characteristics of the UV-A/BL-receptor chromophore(s) are defined by peaks around 390, 450 and 480 nm.

An interesting finding was that, besides the UV-A/BL receptor, a second photoreceptor is present which absorbs at 410 and 650 nm (Fig. 4.2). This violet/RL receptor has a marked lower threshold as compared with the UV-A/BL receptor and operates in an antagonistical manner (compare Fig. 4.1 and 4.2). Activation of the UV-A/BL receptor results in an increase in chlorophyll, the apoproteins of the light-harvesting complexes and their messenger RNAs. The violet/RL receptor reverses these effects (Hermsmeier et al. 1991, Thielmann and Galland 1991, Thielmann et al. 1991). Furthermore, the receptor antagonism dramatically influences the light-adaptation of the photosynthetic apparatus.

Adaptation to BL induces a weak-light (shade) phenotype, i.e., among other things, decreased respiration and photosynthetic capacity, lower compensation point of photosynthesis and increased pigment contents combined with higher light-harvesting capacity relative to electron transport capacity. Cells adapted to RL, by contrast, exhibit a strong-light (sun) phenotype whose characteristics are opposite to those of the weak-light cells (Senger and Bauer 1987, Humbeck et al. 1988).

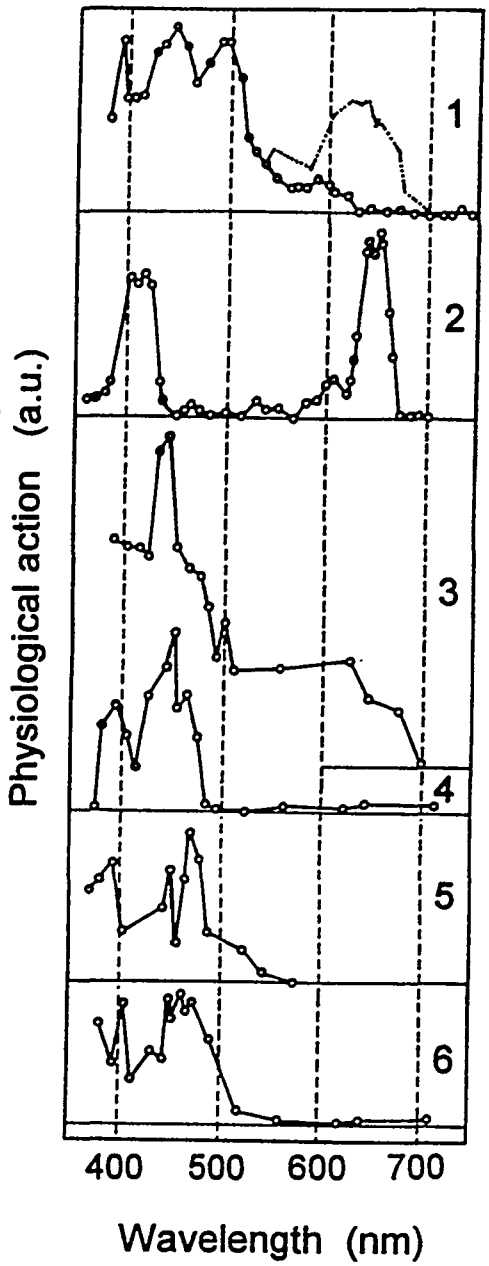

Fig. 4. Action spectra verifying UV-A /BL regulation of fundamental anabolic and catabolic processes in the unicellular green alga *Scenedesmus obliquus*. (1) Induction of chlorophyll (Chl) biosynthesis under high fluence rates (2 mol m^{-2} s^{-1}; dotted line: after 2 h preirradiation) relative to a dark control (Thielmann et al. 1991, Brinkmann and Senger 1980), (2) inhibition of Chl biosynthesis under low fluence-rate conditions ($4 \cdot 10^{-3}$ mol m^{-2} s^{-1}) relative to a dark control (Thielmann and Galland 1991), (3) formation of 5-aminolevulinic acid (ALA), the committed step in Chl biosynthesis (Oh-hama and Senger 1975), (4) enhancement of mitochondrial respiration by UV-A and BL, (5) light-induced decrease in total carbohydrates, (6) light-dependent accumulation of proteins (Brinkmann and Senger 1978a).

Considering all these data it can be stated that UV-A and BL regulate numerous essential processes within the *Scenedesmus* cell (Fig. 5). The different biochemical reactions promoted by UV-A and BL finally result in an enhanced photosynthetic efficiency and the formation of components that constitute the photosynthetic apparatus.

Light Requirements of Algae

As in higher plants, the photosynthetic apparatus of algae and cyanobacteria use light between 400 and 700 nm to drive photochemical reactions. To achieve optimum growth of algae and cyanobacteria under laboratory conditions, proper light sources have to be applied for the illumination of autotrophic cultures.

As indicated by the in vivo absorption spectra of selected members of cyanobacterial and algal taxa (Fig. 6), artificial lighting systems should generally emit high portions of BL and RL to saturate photosynthesis. The majority of algal classes contain peripheral light-harvesting antennae that absorb BL and RL due to their contents of carotenoids, Chl *a* and Chl *b* or Chl *c*. In red algae and cyanobacteria, by contrast, phycobiliproteins serve as light antennae. Phycoerythrin and phycocyanobilin, which constitute the chromophores of the phycobiliproteins, extend the absorption range covered by Chl *a* to the green and orange region of the spectrum (Fig. 6.1-6.3). This

should be taken into consideration if a lighting system is established for the cultivation of cyanobacteria and red algae. By choosing one or the other type of artificial light sources, specific systematic groups of algae can be enhanced in growth in favour of others.

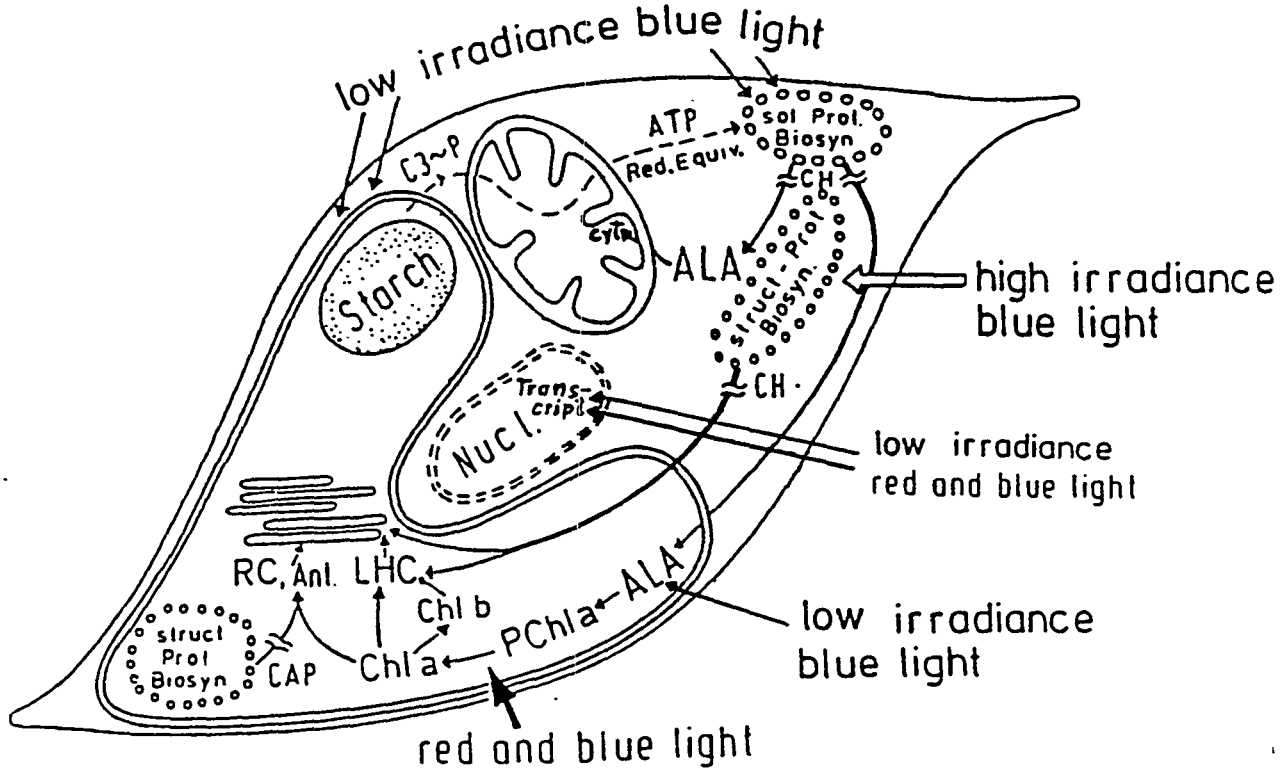

Fig. 5. Target sites of photocontrol of intracellular processes in *Scenedesmus obliquus*. Low- and high-irradiance blue and red light regulate transcription of nuclear genes, e.g. genes encoding the light-harvesting chlorophyll *a/b*-binding proteins, starch degradation, synthesis of soluble and structural proteins, formation of 5-aminolevulinic acid (ALA) and transformation of protochlorophyllide *a* (PChl *a*) into chlorophyllide *a*.

Apart from the importance of light as the primary source of energy, light plays the key role in photomorphogenesis and light-adaptation as described above. Beside the irradiance the ratio of BL to RL determines whether the photosynthetic apparatus is directed towards weak- or strong-light acclimation. During acclimation pronounced changes occur in the molecular organization

of thylakoid membranes.

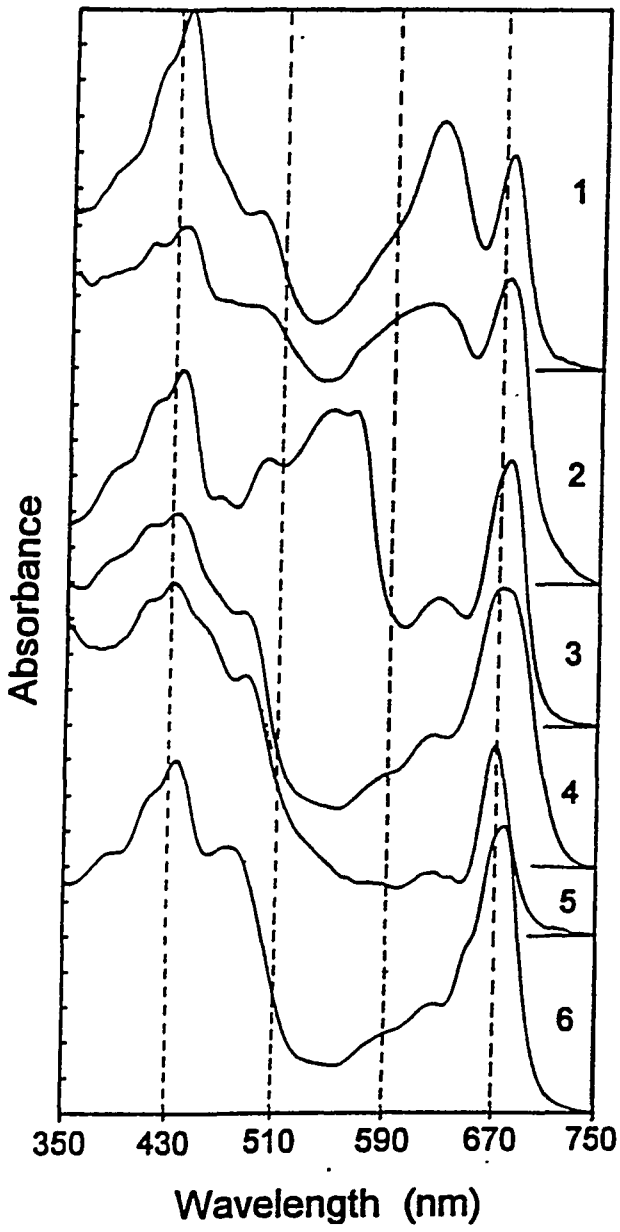

Fig.6. In vivo absorption spectra of the cyanobacteria *Anacystis nidulans* (1) and *Tolypothrix spec.* (2), the red alga *Porphyridium cruentum* (3), *Euglena gracilis* (4), the diatom *Cyclotella meneghiniana* (5) and the green alga *Scenedesmus obliquus* (6).

Therefore, in experiments dealing with the composition of the photosynthetic apparatus, the spectral distribution of the incident light should favour the absorption and excitation of relevant photoreceptors. Attention also has to be given to the intensity of the light source. On one hand, the applied fluence rates must provide sufficient net photosynthesis and, on the other hand, fluence rates inducing photoinhibition or even photodestruction of pigment-protein complexes must be avoided. Therefore, it is recommended to apply irradiance slightly exceeding the light-saturation point of photosynthesis. This ensures optimum growth and saves energy. The light-saturation point is usually determined by plotting photosynthetic oxygen evolution against irradiances. Since light-saturation points vary greatly among different algal species, it is necessary to carry out this procedure for each species of interest.

Practical Applications

The aquatic environment of the algae is characterized by an imbalance of the spectral distribution depending on the type of water, e.g. blue-, green- and orange/red-water seas (Jeffrey 1981 and 1984). A comparison of the spectrum of solar light with the spectrum of a blue-water sea in 5 m depth shows that the spectrum is shifted in favour of shorter wavelengths (Fig.7.1 and 7.2). In the case of laboratory cultures, absorption of water can be neglected since distilled water is used for the preparation of culture media and applied volumes are to small to absorb light significantly. For the set up of experiments which do not aim at daylight simulation, the choice of commercial available lamp types depends only on criteria discussed in the preceding chapters.

Emission spectra of selected lamp types are collected in Fig. 7. Due to their spectral imbalance, common incandescent lamps are fairly useless as a light source for photosynthetic organisms

(Fig. 7.3). Many laboratories use fluorescent lamps because of low running costs, long lifetime, high luminous efficiency and the availability of a great variety of lamp types with different emission properties. However, a substantial decrease in output necessitates replacement after approximately one year. The BIOLUX lamp (Osram, Berlin) simulates solar light to a certain degree (Fig. 7.4) and is recommendable for many biological applications. Because of its balanced spectral emission the BIOLUX lamp is a useful light source for the cultivation of cyanobacteria and red algae which show a high absorption throughout the entire spectrum (confer Fig. 6). The FLUORA lamp (Osram, Berlin) is well suited for cultivation of Chl *a/b*-type plants and algae since this lamp mimics the absorption spectrum of their photosynthetic apparatus (Fig. 7.5).

Fluorescent lamps have high luminous efficiencies but do not emit high irradiances of light. Under certain conditions where high irradiances are demanded, e.g. for the illumination of aquaria deeper than 50 cm, metal-halide or mercury lamps should be prefered to fluorescent lamps. For aquarists a number of mercury-lamp types, e.g. the HQL series (Osram, Berlin; Fig. 7.6) are available which provide both, high irradiances and an unaffected colour of aquatic plants and animals. Xenon lamps also provide high irradiances of light with a spectral emission similar to solar light. However, they emit high amounts of UV-C, UV-B and infra red (IR) and produce ozone which has to be exhausted. Their use requires UV- and heat-absorbing filters which again decrease luminous efficiency and increase costs.

Experimental ecological plant research necessitates sophisticated sunlight simulators which precisely mimic the solar radiation with respect to intensity, spectral balance and direction of light (Warrington et al. 1978, Holmes 1984, Björn 1994, Caldwell and Flint, this volume).

The best approximation of a standard daylight spectrum, so far known, renders a sunlight simulator developed by Seckmeyer and Payer (1993). Daylight simulation is achieved by the combination of 184 lamps of the metal-halide, quartz-halogen, BL-emitting and UV-B-emitting type, filters and reflectors in an appropriate spatial arrangement. Although the growth chamber of this apparatus is laid out for the cultivation of land plants it should be possible to adapt it to the cultivation of algae. However, simulation of fluctuations of the solar spectrum depending on meteorological and astronomical parameters remains an unsolved problem.

CONCLUSIONS

As for higher plants, growth and development of algae depend on light. Besides the light necessary to facilitate photosynthesis, UV-A/BL is of specific necessity for the normal development of algae. Spectral output of artificial light sources should match as close as possible the absorption cross section of the pigments responsible for photosynthesis and morphogenesis. The irradiances of the incident light should not exceed saturating values for photosynthesis to avoid photooxidation. By choosing the appropriate light source one or the other taxonomic group can be enhanced or suppressed in growth and development in comparison to others.

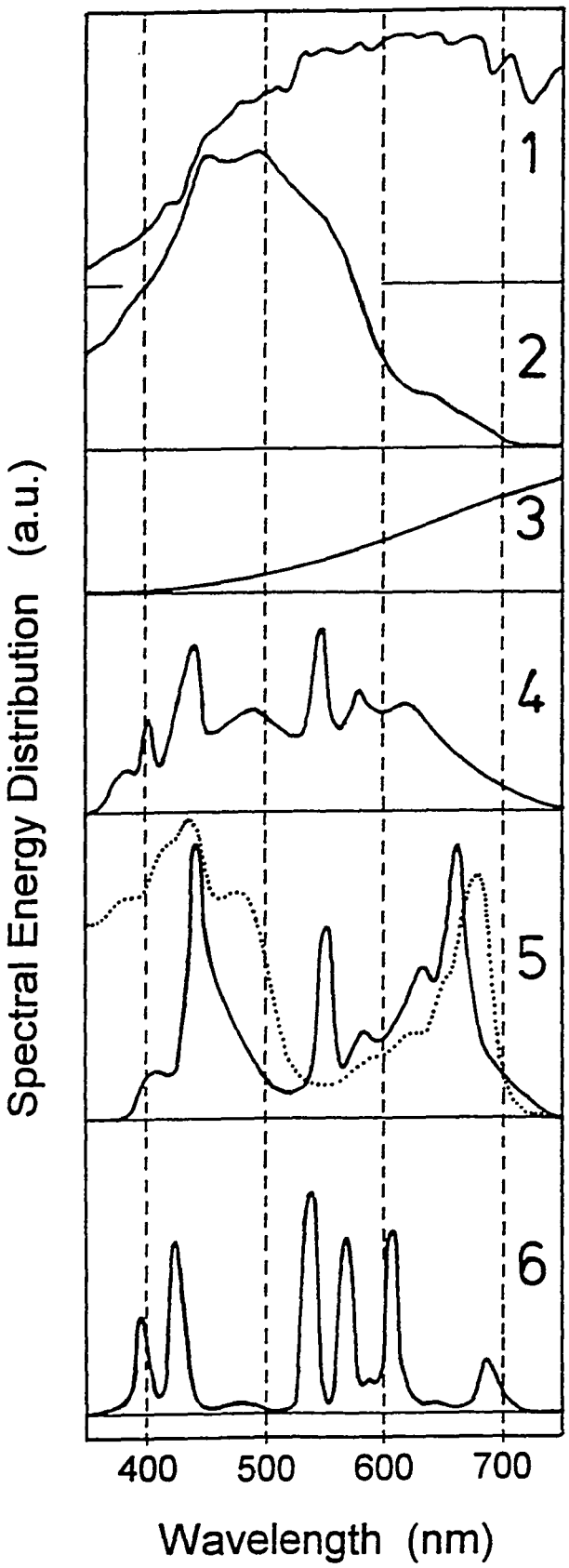

Fig.7. Comparison of the spectral energy distribution of solar light in the air (1) and in 5 m depth of a blue-water sea (2) with the corresponding spectra of technical light sources (3-6). (3) Spectrum of incandescent lamp; (4) fluorescent lamp BIOLUX 72 (Osram, Berlin); (5) fluorescent lamp FLUORA 77 (Osram, Berlin), the dotted line indicates the in-vivo absorption spectra of the unicellular green alga *Scenedesmus obliquus*; (6) mercury lamp HQL DE LUXE (Osram, Berlin). With respect to the spectral emission the BIOLUX light source is suitable to mimic natural daylight, while the FLUORA lamp is a recommendable light source for illuminating land plants and aquatic specimen. The HQL DE LUXE lamp exhibits a high output in the short wavelength range and between 520 and 620 nm and therefore provides maximum excitation of insect rhabdomer cells and retinal cells of mammals. As indicated by (3) incandescent light is not sufficient to cover the spectral range of photobiological processes.

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REQUIREMENTS OF BLUE, UV-A, AND UV-B LIGHT FOR NORMAL GROWTH OF HIGHER PLANTS, AS ASSESSED BY ACTION SPECTRA FOR GROWTH AND RELATED PHENOMENA

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INTRODUCTION

It is very important for experimental purposes, as well as for the practical use of plants when not enough sunlight is available. To grow green higher plants in their normal forms under articicial lighting constructing efficient and economically reasonable lighting systems is not an easy task. One possible approach would be to simulate sunlight in intensity and the radiation spectrum, but its high construction and running costs are not likely to allow its use in practice. Sunlight may be excessive in irradiance in some or all portions of the spectrum. Reducing irradiance and removing unnecessary wavebands might lead to an economically feasible light source. However, removing or reducing a particular waveband from sunlight for testing is not easy. Another approach might be to find the wavebands required for respective aspects of plant growth and to combine them in a proper ratio and intensity. The latter approach seems more practical and economical, and the aim of this Workshop lies in advancing this approach. I summarize our present knowledge on the waveband requirements of higher plants for the regions of blue, UV-A and UV-B.

BLUE LIGHT (BL)

The significance of this waveband was first noticed in phototropism, a response to light direction in which shaded and illuminated plant organs grow at different rates, resulting in curvature towards or away from a light source (Iino, 1990). Although red light, mediated through phytochrome, can induce phototropic responses under special circumstances (Parker et al., 1989), it seems probable that specific BL photoreceptors play a prominent role in most light-oriented growth movements as well as in many photoregulated, turgor-driven responses, such as nastic movements, leaf solar tracking (Koller, 1990) and stomatal opening (Zeiger, 1983). Plant movements have been popular objects of study because they occur rapidly and in many cases are reversible. Nonetheless, in spite of much exquisite physiology, it has not yet been possible to identify positively and BL photoreceptors involved in these responses. This is not surprising, given the likelihood that such photoreceptors are present in low abundance as well as the number of overlapping chromophores in this portion of the spectrum. Flavoproteins are probable candidates for BL photoreceptors (Short and Briggs, 1994). Recent evidence obtained with a mutant of *Arabidopsis* suggests that a putative BL photoreceptor associated with hypocotyl elongation may be closely related to a flavoprotein enzyme responsible for light-mediated repair of cyclobutane phyrimidine dimers in DNA (Ahmad and Cashmore, 1993). Still, other studies continue to support the possibility that pterins (Galland and Senger, 1988) or carotenoids (Quiñones and Zeiger, 1994) play a role in

some BL responses.

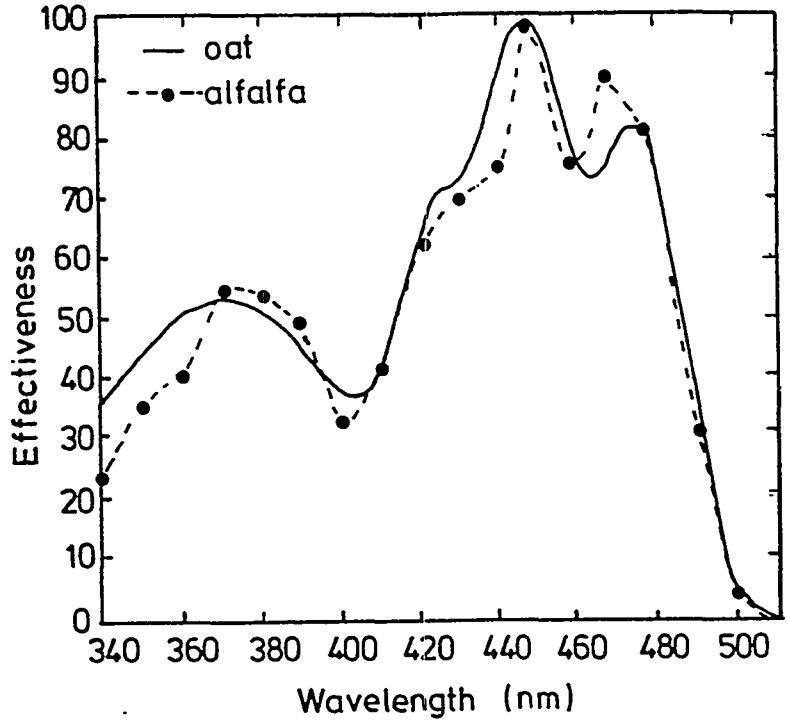

Fig. 1. Action spectra for first-positive phototropic curvature in the oat coleoptile and alfalfa hypocotyl. (Adapted from Thimann and Curry 1960, Baskin and Iino 1987).

Assessing the contribution of BL photoreceptors in a white light environment is complicated by numerous reports that the activity of BL phtoreceptors is influenced by additional photoreceptors absorbing in other spectral bands. For example, red light counteracts BL-induced photoepinastic orientation of rice and wheat leaves but has no effect by itself (Table 1; Inada, 1969; Kimura, 1977). This interaction is presumed to underlie the intermediate nastic response observed under white light. Phytochrome may be involved in many interactions with BL photoreceptors. In fact, formation of Pfr either before or immediately after a BL pulse suppressed the BL-induced unrolling of etiolated rice leaves (Sasakawa and Yamamoto, 1980). However, long wavelength suppression of BL-induced tea leaf orientation activity peaked at 600 nm, while wavelengths of 620 nm or longer were inactive (Aoki et al., 1981).

TABLE 1. Photoepinasty of the 2nd leaf of intact rice seedlings, cv. T 136

Light treatments	Leaf blade angle (degree)
Dark control	2.9 ± 3.5
Blue	67.5 ± 14.1
Red	4.6 ± 5.5
White	14.6 ± 5.0

11 W $m^{-2}s^{-1}$ PAR for 3 days, + S.D. (n = 20) (Inada, 1969)

TABLE 2. Light induced unrolling of the 2nd leaf intact rice seedlings, cv. Norin No. 25

Light treatments	Diameter of rolled leaf (mm ± S.D.)
Dark control	0.40 ± 0.07
Blue	2.08 ± 0.17
Green	0.71 ± 0.20
Red	0.78 ± 0.13
White	1.53 ± 0.40

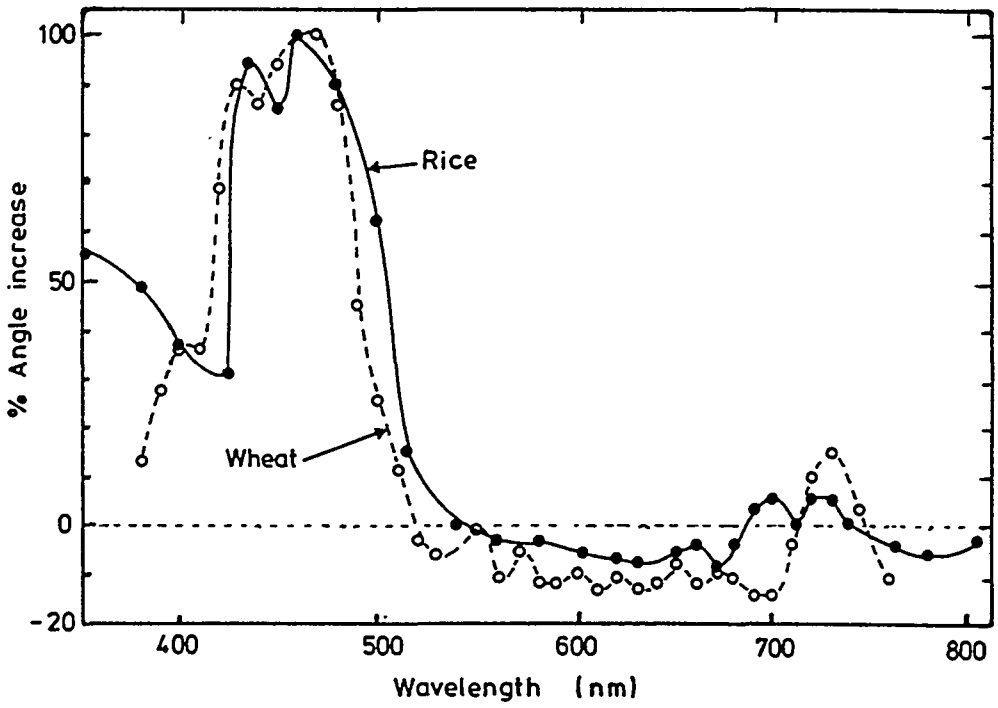

Fig. 2. Response spectra for photonastic inclination of rice and wheat leaf blades (from Inada, 1969 and Kimura, 1974). For rice and wheat, respectively, irradiation, 3 W m^{-2} x 72 h and 0.625 W m^{-2} x 40 h; leaf blade angles of non-irradiated control, 2° and 20°; light-induced maximum increases in angle (100%), 26° and 25°.

Blue light-induced growth inhibition of the stem is a phenomenon distinct from the phototropism of the stem, although the curvature involves a growth inhibition of the lighted side and a growth promotion of the shaded side of the stem. While a phototropic curvature appears approximately 30 minutes after the onset of light, stem growth inhibition occurs in some minutes (Fig. 3). Further, it was found that a phototropically null mutant of *Arabidopsis* showed normal hypocotyl growth inhibition, while another mutant lacking growth inhibition showed normal phototropic response (Liscum et al. 1992). Although the so-called high irradiance response (HIR) has been suggested to be responsible for BL effect as well (Wildermann et al. 1978), and may occur in the seedling stage, there certainly exist

BL-specific actions, which are separable from phytochrome actions by faster appearance and disappearance of growth inhibition after a pulse (Fig. 3) (Gaba and Black 1979, Behringer and Davies 1993). This was also shown by phytochrome-deficient mutant seedlings of *Arabidopsis* (Chory 1993, Goto et al. 1993). An action spectrum for the hypocotyl growth inhibition of the mutant completely lacks action at above 500 nm, while that for a wild type has peaks which suggest an occurrence of a low photon response and HIR of phytochrome (Fig. 4). In the *aurea* tomato mutant the accumulation of transcripts from nuclear genes for thylakoid proteins requires BL even when saturated with RL (Palomares et al. 1991).

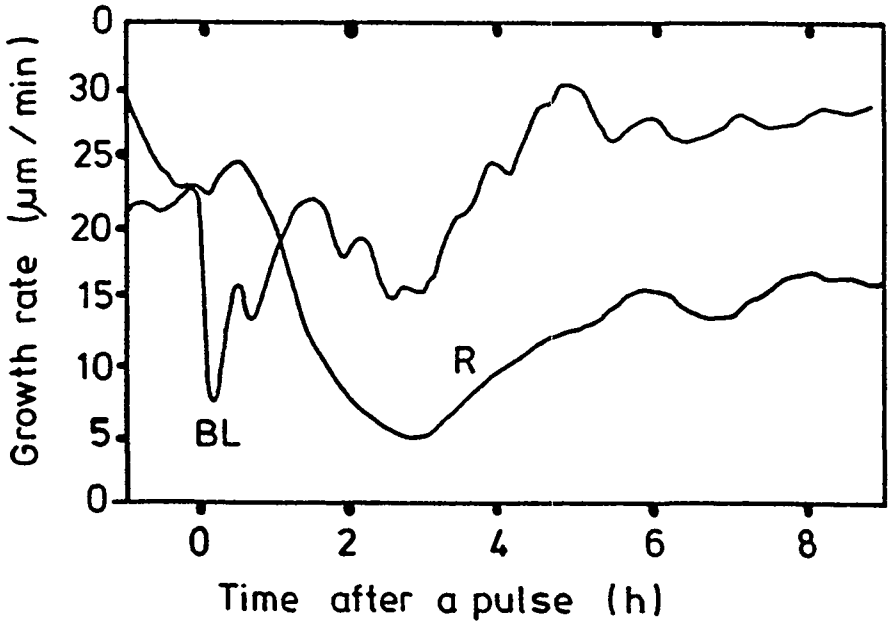

Fig. 3. Early time course of the light growth inhibition of etiolated pea seedlings. (Adapted from Behringer and Davies 1993).

In considering light sources for photoautotrophic growth of plants, our interest is to what extent BL influences plant growth in the background of sufficient photosynthetically active radiation (PAR). Some attempts to see the effects of BL in sunlight have been made. From sunlight or intense white light from "Youkou Lamps" (DR400T, Toshiba, Tokyo) in a phytotron the BL waveband was removed or reduced in intensity by filtering with yellowish polyacrylic resin or polyvinyl chloride sheet (Nakamura et al. 1977, Yamada et al. 1977). The results showed increased growth of the stem and petiole in Japanese honeywort, celery and bean, and a curling of the leaf blade in celery. But in these experiments UV-A and -B were along with BL removed, but it was not indicated whether UV-A and -B were removed in the control as well; thus it is unclear whether or not these are BL-specific action.

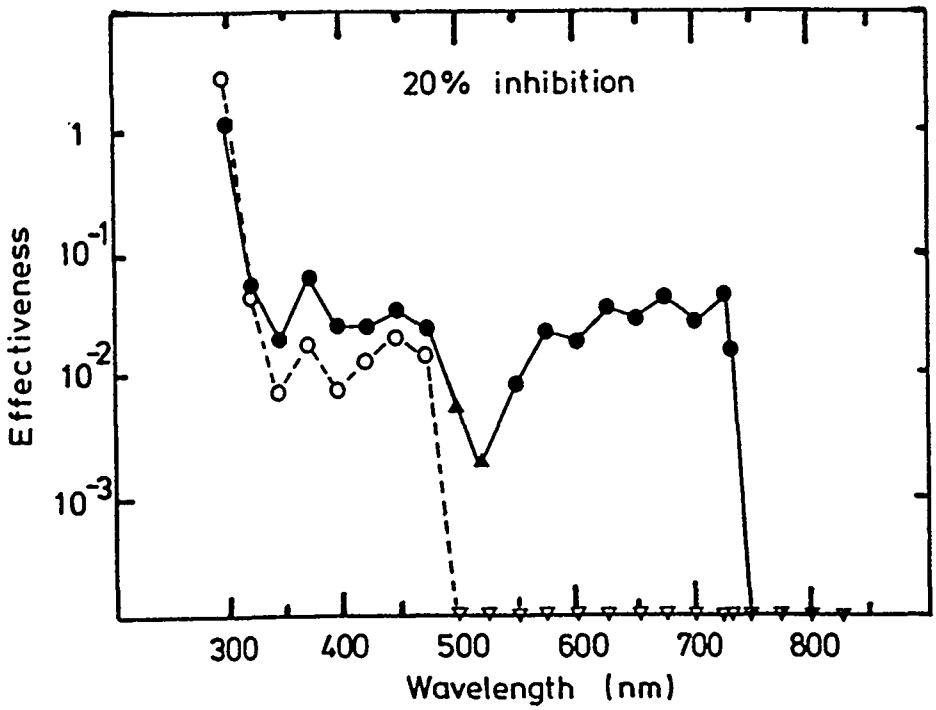

Fig. 4. Action spectra for the light growth inhibition of the hypocotyl in wild-type (solid line) and phytochrome-deficient mutant (*hy2*) (broken line) of *Arabidospsis thaliana.* (From Goto et al. 1993).

In another line of experiments (Inada and Katsura 1977), rice, soybean, tomato, and cucumber were grown for 38 days under WL from "Youkou Lamps" with or without a small BL supplement (Fig. 5). Extra BL caused significant photomorphogenetic effects (e.g. suppression of shoot extension in soybean and rice (Table 3) and increase of stem thickness. In tomato, general growth was promoted as shown by an increase of dry weight, while no apparent suppression in plant height was observed.

These results show BL has specific morphogenetic effects. The BL actions are on balance with OL or RL, and even under intense WL from metal halide lamps or likes, BL supplement is required.

UV-A LIGHT

Many action spectra with their main peak in the blue region (ca. 450 nm) have a subpeak in the UV-A region (ca. 370 nm), and both peaks are assumed to be due to the same photoreceptor, for which the name blue-near UV photoreceptor or cryptochrome has been coined. Such a UV-A requirement may be satisfied by BL. However, there are some other UV-A requirements which are not replaced by BL. In a frame covered with a polyvinyl chloride sheet to cut off UV of wavelengths below 400 nm, spinach grew better than in a control frame covered with UV-transparent sheet (Hasegawa et al. 1979), suggesting a general growth inhibition by the solar UV. Installment of a UV-A source (black light) in the former frame (solar UV-A eliminated), however, increased the growth of spinach (Shibata 1993), whereas an inclusion of a UV-B source inhibited growth. In a similar experiment with polyvinyl sheet frames deprived of solar UV, by contrast, tomato and radish plants grew less than in control frames with solar UV transmitted (Tezuka et al. 1993). The contrasting

results with the solar UV elimination between Hasegawa et al's and Tezuka et al's experiments seem due to the different sensitivities to UV-A or UV-B of the particular plants studied. Since in the UV elimination experiments described above as well as the experiment with a UV supplement to white light, sufficient amounts of BL and RL are supplied from sunlight, the results may suggest the occurrence of UV-A specific action. The construction of an action spectrum of UV-A in the presence of intense white light is required.

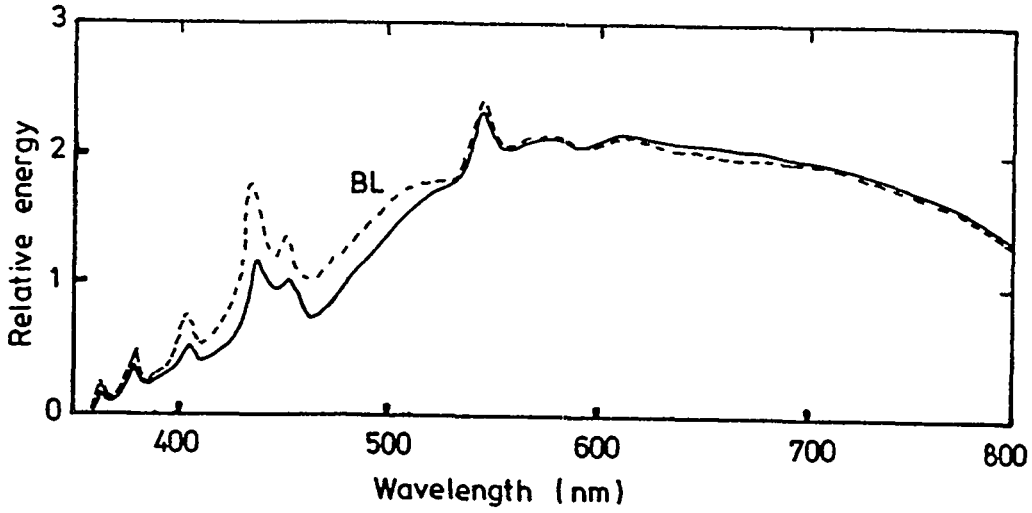

Fig. 5. Spectral energy distribution of the main light source (Youkou Lamps, 400 watts, Toshiba, Tokyo) (solid line) and of the light supplemented with BL from fluorescent tubes (broken line). The colour temperatures: 4000 K and 4500 K, respectively. (from Inada and Katsura 1977).

Photoreactivation of UV damage is an important action not to be neglected in this spectral region. However, few action spectra have been determined with living higher plants. Figure 6 shows action spectra for photoreactivation determined with enzymes isolated from plant tissues, and indicates the necessity of light of this waveband in relation to UV-B.

TABLE 3. Effects on plant morphogenesis of BL supplemented to white light "Toshiba Youkou Lamps"

Plants	Plant height (%)	Dry weight (%)	DW/height (%)
Rice	92**	99	108
Soybean	84**	106	126
Tomato	104	138*	133
Cucumber	87	98	113

White light control = 100%, * and ** denote significant differences at 5% and 1% levels, respectively. White light without BL supplement, 230 W m^{-2}. Day: 15h, 25°C; night: 9h, 20°C. 38 days culture. (Inada and Katsura, 1977).

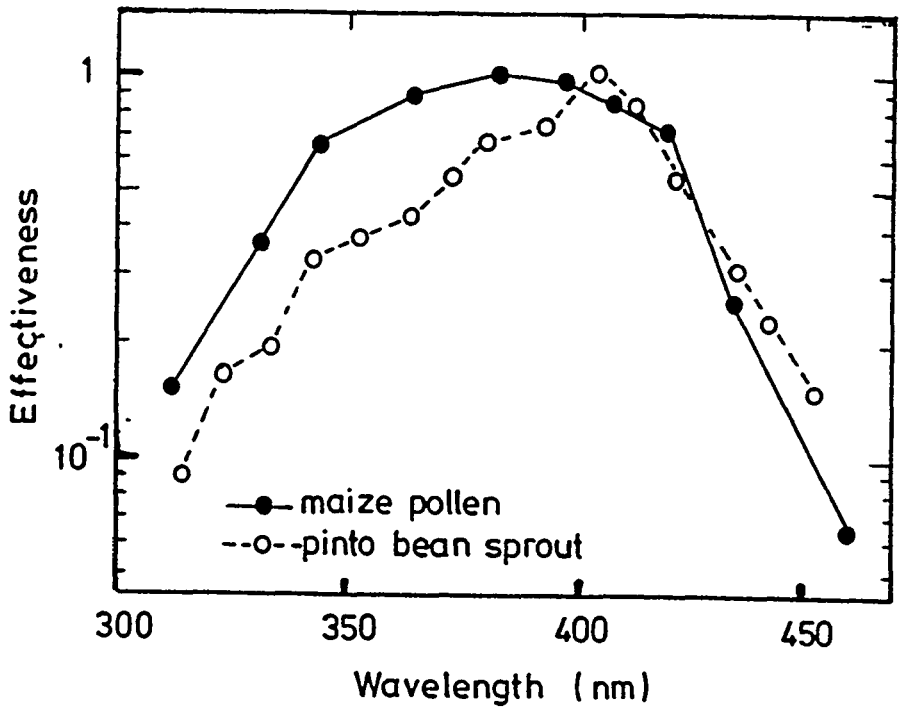

Fig. 6. Action spectra for photoreactivating enzymes isolated from Pinto bean sprouts (Saito and Werbin 1969) and maize pollen (Ikenaga et al. 1974).

UV-B LIGHT

This waveband exerts various actions: suppression of the over-all growth of plants, reducing cell division or elongation; cell damage such as cell collapse and tissue browning; and reduction of biomass production (Caldwell 1971, Tevini and Teramura 1989). Besides, this waveband causes photomorphogenesis, and induces the synthesis of anthocyanin and other flavonoids alone or in coaction with RL absorbed by phytochrome (Beggs et al. 1986). In intact plants flavonoids are synthesized in the epidermis, and serve as a UV-B cut-off filter to the light entering the tissue (Schmelzer et al. 1988, Tevini et al. 1991, Cen and Bornman 1993).

The flavonoid-inducing effect of this waveband is established by action spectra (Fig. 7). They have peaks at ca. 290 nm, differing from the absorption of DNA or RNA, and suggest the occurrence of a particular UV-B photoreceptor. This UV-B action is manifested or enhanced by phytochrome action (Yatsuhashi and Hashimoto 1985), and further enhanced by BL (Drumm and Mohr 1978, Duell-Pfaff and Wellmann 1982). That the flavonoid induction by UV-B really occurs in the natural growing conditions was shown by the effects of UV-B supplements to artificial WL (Adamse and Britz 1992, Arakawa et al. 1985, Maekawa et al. 1980, Cen and Bornman 990) and supplement to sunlight (Flint et al. 1985). The findings that UV-B elimination from sunlight greatly reduced anthocyanin synthesis in rose flowers and eggplant fruits (Mihara et al. 1973, Tezuka et al. 1993) support the view that the solar UV-B produces flavonoid synthesis under the field conditions. Lignin biosynthesis, whose early steps (phenylpropanoid pathway) are shared with flavonoid synthesis, may be under the influence of UV-B, since UV-B makes plants tougher (Hashimoto and Tajima 1980).

When given at a moderate intensity together with sufficient photosynthetically active radiation (PAR), UV-B increases the thickness of the leaf (Cen and Bornman 1990, 1993) and chlorophyll content (Adamse and Britz 1992, Hashimoto and Tajima 1980), and does not suppress photosynthesis (Adamse and Britz 1992, Bornman 1989, Flint et al. 1985) except for sensitive species, strains or varieties. Suppressed growth of the hypocotyl and promoted expansion of the leaf or cotyledons are characteristics of morphogenetic effects of light. UV-B suppresses the growth of the hypocotyl of cucumber, eggplant and radish (Ballare et al. 1991, Hashimoto and Tajima 1980) without causing growth inhibition of the cotyledons. The findings with light-grown cucumber that the cotyledons perceive light and the hypocotyl responds (Ballare et al. 1991) strongly suggest that it is a normal photomorphogenetic action of UV-B. In this UV-B action a small photon leved of UV-B is enough. Wavelengths over 300 nm may be effective. Kondo (Hashimoto et al. 1993) found that an addition of 310 nm light at 0.1 to 1 μmol m^{-2} s^{-1} promoted the growth of cucumber first leaf under intense white light (500 μmol m^{-2} s^{-1}), while 290 nm light at the same photon levels showed neither promotion nor inhibition. Each wavelength was inhibitory when given alone. Although no action spectrum is available yet for either hypocotyl inhibition or cotyledon promotion, the promotive effect of 310 nm distinguishes the effect of the longer wavelength region of UV-B from the general growth inhibitory effects of UV-B. Thus, UV-B is assumed to exert true photomorphogenetic actions in addtion to the deleterious effects. This view has been proposed by Hashimoto and Tajima (1980), Ballare et al.(1992), and Ensminger (1993).

However, it is indeed true that UV-B causes damage in plants. The action spectra for the formation of pyrimidine dimers and (6-4)photoproduct, as examined with a human cell culture or calf thymus DNA solution, peak at about 260 nm and extend their longer wavelength ends into the UV-B region (Matsunaga et al. 1991, Rosenstein and Mitchell 1987), and it is assumed that this is also the case with plants. Coiling, a UV-B-induced abnormal growth of the etiolated sorghum first internode (Fig. 8), closely correlates with the amount of thymine dimer formed by the irradiation (Tsurumi et al. unpublished data), and the action spectrum for coiling corresponds with the absorbance of DNA. An action spectrum for anthocyanin synthesis inhibition shows a similar curve (Fig. 8) (Hashimoto et al. 1991, Wellmann et al. 1984).

Thus, the UV-B region is the crossing zone of the deleterious effects and the normal photomorphogenetic actions, as indicated by the distinct action spectra (Figs. 7, 8). The photon level of UV-B required for the photomorphogenetic actions is lower than for the deleterious effects of UV-B (Fig. 9). The photon ratios (curve A/curve B) required for threshold induction are estimated from Fig. 9 as 1/380, 1/1400, and 1/6500, respectively, at 280, 290, and 297 nm. The trend of the values implies that at above 300 nm the deleterious effects of UV-B are not likely to occur at the photon levels required for the photomorphogenetic effects of UV-B. The presence of sufficient PAR and carbon dioxide ameliolate the harmful effects of UV-B (Adamse and Britz 1992, Cen and Bornman 1990, Nouchi 1993, Teramura et al. 1980). The amelioration of UV-B damage by PAR involves photoreactivation by UV-A and BL and other unknown action mechaninsms of visible light in addition to an increase of the biochemical UV-B filter flavonoids. Thus, to obtain the beneficial effects of UV-B and minimizing potential harmful effects, a long-wavelength UV-B

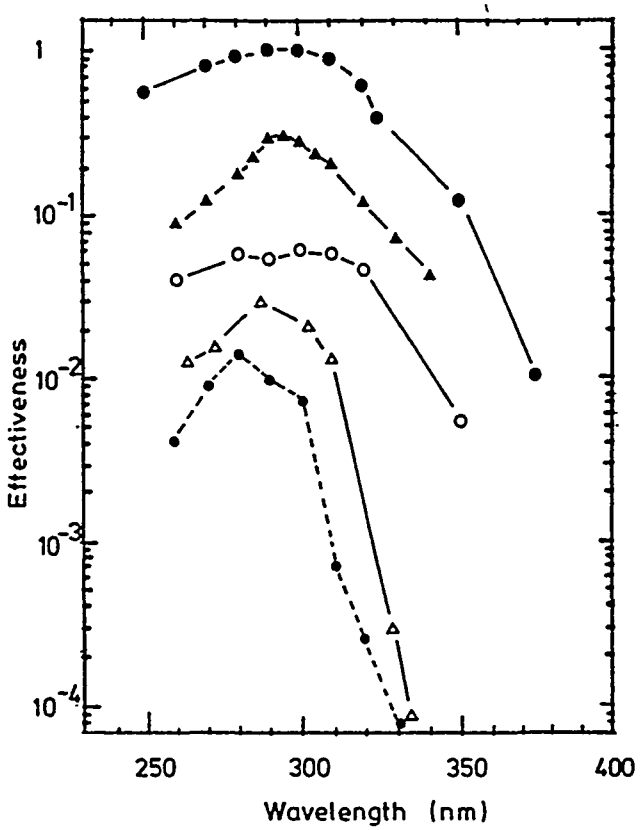

Fig. 7. Action spectra for flavonoid synthesis induction in Spirodela; --●--, anthocyanins; (Ng et al. 1964), parsley --▲--, flavon glycosides; (Wellmann 1975), maize --○--, anthocyanins; (Beggs and Wellmann 1985), sorghum --△--, anthocyanins; (Yatsuhashi et al. 1982), and carrot cell culture --●--, anthocyanins; (Takeda and Abe 1992). (Adapted from Ensminger 1993).

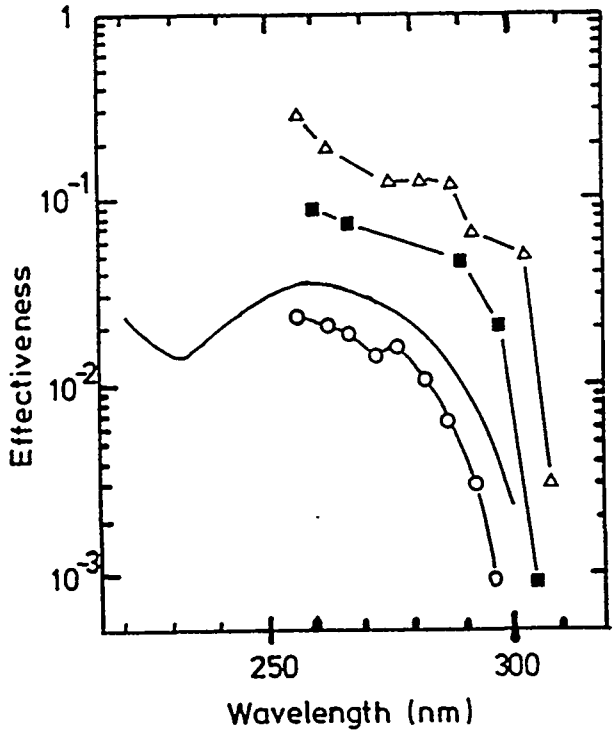

Fig. 8. Action spectra for mesocotyl coiling in sorghum (△) ,(Hashimoto et al. 1984), root growth inhibition in cress (■) , (Steimetz and Wellmann 1986), and anthocyanin induction inhibition in sorghum (○), (Hashimoto et al. 1991), and the absorption spectrum of DNA (solid line).

source should be installed at small UV-B/PAR ratios.

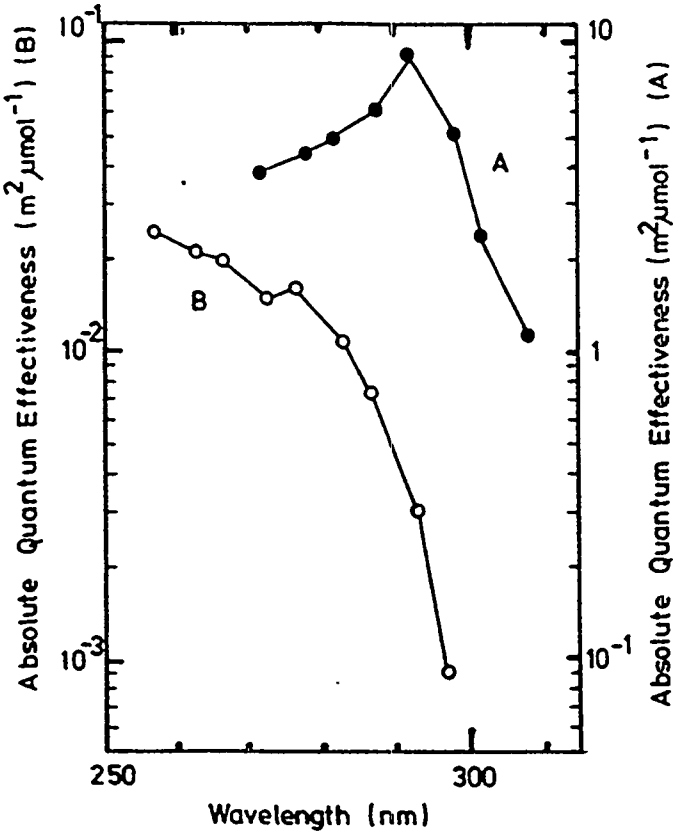

Fig. 9. Distinct effective waveband and different photon effectiveness between the photomorphogenetic actions and deleterious effects of UV-B, as represencted by anthocyanin induction (A) and inhibition (B). (Adapted from Hashimoto et al. 1991).

Since higher plants have developed their present characteristics under sunlight during the long process of evolution, it is quite natural that they adapted themselves to the present state of light environment. Higher plants seem to require all the spectrum bands, except for the band wavelengths 800 nm, of the sunlight coming on the Earth's surface. Blue, UV-A and UV-B light have their respective specific photomorphogenetic actions for higher plants, and are not replaced by light of other wavebands. These wavebands of radiation cooperate (UV-V, RL and BL) or counteract (BL and OL or RL) with light of other wavebands, and their requirements probably depend on the amount of other light. The situations make it difficult to draw a clear formula for lighting. We are required to take a case by case strategy, and gradually to obtain a better combination of individual wavebands. The processes of the development of lighting resembles that of prescription of a culture medium.

For the first step toward lighting formulation, the quantity of PAR should be fixed, because PAR seems to have an absolute quantity requirement. At this step the balance between the RL and BL components in the PAR should be considered. At the next step UV-A should be taken into account. It is less expensive in installment and operation than UV-B, although the functions of UV-A are not clear yet. Finally UV-B comes into consideration. To utilize the

beneficial effects of UV-B and minimizing its deleterious effects, caution should be exercised in the selection of its intensity and waveband.

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ANIMAL & HUMAN REQUIREMENTS

EFFECTS OF LIGHT ON BRAIN AND BEHAVIOR*

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INTRODUCTION

It is obvious that light entering the eye permits the sensory capacity of vision. The human species is highly dependent on visual perception of the environment and consequently, the scientific study of vision and visual mechanisms is a centuries old endeavor. Relatively new discoveries are now leading to an expanded understanding of the role of light entering the eye - in addition to supporting vision, light has various nonvisual biological effects. Over the past thirty years, animal studies have shown that environmental light is the primary stimulus for regulating circadian rhythms, seasonal cycles, and neuroendocrine responses (Aschoff, 1981a; Binkley, 1990; Reiter, 1991). As with all photobiological phenomena, the wavelength, intensity, timing and duration of a light stimulus is important in determining its regulatory influence on the circadian and neuroendocrine systems (Aschoff, 1981b; Cardinali et al., 1972; Takahashi et al., 1984; Brainard et al., 1983; Brainard et al., 1986). Initially, the effects of light on rhythms and hormones were observed only in sub-human species. Research over the past decade, however, has confirmed that light entering the eyes of humans is a potent stimulus for controlling physiological rhythms (Lewy et al., 1980; Moore-Ede et al., 1982; Wurtman et al., 1985; Czeisler et al., 1986). The aim of this paper is to examine three specific nonvisual responses in humans which are mediated by light entering the eye: light-induced melatonin suppression, light therapy for winter depression, and enhancement of nighttime performance. This will serve as a brief introduction to the growing database which demonstrates how light stimuli can influence physiology, mood and behavior in humans. Such information greatly expands our understanding of the human eye and will ultimately change our use of light in the human environment.

STIMULATION OF THE CIRCADIAN AND NEUROENDOCRINE SYSTEMS BY LIGHT

In most vertebrate species, it is known that light enters the eyes and stimulates the retina. Nerve signals are sent from the retina to the visual centers of the brain and permit the sensory capacity of vision. In addition, neural signals are sent from the retina into the hypothalamus, a non-visual part of the brain. The hypothalamus is a complex neural region that influences or controls many basic functions of the body including hormonal secretion, core temperature, metabolism and reproduction as well as higher cognitive functions such as memory and emotions (Morgane and Panskep, 1979). Information about environmental light is sent from the retina to a specific part of the hypothalamus, the suprachiasmatic nucleus (SCN) (Pickard and Silverman, 1981; Moore,

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* This manuscript previously published in *Biologic Effects of Light*, pg. 133-154, 1992, and published with permission of the Walter de Gruyter & Co., Berlin, Germany.

1983). This part of the brain is considered to be a fundamental part of the "biological clock", or circadian system, which regulates the body's physiological rhythms. The circadian system is thought to be responsible for controlling daily rhythms such as sleep and wakefulness, body temperature, hormonal secretion and other physiological parameters including cognitive function. It is now clear that light is the primary stimulus for regulating the circadian system, although other external stimuli such as sound, temperature and social cues may also influence the body's timing functions (Aschoff, 1981a; Binkley, 1990).

The SCN relays retinal information to many of the major control centers in the nervous system (Moore, 1983). One nerve pathway that carries non-visual information about light extends from the SCN to the pineal gland via a multisynaptic pathway with connections being made sequentially in the paraventricular hypothalamus, the upper thoracic intermediolateral cell column, and the superior cervical ganglion (Moore, 1983; Klein et al., 1983). Cycles of light and darkness relayed by the retina entrain SCN neural activity which, in turn, entrains the rhythmic production and secretion of melatonin from the pineal. In humans and all other vertebrate species studied to date, high levels of melatonin are secreted during the night and low levels are released during the day (Binkley, 1990; Reiter, 1991; Lewy et al., 1980; Vaughan et al., 1976).

THE EFFECTS OF LIGHT INTENSITY AND WAVELENGTH ON MELATONIN SUPPRESSION

In addition to entraining melatonin secretion from the pineal gland, light can have an acute suppressive effect on melatonin . Specifically, exposure of the eyes to light during the night can cause a rapid decrease in the high nocturnal synthesis and secretion of melatonin (Brainard et al., 1983; Klein and Weller, 1972; Rollag and Niswender, 1976). Early studies on humans did not demonstrate the acute suppressive influence of light on plasma melatonin (Vaughan et al., 1976; Jimerson et al., 1977; Wetterberg, 1978; Vaughan et al., 1979). However, Lewy and colleagues (1980) demonstrated that exposing the eyes of normal volunteers to 2500 lux of white light during the night induced an 80% decrease in circulating melatonin within one hour. In contrast, volunteers exposed to 500 lux of white light exhibited no significant melatonin suppression (Lewy et al., 1980). Earlier attempts at suppressing melatonin in humans with light failed when investigators used typical indoor light levels of 100 to 800 lux (Vaughan et al., 1976; Jimerson et al., 1977; Wetterberg, 1978; Vaughan et al., 1979). Whereas such typical room light would be sufficient for suppressing melatonin in many animal species (Binkley, 1990; Reiter, 1991; Brainard et al., 1983; Klein and Weller, 1972; Rollag and Niswender, 1976), and would be adequate for human vision, it was not enough to suppress melatonin in those experiments. Simply put, it takes much more light to suppress melatonin than is required for vision. The discovery that much brighter light is needed to suppress melatonin in humans provided the groundwork for numerous studies on the internal responses of humans to bright artificial light. However, the notion that only "bright" light can drive neuroendocrine and circadian responses is not entirely accurate.

To begin with, the term "bright" refers to a subjective visual sensation and is thus a relative descriptor (Kaufman, 1984). A 2500 lux light indoors indeed appears "bright" relative to typical indoor levels ranging from 100 to 800 lux. In contrast, 2500 lux of light outdoors is relatively dim compared to daylight at high noon which reaches 100,000 lux (Thorington, 1985). Several years after it was discovered that light at 2500 lux can suppress melatonin in humans, a study

was done to more precisely determine the dosages of light needed to suppress melatonin in normal volunteers (Brainard et al., 1988). In that study, six normal males were exposed to carefully controlled intensities of monochromatic green light at 509 nm for one hour during the night. Specifically, the volunteers were continuously exposed to the experimental light between 02:00 and 03:00 hours with their pupils fully dilated by a mydriatic agent, their heads held steady relative to the light source by an ophthalmologic head holder, and with translucent white integrating spheres covering both eyes. This procedure produced a constant and uniform illumination of the whole retina during the entire light exposure. The data from this experiment (Figure 1) demonstrated that light affects a human hormone in a dose-response fashion: i.e., the brighter the photic stimulus the greater the suppression of melatonin (Brainard et al., 1988).

It is interesting that all of the stimuli used in this study activated the visual system: both the volunteers and the experimenters saw all the different light intensities and accurately reported them to be green. The lower light intensities, however, did not change hormone levels whereas the higher intensities induced a 60-80% decrease in this hormone. Thus, light that activates vision does not necessarily cause neuroendocrine change. It appears to be generally true in both animals and humans that much more light is needed for biological effects than for vision. The data shown in Table 1 provide the photometric and radiometric values for the stimuli used in constructing this dose-response function.

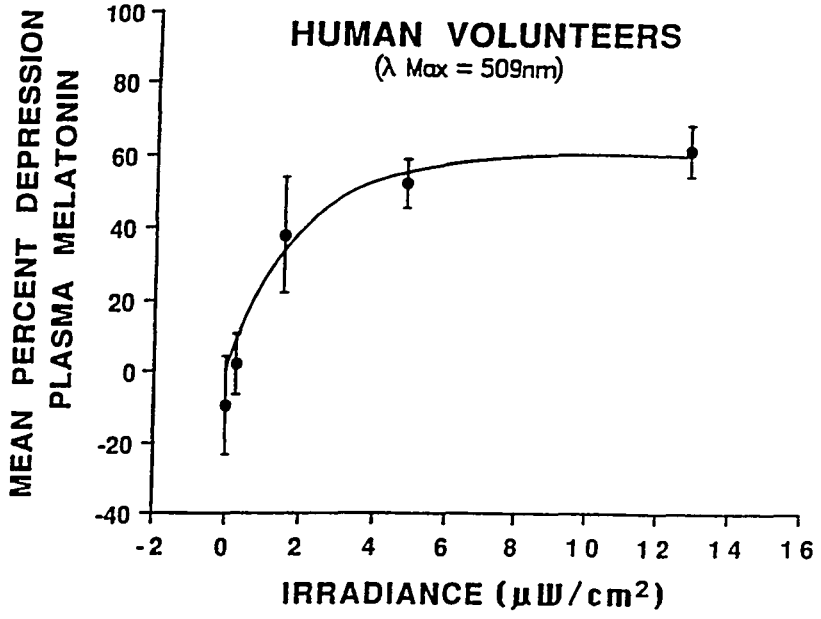

Fig. 1. The dose-response relationship between green monochromatic light (509 nm, 10 nm half-peak bandwidth) exposure of normal volunteers eyes and suppression of the hormone melatonin (Brainard et al., 1988). Data points indicate mean ± SEM.

TABLE 1 Radiometric and Photometric Stimuli Used in the Melatonin Dose-Response Curve (Brainard et al., 1988)

$\mu W/cm^2$	photons/cm^2	photopic lux	scotopic lux	% melatonin suppression
0.01	9.19×10^{13}	0.03	0.17	-9.67
0.3	2.76×10^{15}	1.03	5.25	1.83
1.6	1.47×10^{16}	5.50	27.98	37.33
5.0	4.59×10^{16}	17.18	85.90	51.67
13.0	1.19×10^{17}	44.66	227.37	60.67

The demonstration of the dose-response function for light suppression of melatonin in humans produced an unexpected result: very bright light is not necessarily needed for melatonin suppression. As demonstrated by Table 1, the mean threshold illuminance for suppressing melatonin was between 5 and 17 lux in normal volunteers - a level of illumination equal to civil twilight and well below typical indoor light . This means that under the proper conditions, 25 to 100 times less light can suppress melatonin than originally thought (Lewy et al., 1980). Why did ambient room light at levels much higher than 17 lux not suppress melatonin in earlier experiments? In those early studies (Lewy et al., 1980; Vaughan et al., 1976; Jimerson et al., 1977; Wetterberg, 1978; Vaughan et al., 1979), neither the exposure conditions nor the light stimuli were optimized. Often the experimental light stimulus consisted of turning on the overhead light provided with the experimental room. In almost any given room, it is possible to vary the light illuminance entering the eyes by a factor of 10 simply by changing the direction of gaze. Thus, in a room characterized as having "typical" illumination levels of 500 lux, the occupants may be able to see up to 500 lux if they look directly towards the light fixtures, but if they look at the floor or walls, this light reaching their eyes may be as low as 50 lux. Furthermore, the pupil of the eye adjusts dynamically to further restrict the amount of light which reaches the retina. A maximally restricted pupil can reduce the light reaching the retina to as little as one sixteenth of the light falling on the cornea (Sliney and Wolbarsht, 1980). In addition, the amount of the retina exposed to the light stimulus varies greatly with the geometry of the light source and the relative direction of gaze. A recent study by Gaddy (1992) and colleagues has shown partial retinal exposure is less effective compared to the whole retinal exposure for suppressing melatonin (Gaddy et al., 1992). Finally, the amount of light entering the eye can be further reduced by shadowing of the cornea by the bony orbit, squinting and eye blink. Thus, both behavioral and ocular factors can functionally reduce the amount of light reaching the retina to a level where it is not effective in suppressing melatonin levels. In the early studies, we presume that no efforts were made to control pupil size, direction of gaze, and retinal field exposure since none of these experimental details were reported. Hence, in those experiments "ordinary room levels of illumination" did not suppress melatonin (Lewy et al., 1980; Vaughan et al., 1976; Jimerson et al., 1977; Wetterberg, 1978; Vaughan et al., 1979) and only when much brighter light was used (Lewy et al., 1980) could hormone production be altered. However, it is clear that very low levels of light can indeed suppress melatonin when the exposure factors are optimized (Brainard et al., 1988).

In addition to exposure factors and light intensity being critical in determining if a light stimulus will suppress melatonin, the spectral quality of light is important in determining its relative biological impact. Studies done on the effects of different wavelengths on hamsters, rats and

mice suggest that wavelengths in the blue and green portion of the spectrum have the strongest impact on circadian and neuroendocrine regulation (Cardinali et al., 1972; Takahashi et al. 1984; Brainard et al., 1984; Brainard et al., 1985; Vaughan et al., 1985; Brainard et al., 1986; Bronstein et al., 1987; Podolin et al., 1987; Thiele and Meissl, 1987; Millette et al., 1987; Benshoff et al., 1987; Brainard et al., 1987; Brainard et al., 1991a). Some data have supported the hypothesis that the rod photopigment rhodopsin is the primary receptor for circadian and neuroendocrine regulation (Cardinali et al., 1972; Takahashi et al. 1984; Brainard et al., 1984; Podolin et al., 1987; Thiele and Meissl, 1987; Benshoff et al., 1987; Brainard et al., 1987). In contrast, other data have suggested that one or more cone photopigments may be involved in these regulatory effects (Brainard et al., 1984; Podolin et al., 1987; Thiele and Meissl, 1987; Millette et al., 1987; Benshoff et al., 1987; Brainard et al., 1987). It is important to note that while the highest sensitivity is in the blue-green range, this does not preclude other wavelengths from participating in circadian and neuroendocrine regulation. For example, in terms of melatonin suppression, short wavelengths in the ultraviolet region of the spectrum (Podolin et al., 1987; Benshoff et al., 1987; Brainard et al., 1987; Brainard et al., 1991a) and longer wavelengths in the red portion of the spectrum are quite capable of suppressing melatonin in rodents if the intensity is sufficiently high (Vanecek and Illnerova, 1982; Nguyen et al., 1990; Broker et al., 1990). Further studies are required to conclusively identify what specific photoreceptors and photopigments are involved in regulating the circadian and neuroendocrine systems in animals.

Only one study has specifically examined wavelength regulation of melatonin in humans (Brainard et al., 1988). That study suggested that the peak sensitivity for melatonin suppression is in the blue-green range as seems to be the case in some lower mammals. It is premature, however, to draw any conclusions as to what photoreceptors are involved in any nonvisual physiological regulation in humans.

USE OF LIGHT TO TREAT WINTER DEPRESSION

While research over the past decade has proceeded on the biological effects of light in humans, concurrent studies have tested the use of light as a therapeutic tool for improving mood and psychological status of patients diagnosed with winter depression. It has been noted since antiquity that some individuals are adversely affected by the changing seasons. More recently, the specific condition of fall and winter depression or Seasonal Affective Disorder (SAD), has been formally described in the scientific literature (Lewy et al., 1982; Rosenthal et al., 1984; Rosenthal et al., 1988; Terman et al., 1989a; Terman and Terman, 1992) and been included in the latest edition of the American Psychiatric Association's diagnostic manual (DSM-III-R, American Psychiatric Association, 1987). People affected with this malady often experience a dramatic decrease in their physical energy and stamina during the fall and winter months. As daylengths become shorter and temperatures become cooler, individuals with SAD often find it increasingly difficult to meet the demands of life - they can not function well in their jobs or can not cope with everyday family life. In addition to a general decrease in energy, they experience emotional depression and feelings of hopelessness and despair. Other symptoms of winter depression or SAD may include increased sleepiness and need for sleep, increased appetite (particularly for sweets and other carbohydrates), and a general desire to withdraw from society. People afflicted with this malady often feel compromised in meeting the ordinary demands and responsibilities of everyday life. Fortunately, among those who are accurately diagnosed with

SAD, daily light therapy has been found to effectively reduce symptoms in many patients (Lewy et al., 1982; Rosenthal et al., 1984; Rosenthal et al., 1988; Terman et al., 1989a; Terman and Terman, 1992).

There are now numerous clinics across the United States that offer light therapy for people who are afflicted with winter depression (Rosenthal, 1990; Society for Light Treatment and Biological Rhythms, 1991a). Specific treatment protocols vary somewhat between different clinics. One frequently used procedure involves a patient sitting at a specific distance from a fluorescent light panel which provides a 2500 lux exposure when looking directly at the lamp. The patient is told not to gaze steadily at the bright light, but rather to glance directly at the unit for a few seconds each minute over a two hour period. During the therapy period, a patient may read, watch television, work at a computer or do other hand work. Patients often respond to this therapy after two to seven days of light treatment and continue to benefit as long as the treatment is repeated daily throughout the months that the individual experiences winter depression (Rosenthal et al., 1984; Rosenthal et al., 1988; Terman et al., 1989a; Terman and Terman, 1992).

The white light used for treating SAD can be effectively provided by a range of lamp types including incandescent, cool-white fluorescent, and "sunlight simulating" fluorescent, (Lewy et al., 1982; Rosenthal et al., 1984; Rosenthal et al., 1988; Terman et al., 1989a; Terman and Terman, 1992; Yerevanian et al., 1986; Lewy et al., 1987; Terman et al., 1990; Stewart et al., 1990; Moul et al., 1993; Joffe et al., 1993; Terman et al, 1989b; Avery et al., 1993). Furthermore, there is an assortment of light devices available for treating SAD. Light therapy instruments come in a variety of shapes and configurations including workstations (Terman et al., 1990), head-mounted light visors (Stewart et al., 1990; Moul et al., 1993; Joffe et al., 1993) and automatic dawn simulators (Terman et al, 1989b; Avery et al., 1993). These devices are configured to shorten therapeutic time, increase patient mobility or to permit therapy during the sleep period. Doubtless there will be continued development, diversification and improvement of light therapy devices and strategies.

THE EFFECTS OF DIFFERENT WAVELENGTHS IN SAD PHOTOTHERAPY

Current evidence supports the hypothesis that light therapy for SAD works by way of light shining into the eyes as opposed to light on the skin (Wehr et al., 1987). It is not known, however, what ocular photoreceptors or photopigments mediate the therapeutic benefits of light in winter depression. To date, three consecutive studies have specifically compared different portions of the spectrum for clinical efficacy in treating SAD (Brainard et al., 1990; Oren et al., 1991; Stewart et al., 1991). In the first study, 18 patients were treated with an equal photon dose of white, blue or red light for a period of one week. The photon dose of 2.3×10^{15} photons/cm^2/sec was selected because this particular photon density of broad spectrum white light (400-760 nm half-peak bandwidth, Vitalite® lamps, Durotest Corp.) had been shown in many previous studies to be clinically effective in one week of therapy (Rosenthal et al., 1988; Terman et al., 1989a). The red and blue light sources used in this study (F40R and F40BB lamps, Westinghouse Div., Philips Inc.) had half-peak bandwidths of approximately 615-685 nm and 430-465 nm, respectively. Patients' clinical status before and after light therapy was followed by means of the 21-item Hamilton Depression Rating Scale (HDRS), a standard scale for measuring symptoms associated with depression (Hamilton, 1967). The results of this study are illustrated in Figure 2.

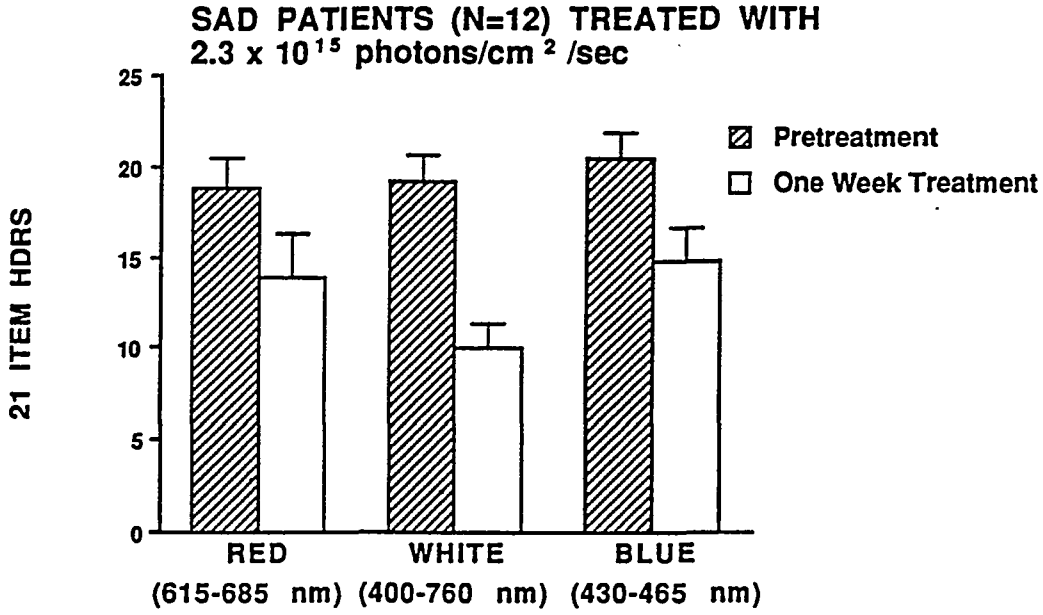

Fig. 2. The bars in this graph indicate mean + SEM Hamilton Depression Rating Scale values for patients before treatment (hatched bars) and after one week of treatment with equal photon densities of different light spectra (open bars). Numbers in parentheses indicate the half-peak bandwidth of the light source (Brainard et al., 1990).

This study was the first step towards defining an action spectrum of light therapy for winter depression. As shown in Figure 2, one week of light therapy with each of the three light sources produced an improvement in depression symptoms among the groups of patients tested. Specifically, the percent drop in mean HDRS scores were 26%, 47% and 27% for the red, white and blue light sources, respectively. Thus, the photon density emitted from the white light source elicited a significantly stronger clinical response compared to the results obtained from an equal photon density from the blue and red light sources (Brainard et al., 1990). This suggests that broad spectrum white light at this particular photon density is superior to restricted bandwidths of light in the red and blue portions of the visible spectrum. That result implies that light sources for SAD light therapy could not be improved by narrowing the wavelengths provided and shifting them towards either end of the visible spectrum. It is logical, however, to question the relative efficacy of a green bandwidth of light for treating winter depression.

To resolve that question, a second study was done comparing green light to red light at 2.3×10^{15} photons/cm^2/sec for treating SAD (Oren et al., 1991). The green and red light (F40G and F40R lamps, Westinghouse Div., Philips Inc.) had half-peak bandwidths of approximately 505-555 nm and 615-685 nm, respectively. Patients' clinical status before and after one week of light therapy was followed by means of the 21-item HDRS. The results of this study are illustrated in Figure 3.

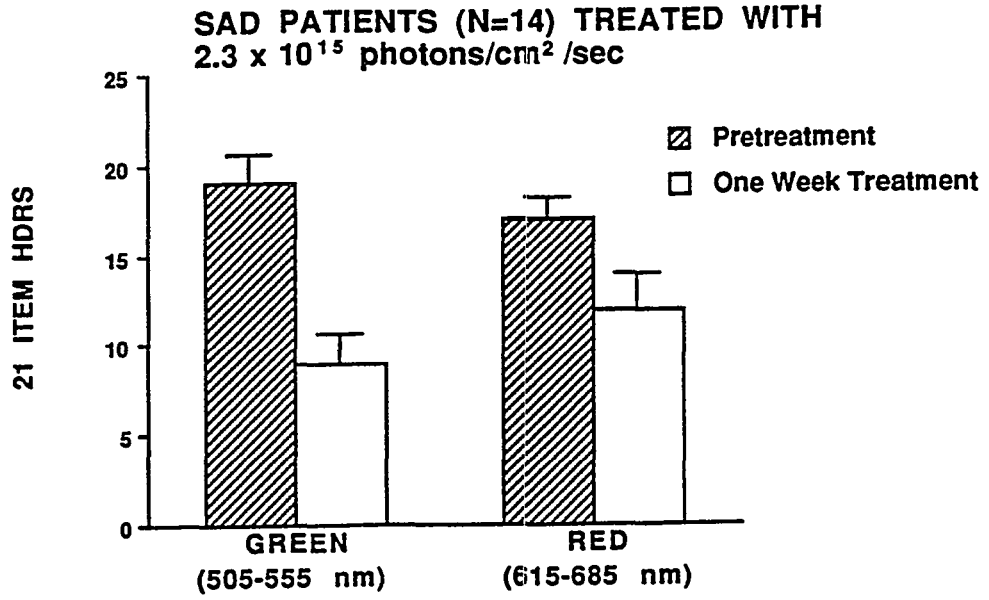

Fig. 3. The bars in this graph indicate mean + SEM HDRS values for patients before treatment (hatched bars) and after one week of treatment with equal photon densities of green or red light. Numbers in parentheses indicate the half-peak bandwidth of the light source (Oren et al., 1991).

As illustrated in Figure 3, one week of light therapy with both green and red light sources produced an improvement in depression symptoms in the groups of patients tested. The percent reduction in mean HDRS scores was 51% and 30% for the green and red light sources, respectively. Hence, at this photon density, green light was significantly stronger than the red light for treating winter depression (Oren et al., 1991). The results of this study (Figure 3) considered alongside the results from the study comparing red, white and blue light therapy at the same photon density (Figure 2) suggest that broad spectrum white light and narrower band green light are equivalent in their capacity to reduce symptoms of SAD. Between the two studies, white and green light treatments were associated with a 48% and 53% reduction in HDRS scores, respectively. Comparisons of group responses between different studies, however, are not conclusive. Are white and green light really equivalent in their phototherapeutic strength?

To answer that question, 12 patients were given one week of light therapy for SAD with either green or white light at an equal photon density (Stewart et al., 1991). Since therapy with white and green light appeared to cause roughly equivalent HDRS reductions across the first two studies, the experimental photon density was lowered to 1.23 x 10^{15} photons/cm²/sec in the third study. As in the first two studies, patients' clinical status before and after one week of light therapy was followed by means of the 21-item HDRS. The results of this study are illustrated in Figure 4.

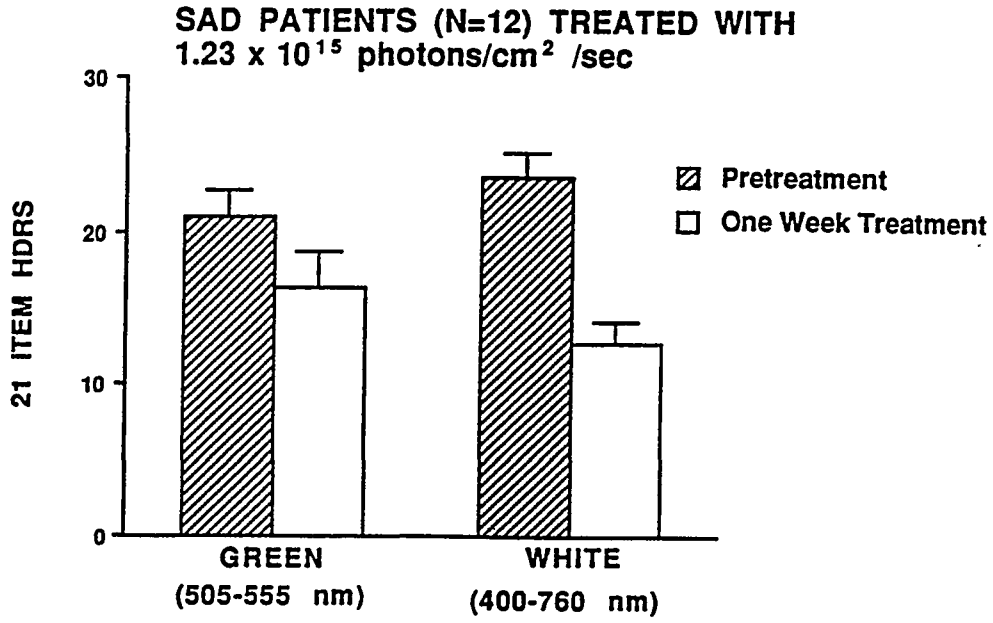

Fig. 4. The bars in this graph indicate HDRS values (mean + SEM) for patients before treatment (hatched bars) and after one week of treatment with equal photon densities of white or green light. Numbers in parentheses indicate the half-peak bandwidth of the light source (Stewart et al., 1991).

As shown in Figure 4, one week of therapy with each of the light sources produced an improvement in depression symptoms. Specifically, the percent drop in mean HDRS scores was 22% for the green light and 46% for the white light sources. At this lower photon density, white light was superior to the green light in treating SAD (Stewart et al., 1991). Hence, in this study, white and green light were not equivalent in their therapeutic efficacy as the preliminary comparison of the data from the first two wavelength studies suggested.

Together, these three studies form the ground work for determining the action spectrum for SAD light therapy (Brainard et al., 1990; Oren et al., 1991; Stewart et al., 1991). The traditional approach to defining a complete action spectrum, however, requires substantially more testing (Coohill, 1991). A thoroughly defined action spectrum can guide the development of light treatment devices that emit the optimum balance of wavelengths for treating SAD. Furthermore, an action spectrum will yield important information about the photosensory mechanism(s) responsible for the beneficial effects of light therapy. Currently, it is premature to predict what photopigment(s) or photoreceptor(s) mediate the antidepressant effects of light.

A practical issue debated among SAD researchers concerns the role of ultraviolet radiation (UV) in light therapy. Most of the early studies on SAD therapy successfully utilized fluorescent lamps that emitted white light containing a portion of UV wavelengths (Rosenthal et al., 1988; Terman et al., 1989a). Those early results erroneously led to the suggestion that UV wavelengths are necessary for successful therapy. The literature, however, shows clearly that SAD symptoms can be reduced by lamps which emit little or no UV (Yerevanian et al., 1986; Lewy et al., 1987; Stewart et al., 1990; Moul et al., 1993; Joffe et al., 1993; Brainard et al., 1990;

Oren et al., 1991; Stewart et al., 1991; Lam, 1991). Hence, UV wavelengths do not appear to be necessary for eliciting positive therapeutic results. Does this rule out UV having any role in relieving winter depression? Studies demonstrate that UV wavelengths can regulate seasonal reproduction, melatonin production, and circadian rhythms in some animal species (Brainard et al., 1985; Vaughan et al., 1985; Podolin et al., 1987; Benshoff et al., 1987; Brainard et al., 1987; Brainard et al., 1991a). Furthermore, in normal, healthy humans up to the age of at least 25 years, UV-A can be detected by the visual system (Tan, 1971; Brainard et al., 1992; Sanford et al., 1992). Although the latest studies show no decrement in therapeutic response when UV is specifically excluded in SAD treatment, they do not demonstrate that UV is totally noncontributory. Whether or not UV wavelengths can contribute to the optimum balance of wavelengths for SAD therapy remains an open question.

The data presented here make it clear that several methodological problems will have to be overcome before further progress can be made in defining an action spectrum for SAD light therapy. One complication for the wavelength studies and nearly all studies on SAD involves the fact that they are done on an outpatient basis. Hence, patient compliance on treatment timing, frequency and duration cannot be closely controlled even with the most cooperative subjects. Furthermore, very small changes in gaze direction and patient position relative to the light source can cause great variability in the amount of light transmitted to the patients' eyes (Gaddy, 1990; Dawson and Campbell, 1990). Did patients have different gaze behaviors or different patterns of light usage with the different wavelength light sources? The optimum method of comparing different wavelengths - or any other photic parameter - for SAD therapy is to work with more carefully controlled exposures. As demonstrated in the melatonin suppression studies, tight control of ocular light exposure permits substantially lower light levels to regulating hormone secretion. Could the general requirement of 2500 lux or more for SAD therapy be a compensation for differences in patient compliance and exposure variables?

Across the three wavelength studies outlined above, each light treatment produced some therapeutic improvements. Does this indicate that each light was at least partially effective in treating SAD symptoms, or are some of the therapeutic benefits of light therapy due to a non-specific or placebo response? Since patient expectations of treatment outcome are thought to contribute significantly to the placebo effect, evaluation of expectations before treatment is one strategy for approaching this question. Prior to any light treatment, subject expectations were systematically probed in each of the three wavelength studies. In general, all subjects had positive expectations about the success of light therapy but there were no differences between the expectations for the different light spectra in these studies (Brainard et al., 1990; Oren et al., 1991; Stewart et al., 1991). This evidence supports the idea that some of the therapeutic benefit of the different light spectra may have been due to a placebo response but that the differential therapeutic responses to the different light spectra were not merely an extension of the patients' preconceived beliefs.

In the medical literature it has been well documented that patients with a wide range of disorders - depression, schizophrenia and anxiety as well as cancer, diabetes and ulcers - can successfully respond to inactive or placebo treatments (Ross and Olson, 1981; Eastman, 1990a; Eastman et al., 1993). Hence it would be remarkable if SAD patients did not show some level of placebo response to light therapy. In fact, therapeutic improvements are almost always observed with

light treatments regardless of light intensity, wavelength and duration (Rosenthal et al., 1988; Terman et al., 1989a; Terman and Terman, 1992). Although it is obvious that light therapy indeed will reduce patients' depression symptoms, the critical question is how much of the patients' response to light therapy is due to a non-specific placebo response versus a genuine clinical response? This remains an open question in the SAD field and has been discussed most insightfully by Eastman (1990a). Unfortunately, until this question is resolved, a more conclusive action spectrum for SAD phototherapy may not be possible. The inability to accurately separate placebo responses from genuine clinical antidepressant responses causes an element of "noise" in phototherapy data which seriously hinders the accurate discrimination of differential wavelength effects in light therapy.

USE OF LIGHT FOR ENHANCING PERFORMANCE AND TREATING PROBLEMS OF NIGHT WORKERS

Over the past decade, most of the studies on light therapy have been concerned with winter depression. Other research, however, has begun to extend the applications of light therapy. Investigators have had some success in treating certain sleep disorders with phototherapy (Rosenthal et al., 1990; Dawson et al., 1989). In addition, studies have indicated that individuals with either non-seasonal depression (Yerevanian et al., 1986; Kripke et al., 1989) or pre-menstrual syndrome (PMS) may benefit from light therapy (Parry et al., 1987; Parry et al., 1989). Much more work needs to be done in determining the utility of light for treating these disorders. It appears that we are entering a frontier of medicine in which man's biological response to light is being harnessed to alleviate specific illnesses. Such medical developments have encouraged investigators to explore the possibilities of using light for various domestic or non-medical applications.

One area of study involves the function and dysfunction of the human circadian physiology under more challenging situations. Some preliminary studies have tested the use of strategic light exposure to prevent or ameliorate jet lag (Daan and Lewy, 1984; Wever, 1985; Cole and Kripke, 1989). The preliminary findings are generally positive and some investigators are optimistic that light will be a useful tool for quickly resetting the traveler's internal biological clock and overcoming some of the problems associated with jet travel over multiple time zones. There is a consensus among scientists however, that the data in this field - as of August, 1991 - are preliminary and insufficient for a specific prescription on how to best use light for this modern malady (Society for Light Treatment and Biological Rhythms, 1991b).

Shift work may pose problems associated with circadian desynchronization analogous to that found in jet lag (Moore-Ede et al., 1982; U. S. Congress, 1991). Instead of rapidly flying to distant countries, the shift worker stays in one place but may just as suddenly change the time period that he is awake or asleep. By the broadest definition, shift workers are individuals who do not work a standard daytime schedule. Instead, they work nights, evenings, rotating shifts, split shifts or extended shifts. It is estimated that one out of five full time workers in the United States (20 million people) is a shift worker (U. S. Congress, 1991).

As Campbell and Dawson (1992) have reported, the two most common and destructive problems associated with shiftwork are reduced quality of sleep following night work and reduced

capacity to maintain alertness while at work. Thus, shift work has drawbacks in increased accidents, decreased production and performance deficits among those who are working at night when the body has a natural tendency to be asleep. Furthermore, evidence indicates that shift workers have increased health problems including higher risk to cardiovascular disease, gastrointestinal distress, as well as cognitive and emotional problems (Moore-Ede et al., 1982; U. S. Congress, 1991; Campbell and Dawson, 1992; Folkard and Monk, 1985; Eastman, 1990b; Moore-Ede et al., 1983; Akerstedt et al., 1984). Despite these deleterious effects on worker health and efficiency, the number of people involved in shift work is likely to increase. Researchers believe that poor chronobiological adjustment to a permanent or rotating schedule causes some of these ailments (U. S. Congress, 1991). Not all of these problems, however, are solely due to a maladapted biological clock. In addition to a desynchronized circadian system, shift workers generally tend to be chronically sleep deprived and experience domestic stresses that are more or less independent of circadian adaptation (Moore-Ede et al., 1982; U. S. Congress, 1991; Folkard and Monk, 1985) Hence, there is no single solution to all of the problems associated with shift work.

On the frontiers of shift work research, some investigators are attempting to develop strategies of light stimulation to improve circadian entrainment and to enhance performance and alertness in night workers. In one study, Czeisler and colleagues simulated a night shift routine in the laboratory and tested both biological adaptation and behavioral performance under different lighting stimuli (Czeisler et al., 1990). They found that workers given 7,000 to 12,000 lux of white fluorescent light during their work hours and complete darkness to sleep in during the daylight hours, adapted better biologically and had improved alertness and cognitive performance compared to subjects who worked under 150 lux of light and had no complete darkout for sleeping during the day (Czeisler et al., 1990). Other studies on simulated shift work have shown that exposure to bright white fluorescent light at specific times can improve sleep quality, enhance performance and speed the adjustment of the circadian system (Society for Light Treatment and Biological Rhythms, 1991b; Campbell and Dawson, 1992; Eastman, 1990b). All of these studies were aimed primarily at finding a means of improving adjustment of the circadian system, sleep quality and performance of the shift worker. This experimental approach requires a minimum of 3 to 5 testing days and, under optimum conditions, even longer test periods to adequately discern circadian and sleep changes.

A different experimental approach has been to examine the immediate effects of light stimuli in a single night of work or during prolonged periods of work. The principal focus of this research has been to determine if bright light stimuli can help sustain alertness without degrading performance. In a study by French and colleagues (1990), healthy young volunteers stayed awake and worked continuously at a computer for 30 hours, taking only short breaks to eat or go to the bathroom. While working under 3,000 lux of white fluorescent light during 18:00 to 06:00 hours, the volunteers exhibited significantly improved behavioral and cognitive performance on selected tasks compared to their own performance on a separate occasion under 100 lux. In addition to these behavioral effects, there were significant differences in the body temperatures, plasma cortisol levels and plasma melatonin levels in these volunteers under the bright versus dim light condition (French et al., 1990; Brainard et al., 1991b). A similar study done in a separate laboratory has also shown that young men doing night work from 21:00 to 08:00 hours under 5000 lux of white light performed better on selected behavioral tasks versus when they

worked under light at 50 lux (Hannon et al., 1991). Again, in this study body temperatures and melatonin levels were significantly influenced by light levels. In these acute studies, it is not clear how light is influencing performance. Could the correlated biological changes in body temperature and hormone levels be directly related to improvement in behavioral tests? Is the circadian system involved in these acute effects of light? Are the acute effects of light due to a "masking" of circadian rhythms? Clearly, further studies are needed to clarify the mechanism(s) by which light enhances performance.

There are many occasions when individuals work through the night on an irregular basis, either by free choice, or by unexpected needs emerging in the home or at work. What are the longer term consequences of a single night of bright light exposure for improving alertness and performance? Will the short term gains of enhanced performance or alertness be offset by a longer term disruption of circadian physiology when the individual returns to a regular schedule? This new research raises many unanswered questions. As with jet lag applications, there is a consensus among scientists - as of September, 1991 - that it is still premature to formulate a set prescription on how to best use light for both short term and long term work applications (Society for Light Treatment and Biological Rhythms, 1991b; U. S. Congress, 1991). Much additional work is needed in both laboratory simulations and field tests before the overall consequences of using bright light stimuli can be determined and the optimum lighting strategy can be recommended for the varieties of shift work.

As with research on phototherapy for SAD and other disorders, it should be noted that the studies on using light stimuli to improve problems associated with night work may have complications of placebo responses. Simply put, most volunteers can readily see that a manipulation of light is part of the experiment. In such a circumstance, the investigator runs the distinct risk of finding a placebo reaction to the specific light treatments. There are good experimental strategies which can help address the potential problem of a placebo response and some of them are discussed above. One of the best means to avoid placebo problems in lighting studies is to collect both behavioral and biological data. Whereas behavioral variables and subjective mood states may be quite susceptible to the volunteers' mental preconceptions, objective biological variables such as circadian rhythms, hormone levels, electrophysiological responses, body temperature, urine volume and the like are much less likely to be directly influenced by a placebo response. Collecting physiological and behavioral measures together can greatly improve the reliability of data on nonvisual biological effects of light of light.

CONCLUSION

Experimental research on animals during the past thirty years and on humans in the past decade confirm that light can strongly influence the physiology and behavior of many species. With humans, light is a primary stimulus to the circadian system and can regulate many biochemical and physiological processes in the body. The critical parameters of light intensity and wavelength needed to provide this nonvisual biological stimulation are still under study. In addition to these biological effects of light, a high percentage of patients who suffer from winter depression are responsive to bright light therapy. Other clinical disorders also may be treatable with light stimuli. Further pioneering studies are now examining the use of light to improve performance and ameliorate problems associated with shift work. Taken together, these studies

provide the initial database for a frontier in medicine and biology. Beyond therapeutic applications, however, what are the potential consequences of this research?

Modern man has become very sophisticated in the specific use of light in his living and working environment. Currently, building interiors are illuminated for three main purposes: 1) providing light for visual performance; 2) providing light for visual comfort; and 3) providing light for aesthetic appreciation of the environment and its contents (Kaufman, 1984; Kaufman, 1987). The studies discussed here demonstrate that light can also influence human physiology, mood and behavior. These data may be the seeds for a revolution in architectural lighting. It is appropriate to begin exploring ways to incorporate these laboratory results into practical architectural lighting designs. Such designs will need to optimize architectural light for nonvisual biological stimulation as well as follow the traditional guidelines for providing correct visual stimulation and comfort. In the long range, this new design consideration is likely to dramatically alter illumination strategies for homes, factories, offices, schools, hospitals and most interior living spaces.

ACKNOWLEDGMENTS

This paper is an updated and slightly modified version of a chapter entitled "Biological Effects of Light in Humans: the Regulation of Physiology, Mood and Behavior" which appeared in Biologic Effects of Light (M.F. Holick and A. M. Kligman, eds.) Walter de Gruyter & Co., New York 1992. Special thanks to John Hanifin for his astute assistance in revising this manuscript. Supported, in part, by grants from NIMH (#R3MH44890A), Lighting Research Institute (#91 SP1), NASA (# NAGW 1196), USAFOSR (#91-0271) and the Philadelphia Section of the Illuminating Engineering Society.

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OCULAR HAZARDS OF LIGHT

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BACKGROUND

The eye is protected against bright light by the natural aversion response to viewing bright light sources. The aversion response normally protects the sun against injury from viewing bright light sources such as the sun, arc lamps and welding arcs, since this aversion limits the duration of exposure to a fraction of a second (about 0.25 s).

There are at least five separate types of hazards to the eye and skin from optical sources:[1]

(a) Ultraviolet photochemical injury to the skin (erythema and carcinogenic effects), and to the cornea (photokeratitis) and lens (cataract) of the eye (180 nm to 400 nm).

(b) Thermal injury to the retina of the eye (400 nm to 1400 nm).

(c) Blue-light photochemical injury to the retina of the eye (principally 400 nm to 550 nm; unless aphakic, 310 to 550 nm)[2]

(d) Near-infrared thermal hazards to the lens (approximately 800 nm to 3000 nm).

(e) Thermal injury (burns) of the skin (approximately 400 nm to 1 mm) and of the cornea of the eye (approximately 1400 nm to 1 mm).

The principal retinal hazard resulting from viewing bright light sources is photoretinitis, e.g., *solar retinitis* with an accompanying scotoma which results from staring at the sun. Solar retinitis was once referred to as "eclipse blindness" and associated "retinal burn." Only in recent years has it become clear that photoretinitis results from a photochemical injury mechanism following exposure of the retina to shorter wavelengths in the visible spectrum, i.e., violet and blue light. Prior to conclusive animal experiments at that time (Ham, Mueller and Sliney, 1976), it was thought to be a thermal injury mechanism. However, it has been shown conclusively that an intense exposure to short-wavelength light (hereafter referred to as "blue light") can cause retinal injury.

The product of the dose-rate and the exposure duration always must result in the same exposure dose (in joules-per-square centimeter at the retina) to produce a threshold injury. Blue-light retinal injury (photoretinitis) can result from viewing either an extremely bright light for a short time, or a less bright light for longer exposure periods. This characteristic of photochemical injury

mechanisms is termed *reciprocity* and helps to distinguish these effects from thermal burns, where heat conduction requires a very intense exposure within seconds to cause a retinal coagulation; otherwise, surrounding tissue conducts the heat away from the retinal image. Injury thresholds for acute injury in experimental animals for both corneal and retinal effects have been corroborated for the human eye from accident data. Occupational safety limits for exposure to UVR and bright light are based upon this knowledge. As with any photochemical injury mechanism, one must consider the *action spectrum*, which describes the relative effectiveness of different wavelengths in causing a photobiological effect. The action spectrum for photochemical retinal injury peaks at approximately 440 nm.

CALCULATING RETINAL EXPOSURE

From knowledge of the optical parameters of the human eye and from radiometric parameters of a light source, it is possible to calculate irradiances (dose rates) at the retina. Exposure of the anterior structures of the human eye to ultraviolet radiation (UVR) may also be of interest; and the relative position of the light source and the degree of lid closure can greatly affect the proper calculation of this ultraviolet exposure dose. For ultraviolet and short-wavelength light exposures, the spectral distribution of the light source can also be important.

Quantities and units

Two sets of light-measurement quantities and units are useful in defining light exposure of the retina: *radiometric* and *photometric*. Radiometric quantities such as radiance--used to describe the "brightness" of a source [in $W/cm^2 \cdot sr$] and irradiance--used to describe the irradiance level on a surface [in W/cm^2] are particularly useful for hazard analysis. Radiance and luminance are particularly valuable because these quantities describe the source and do not vary with distance. Photometric quantities such as luminance (brightness in cd/cm^2 as perceived by a human "standard observer") and illuminance in lux (the "light" falling on a surface) indicate light levels spectrally weighted by the standard photometric visibility curve which peaks at 550 nm for the human eye (Figure 1). To quantify a photochemical effect it is not sufficient to specify the number of photons-per-square-centimeter (photon flux) or the irradiance (W/cm^2) since the efficiency of the effect will be highly dependent on wavelength. Generally, shorter-wavelength, higher-energy photons are more efficient.

Photometric quantities are hybrid quantities which are defined by an action spectrum for vision--a photochemically initiated process. Photometric quantities may not have much value in describing retinal effects other than vision or in research relating to neuroendocrine effects mediated by the visual system. Unfortunately, since the spectral distributions of different light sources vary widely, there is no simple conversion factor between photometric (either photopic or scotopic) and radiometric quantities. This conversion may vary from 15 to 50 lumens/watt (1m/W) for an incandescent source to about 100 1m/W for the sun or a xenon arc, to perhaps 300 to 400 lm/W for a fluorescent source (Sliney and Wolbarsht, 1980).[1]

HUMAN EXPOSURE LIMITS

A number of national and international groups have recommended occupational or public exposure limits (ELs) for optical radiation [i.e., ultraviolet (UV), light and infrared (IR) radiant energy]. Although most such groups have recommended ELs for UV and laser radiation, only one group has recommended ELs for visible radiation (i.e., light). This one group is well known in the field of occupational health--the American Conference of Governmental Hygienists (ACGIH). The ACGIH refers to its ELs as "Threshold Limit Values," or TLVs and these are issued yearly, so there is an opportunity for a yearly revision[3-4]. The current ACGIH TLV's for light (400 nm to 760 nm) have been largely unchanged for the last decade, although they have been on a tentative list for much of that time. They are based in large part on ocular injury data from animal studies and from data from human retinal injuries resulting from viewing the sun and welding arcs. The TLVs also have an underlying assumption that outdoor environmental exposures to visible radiant energy is normally not hazardous to the eye except in very unusual environments such as snow fields and deserts.

On the international scene there are currently no limits for optical radiation except for the special case of laser radiation. The International Non-ionizing Radiation Committee (INIRC) of the International Radiation Protection Association (IRPA) published Guidelines on Limits of Exposure to Laser Radiation in 1985[5] and revised them in 1988. INIRC guidelines are developed through collaboration with the World Health Organization (WHO) by jointly publishing criteria documents which provide the scientific data base for the exposure limits[6].

THE ACGIH THRESHOLD LIMIT VALUES

Ultraviolet Radiation

The ACGIH TLV[3] and the INIRC EL for exposure to the eye and skin to UVR is 3 mJ/cm^2-effective, when the spectral irradiance E_λ at the eye or skin surface is mathematically weighted against the hazard sensitivity spectrum S_λ from 180 nm to 400 nm as follows:

$$E_{eff} = \sum E_\lambda \cdot S_\lambda \cdot \Delta \lambda \qquad [1]$$

In addition to the above requirement, the ocular exposure is also limited to 1 J/cm^2 for periods up to 1000 s (16.7 min) and to 1 mW/cm^2 for greater periods. For this requirement, the total irradiance, E-uva, in the UV-A spectral region is summed from 315 nm to 400 nm:

$$\text{E-uva} = \sum E_\lambda \cdot \Delta \lambda \qquad [2]$$

where E_λ is the spectral irradiance in W/(cm^2-nm).

The permissible exposure duration, t_{max}, in seconds, to UVR is calculated by:

$$t_{max} = (3 \text{ mJ/cm}^2) / E_{eff} \text{ (W/cm}^2) \qquad [3]$$

and if the UV-A irradiance exceeds the 8-hour criterion of 1 mW/cm^2, the maximum exposure must also be less than:

$$t_{max} = (1\ J/cm^2) / E_{UVA}\ (W/cm^2) \qquad [4]$$

Retinal Thermal Hazards

The ACGIH TLV derived to protect the human retina from *thermal injury* requires the use of another spectral weighting function, R_λ.[18] The TLV for the hazardous radiance is termed L_{HAZ}, which is a function of the angular subtense α of the source (which is the light-source dimension D_L divided by the viewing distance r to give the angle in radians) and the exposure duration t (in seconds):

$$L_{HAZ} = 5 / \alpha \cdot t^{3/4} \quad [\text{in } W/(cm^2\text{-sr}] \qquad [5]$$

The spectral radiance L_λ of the source is weighted against the retinal hazard function R_λ and the resulting effective radiance must not exceed L_{HAZ}:

$$\Sigma\ L_\lambda\ R_\lambda\ \Delta\lambda \leq L_{HAZ} \qquad (\text{for } t < 10\ s) \qquad [6]$$

For small sources such as an optical fiber source, the closest distance at which the human eye can sharply focus upon a small object is about 10 cm. The value of 10 cm is an exceptionally small value for the near-point of accommodation for the human eye. At shorter distances the image of a light source would be out of focus and blurred.

Blue-Light Photochemical Retinal Hazard

The ACGIH TLV[3] to protect the human retina against photoretinitis,[7] "the blue-light hazard" is an effective blue-light radiance L_B of 100 J/(cm^2·sr), for t < 10,000 s, i.e.,

$$L_B = \Sigma\ L_\lambda \cdot B_\lambda \cdot \Delta\lambda \leq 100\ J/(cm^2\cdot sr)\ \text{effective} \qquad [7]$$

and for t > 10,000 s (2.8 hrs.):

$$L_B \leq 10\ mW/(cm^2\cdot sr) \qquad [8]$$

To calculate the maximum direct viewing duration when [8] is not satisfied, this maximum "stare time," t-max, is found by inverting Eqn. [7]:

$$t\text{-max} = 100\ J/(cm^2\cdot sr) / L_B \qquad [9]$$

For very small sources that subtend a viewing angle less than α_{MIN}, which is 11 mrad = 0.011 rad. The blue light hazard is evaluated by mathematically weighting the spectral irradiance, E_λ, against the blue-light hazard function to obtain E_B to give:

$$E_B = \Sigma E_\lambda \cdot B_\lambda \cdot \Delta\lambda \leq 10 \text{ mJ/cm}^2 \text{ for } t \leq 10{,}000 \text{ s} \quad [10]$$

and for $t > 10{,}000$ s (2.8 hrs.):

$$E_B \leq 1 \ \mu\text{W/cm}^2 \quad [11]$$

To calculate the maximum direct viewing duration when [11] is not satisfied, this maximum "stare time," t-max, is found by inverting Eqn. [10]:

$$\text{t-max} = 10 \text{ mJ/(cm}^2\cdot\text{sr)} / E_B \quad [12]$$

Retinal Photochemical Hazard to the Aphakic Eye.

The third type of retinal hazard--the aphakic photochemical retinal hazard--is evaluated by spectrally weighting the radiance against the aphakic retinal hazard function A_λ.[18] This photochemical retinal injury hazard is merely an extension of the blue-light hazard and must be analyzed only for individuals with at least one aphakic eye (i.e., an eye with the normal lens removed, as in cataract surgery). The approach is to substitute A_λ for B_λ in Eqns. [7] through [12]. For example, the aphakic hazard radiance L-aphake is:

$$\text{L-aphake} = \text{E-aphake}/\Omega \quad [13]$$

$$L_A = \Sigma L_\lambda \cdot A_\lambda \cdot \Delta\lambda \leq 100 \text{ J/(cm}^2\cdot\text{sr) effective for } t \leq 10{,}000 \text{ s (2.8 hrs.).} \quad [14]$$

Infrared Radiation Hazards to the Eye

Any calculation of potential retinal thermal hazards to the eye normally includes a consideration of the contributions of IR-A (700-1400 nm) and IR-B (1.4 μm-3.0 μm). In contrast to blue light, IR-A is very ineffective in producing retinal injuries (Ham, et al., 1982, 1976).[1,3] The data which could be used as the basis of an exposure limit for chronic exposure of the anterior of the eye to infrared radiation are very limited. Sliney and Freasier (1973) stated that the average corneal exposure from infrared radiation in sunlight was of the order of 1 mW/cm^2.[8] Glass and steel workers exposed to infrared irradiances of the order of 80-400 mW/cm^2 daily for 10-15 years have reportedly developed lenticular opacities.[8]

The ACGIH guideline for IR-A exposure of the anterior of the eye is a time-weighted total irradiance of 10 mW/cm^2 for exposure durations exceeding 1,000 s (16.7 minutes). Pitts, et al. (1979) showed that the threshold radiant exposures to cause lenticular changes from IR-A were of the order of 5000 J/cm^2.[7] Threshold damage irradiances were at least 4 W/cm^2. There is also a second ACGIH criteria to protect the retina against thermal injury from viewing specialized infrared illuminators which have visible light filtered out so that the aversion response stimulus is not present.[1]

RADIOMETRIC MEASUREMENTS REQUIRED

To evaluate the potential optical radiation hazard to the eye, the ultraviolet spectral irradiance at from 200 - 400 nm would be determined at the nearest location of the eye. Spectral irradiance and radiance of the light emitted from the source in the 400 - 770 nm range (and sometimes to 1,400 nm) may also be required to analyze potential retinal hazards to an observer. Spectral irradiance at longer wavelengths could also be measured, although a measurement of total irradiance in this region is sufficient. The spectral radiance can be determined by measuring the spectral irradiance at a fixed distance (e.g., 30 cm) and dividing by the solid angle Ω subtended by the source.

$$L_B = E_B/\Omega \qquad [15]$$

The spectral radiance is then independent of viewing distance because of the law of conservation of radiance.

Whenever spectroradiometric measurements are made for the purpose of a safety study, it is imperative that errors are not introduced. For this reason, it is useful to check measured spectroradiometric values with check-measurements made with illuminance and spot-luminance measurements. This is cone by also calculating the illuminance E_v or luminance L_v from the spectral irradiance measurements, e.g.,

$$E_v = 683 \, \Sigma \, V_\lambda \cdot E_\lambda \cdot \Delta\lambda \qquad [16]$$

The luminance L_v is then the illuminance divided by the angular subtense of the source Ω:

$$L_v = E_v/\Omega \qquad [17]$$

where the luminance would be expressed in cd/cm^2 if the illuminance was expressed in lm/cm^2.

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THE ENERGY POLICY ACT OF 1992

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As a consequence of the National Energy Strategy, which was conceived by the Bush Administration, Congress enacted and the President signed into law, the Energy Policy Act of 1992 on October 24, 1992, (EPACT 1992).

Of the thirty-three titles of EPACT, Title I - Energy Efficiency, is the longest and most comprehensive section. In concert with the goals of the International Lighting in Controlled Environments Workshop, this Section 103, Energy Efficient Lighting and Building Centers of EPACT, provides an opportunity for the nation to design, test and implement the most advanced, efficient lighting systems.

The purpose of Section 103 is to encourage energy efficiency in buildings through the establishment of regional centers to promote energy efficient lighting, heating and cooling, and building design.

EPACT provides for grants to nonprofit institutions, or to consortiums that may include nonprofit institutions, State and local governments, universities, and utilities, to establish or enhance one regional building energy efficiency center in each of the 10 regions served by a Department of Energy regional support office.

Each regional center established is permitted to accomplish the following:

Provide information, training, and technical assistance to building professionals such as architects, designers, engineers, contractors, and building code officials, on building energy efficiency methods and technologies, including lighting, heating and cooling, and passive solar;

Operate an outreach program to inform such building professionals of the benefits and opportunities of energy efficiency and the services of the center;

Provide displays demonstrating building energy efficiency methods and technologies, such as lighting, windows, and heating and cooling equipment;

Coordinate its activities and programs with other institutions within the region, such as State and local governments, utilities, and educational institutions in order to support their efforts to promote building energy efficiency;

Serve as a clearinghouse to ensure that information about new building energy efficiency technologies, including case studies of successful applications, is disseminated to end-users in the region;

Study the building energy needs of the region and make available region-specific energy efficiency information to facilitate the adoption of cost-effective energy efficiency improvements;

Assist educational institutions in establishing building energy efficiency engineering and technical programs and curricula;

Evaluate the performance of the center in promoting building energy efficiency;

Any nonprofit institution or consortium interested in receiving a grant under this section shall submit to the Secretary an application in such form and containing such information as the Secretary may require. A lighting or building energy center in existence on the date of enactment of this section which is owned and operated by a nonprofit institution or consortium as described in the subsection above shall be eligible for a grant under this section.

SELECTION CRITERIA: The Secretary shall select recipients of grants under this section on the basis of the following criteria:

The capability of the grant recipient to establish a board of directors for the regional center composed of representatives from utilities, State and local governments, building trade and professional organizations, manufacturers, and nonprofit energy and environmental organizations.

The demonstrated or potential resources available to the grant recipient for carrying out this subsection.

The demonstrated or potential ability of the grant recipient to promote building energy efficiency by carrying out the activities specified in the permitted activities.

The activities which the grant recipient proposes to carry out under the grant.

MATCHING FUNDS: The Federal share of a grant under this section shall be no more than 50 percent of the cost of establishing, and no more than 25 percent of the cost of operation of the regional center.

No grant may be made under this section in any fiscal year unless the recipient of such grant enters into such agreements with the Secretary, as the Secretary may require, to ensure that such recipient will provide the necessary non-Federal contributions. Such non-Federal contributions may be provided by utilities, State and local governments, nonlocal governments, nonprofit institutions, foundations, corporations, and other non-Federal entities.

TASK FORCE - The Secretary shall establish a task force to:

Advise the Secretary on activities to be carried out by grant recipients; Review and evaluate programs carried out by grant recipients;

Make recommendations regarding the building energy efficiency center grant programs.

LIGHTING APPLICATIONS

LAMPS

SHORT REPORT

SPECTRAL COMPARISONS OF SUNLIGHT AND DIFFERENT LAMPS

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The following tables were compiled to characterize the spectra of available lamp types and provide comparison to the spectra of sunlight.

Table 1 reports the spectral distributions for various lamp sources and compares them to those measured for sunlight. All of the values are normalized to 100 μmol $m^{-2}s^{-1}$ of PAR (400-700 nm) in order to simplify calculations. To use this table, simply establish the level of PAR that is desired, or measured, under various lamp sources and multiply by a multiple of 100. For example, if 300 μmol $m^{-2}s^{-1}$ of PAR are desired and you are using Cool-White fluorescent lamps, multiply any spectral range listed for Cool-White lamps by 3. Thus, if you are interested in the amount of ultraviolet light (350-400 nm) present in 300 μmol $m^{-2}s^{-1}$ of Cool-White fluorescent light, simply multiply 1.11 by 3 which gives a total of 3.33 μmol $m^{-2}s^{-1}$ of ultraviolet light. The amount of red light (600-700 nm) available under these conditions would be 3 x 22.56 = 67.68 μmol $m^{-2}s^{-1}$, the amount of far-red light (700-750 nm) would be 1.40 x 3 = 4.2 μmol $m^{-2}s^{-1}$, etc. Note that the wavelength ranges do not correspond exactly to the defined regions for UV-B (280-320 nm), UV-A (320-400 nm) and Far-red (700-800 nm). This was done arbitrarily to facilitate comparison of the active wavebands for different plant responses. The percentages relate the relative number of photons in various sources to sunlight. Thus, only Xenon has a solar spectral distribution in all of the visible wavelength regions, but it has about twice the relative amount of short wave UV-B. It also has much more infra-red radiation that does not appear in this table, which limits its usefulness. Other sources should be chosen for the relative importance of different wavelength regions since they all vary significantly from sunlight.

Table 2 provides the amount of energy in Wm^{-2} relative to the number of photons of PAR (400-700 nm) for each light source. This calculation can be further simplified by simply multiplying the PAR value in μmol $m^{-2}s^{-1}$ by 0.2 to obtain the energy content of this region since none of the sources tested vary by more than 0.02 Wm^{-2}. In addition, Table 2 allows an accurate determination of the number of photons of PAR, even if a photometric instrument (lux or foot-candle meter) is used to measure this value. Simply multiply the number of lux or the number of foot-candles given in the table by the number of photons of PAR desired for each lamp source and set the corresponding photometric value accordingly. Thus, if 300 μmol $m^{-2}s^{-1}$ of Cool-White fluorescent light is desired multiply 79 lux or 7.3 foot-candles by 300 and set the meter to read 23,700 lux or 2,190 foot candles. For Vita-Lite fluorescent the same amount of PAR would be obtained by setting 18,900 lux or 1,770 ft-c; for metal halide 22,350 lux or 2,070 ft-c, but low pressure sodium would require 31,800 lux or 2,955 ft-c. Note that only the wide spectrum Gro-Lux and Xenon are equivalent to sunlight for this calculation.

TABLE 1. Spectroradiometer measured photons in various wave bands for sunlight and different lamp types normalized to 100 µmol m-2 s-1 of PAR (400-700 nm). Percentages are the amounts of photons relative to sunlight.*

Light Source	Barrier	ULTRAVIOLET 250-350	ULTRAVIOLET 350-400	BLUE 400-500	GREEN 500-600	RED 600-700	FAR-RED 700-750
Sunlight	**None**	**2.88**	**6.21**	**29.16**	**35.20**	**35.64**	**17.00**
Incandescent (100W)	1/8 in. Plexiglas	0.00 0%	0.47 7%	7.52 26%	28.49 81%	63.98 180%	47.00 276%
Cool White Plexiglas	1/8 in.	0.03 1%	1.11 18%	24.85 85%	52.59 149%	22.56 63%	1.40 8%
Vita-Lite	None	0.54 19%	2.32 37%	26.31 90%	40.69 116%	33.00 93%	7.00 41%
Gro-Lux Original	None	0.16 6%	3.72 13%	29.36 101%	20.22 57%	50.42 141%	1.01 6%
Gro-Lux Wide Spectrum	1/8 in. Plexiglas	0.00 0%	0.83 13%	19.78 68%	32.52 92%	47.70 134%	10.00 59%
High Pressure Sodium	None	0.17 6%	0.53 9%	6.52 22%	56.57 161%	36.91 104%	4.00 24%
Low Pressure Sodium	None	0.03 1%	0.15 2%	0.12 0%	99.33 282%	0.54 2%	0.04 0%
Metal Halide	None	0.66 23%	6.71 108%	20.38 70%	55.52 158%	24.10 68%	4.00 24%
Xenon	None	5.81 202%	7.66 123%	26.88 92%	34.17 97%	38.94 109%	19.00 112%
Microwave	1/4 in. Plexiglas	0.00 0%	0.68 11%	23.99 82%	45.00 128%	31.00 87%	10.00 59%
Cool White plus Incandescent (100W) In a 3:1 ratio	1/8 in. Plexiglas	0.02 1%	1.03 17%	22.63 78%	49.22 140%	28.15 79%	8.00 47%
LED 660	None	0.00 0%	0.00 0%	0.00 0%	0.06 0%	99.94 280%	0.31 2%
LED 735	None	(0.07) -2%	0.00 0%	(0.03) 0%	(0.03) 0%	0.00 0%	100.00** ---

* Measurements by Gerald Deitzer, University of Maryland.

** Normalized to 100 µmol $m^{-2}s^{-1}$ of photons in 700-750 nm waveband.

Table 2. Calculated conversion values for spectroradiometric data of Table 1.*

Light Source	Barrier	PAR	Photometric	
		W m^{-2} per µmol $m^{-2}s^{-1}$	Lux per PAR (µmol $m^{-2}s^{-1}$)	Ft-c per PAR (µmol $m^{-2}s^{-1}$)
Sunlight	None	0.22	55.18	5.13
Incandescent	1/8 in. Plexiglas	0.20	49.00	4.56
Cool White (100 W)	1/8 in. Plexiglas	0.22	78.75	7.32
Vita-Lite	None	0.22	62.78	5.84
Gro-Lux Original	None		37.02	3.44
Gro-Lux Wide Spectrum	1/8 in. Plexiglas	0.21	55.09	5.12
High Pressure Sodium	None	0.20	83.28	7.74
Low Pressure Sodium	None	0.20	106.12	9.87
Metal Halide	None	0.22	74.50	6.93
Xenon	None	0.22	54.16	5.04
Microwave	1/4 in. Plexiglas	0.22	67.43	6.27
CoolWhite + Incandescent (100 W) In 3:1 W ratio	1/8 in. Plexiglas	0.21	74.53	6.93
LED 660	None	0.18	11.75	1.09
LED 735	None	----	----	----

* Calculations by Gerald Deitzer, University of Maryland.

DISCHARGE LAMP TECHNOLOGIES

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INTRODUCTION

This talk is an overview of discharge lamp technology commonly employed in general lighting, with emphasis on issues pertinent to lighting for plant growth. Since the audience is primarily from the plant growth community, and this begins the light source part of the program, we will start with a brief description of the discharge lamps. Challenges of economics and of thermal management make lamp efficiency a prime concern in controlled environment agriculture, so we will emphasize science considerations relating to discharge lamp efficiency. We will then look at the spectra and ratings of some representative lighting products, and conclude with a discussion of technological advance. A general overview of discharge lighting technology can be found in the book of Waymouth (1971). A recent review of low pressure lighting discharge science is found in Dakin (1991). The pioneering paper of Reiling (1964) provides a good introduction to metal halide discharges. Particularly relevant to lighting for plant growth, a recent and thorough treatment of high pressure Na lamps is found in the book by deGroot and vanVliet (1986). Broad practical aspects of lighting application are thoroughly covered in the IES Lighting Handbook edited by Kaufman (1984).

DISCHARGE TYPES

It is helpful to view discharge light sources from the perspective of the ubiquitous incandescent lamp, whose tungsten filament is heated by the passage of electric current, and cooled by radiation. The filament temperature, about 2800 K, is a compromise between the desires to have longer life (cooler filament) and higher efficiency (hotter filament). At the melting temperature of tungsten, 3655 K, its life would be very short indeed.

A discharge light source, shown schematically in Figure 1, changes the game entirely. Electric current heats a gaseous plasma formed between two electrodes and contained within an arctube. The plasma is incapable of *burning out* in the sense of the incandescent filament, and operates at substantially higher temperatures where it is a more efficient radiator. Life is limited by phenomena at the electrodes and arctube walls. A typical discharge light source has roughly an order of magnitude advantage in both efficiency and life when compared to its incandescent counterpart.

Important physical characteristics of common lighting discharge types are summarized in Table 1. In each case, the arctube is characterized by its wall material, internal diameter, gap between electrode tips, and wall temperature. An average power density or loading is simply the total power divided by the volume between the electrode tips. In most cases there are at least two gaseous species present, one of which has the dominant partial pressure, and the other of which is responsible for the radiation. The gas is further characterized by an operating pressure and center temperature. The gas is ionized to create electrons, which gain energy from the electric field, and lose energy to collisions with atoms in the gas. Some of these collisions create excited atoms which in turn radiate releasing photons. It is useful to characterize the electrons by their temperature.

Low Pressure Hg-Ar Discharges

The most familiar form of discharge light source occurs within a fluorescent lamp. The discharge in this lamp is referred to as a low pressure Hg-Ar discharge, which is also found in many neon signs. As indicated in Table 1, the dominant gas is Ar, but the radiation comes from Hg. This radiation is predominantly ultraviolet radiation at 254 nm. The *low pressure* designation signifies that the collision rates are too low for the electrons (11000 K) to reach thermal equilibrium with the gas atoms (300 K). A higher pressure would lead to more collisions and better equilibration. The design of the discharge, however, is chosen to optimize the production of ultraviolet Hg radiation, for which a low pressure is desirable.

TABLE 1 Discharge Lamp Types

Type	Watts	Arctube					Gas		Press. (Atm)	Temperature	
Pow	(W)	mat'l	diam (cm)	gap (cm)	loading W/cc	temp (C)	dominant	radiating		gas (K)	elec. (K)
LP Hg-Ar	40	glass	3.6	98.0	0.04	42	Ar	Hg	0.004	300	11000
HP Hg	400	S_1O_2	1.8	8.0	19.65	700	Hg	Hg	2.500	6000	6000
HP MH	400	S_1O_2	2.0	4.3	29.61	800	Hg	Na,Sc	4.000	5000	5000
HP Na	400	Al_2O_3	0.7	8.7	112.92	1150	Hg,Xe	Na	0.900	4000	4000

Visible radiation is produced fluorescence when the ultraviolet radiation strikes a phosphor coating on the inner arctube wall. While the discharge is very efficient at creating ultraviolet radiation, the conversion to visible radiation in the phosphor is inherently inefficient. This is because one ultraviolet photon has sufficient energy to make roughly two visible photons, but due to the quantum nature of the conversion process makes at most one.

High Pressure Discharges

The high pressure discharge lamps in Table 1 are distinguished from the low pressure Hg-Ar discharge by their higher powers, smaller sizes, hotter arctube walls, higher power densities, and higher pressures (The power density or loading, is the power divided by the volume of the cylander. The cylander volume defined by the diameter and the arc gap). These high pressure discharges operate very close to thermal equilibrium, with the electron temperature very close to the gas temperature. The centers of these discharges are about 5000 K, close to the temperature of the sun.

In the *high pressure* Hg discharge, Hg is both the dominant gas and the radiating gas. Unlike the low pressure Hg-Ar case, this discharge is designed to optimize the release of visible Hg radiation, predominantly in the 405, 435 and 545 nm lines. Even under optimal conditions, much ultraviolet radiation remains, limiting its visible efficiency.

The high pressure Metal Halide or MH discharge is very closely related to the high pressure Hg. Both involve high pressure Hg in a fused quartz arctube. In the MH case, the arctube also contains small amounts of metal halide salts such as NaI and ScI_3. Under operating conditions, these salts reside as molten condensates on the arctube walls and low concentrations of their vapors are introduced into the gas volume within the tube. Relatively small numbers of Na and Sc atoms in the discharge radiate more readily than do the more numerous Hg atoms. The Na and Sc atoms can do this because their energy levels are lower than

those of the Hg atoms. Furthermore, these Na and Sc energy levels radiate predominantly in the visible rather than the ultraviolet. This gives the MH discharge a higher visible efficiency than the high pressure Hg discharge.

The visible efficiency of the MH discharge can generally be increased either by increasing the power density or by increasing the halide vapor pressure. These approaches go hand in hand with increased arctube wall temperature. A practical limit is imposed by the fused quartz arctube material, whose life is severely limited at operating temperatures above 900 C.

The high pressure Na discharge is similar to the MH discharge, involving radiation from Na atoms in the presence of Hg. Here, however, much higher Na vapor pressures are achieved by introducing elemental Na rather than NaI. The polycrystalline Al_2O_3 arctube material, unlike quartz, is impervious to elemental Na. Furthermore, the Al_2O_3 is able to operate at a much higher (1150 C).

The high pressure Na discharge, like the other two high pressure discharges, has a significant thermal conduction energy loss due to the several thousand degree temperature difference between the core of the discharge and the arctube walls. This loss could be reduced if the intervening gas had lower thermal conductivity. In fact, Hg vapor is a pretty good insulator, as gases go, owing to its large atomic mass. About the only better choice is Xe. Discharge efficiencies can be increased by using Xe in place of Hg, however this introduces practical problems associated with starting and operating voltage.

LAMP RATINGS AND SPECTRA

Typical Ratings

Ratings of representative commercial lamp types are shown in Table 2. Parameters of most immediate interest for general lighting are the rated life, and the photopic efficacy (plm/W). In both categories, the discharge lamp types all have a considerable edge over the incandescent lamps. The fluorescent and high pressure lamp types have "F" and "HP" designations respectively. More will be said about the "MLX" types later.

TABLE 2 Lamp Ratings

Type	Watts (W)	Life (hours)	Photopic lumens		Plant growth		Scotopic lumens		Vis. eff. Wv/W
			plm	plm/W	RA/plm	RA/W	slm/plm	slm/W	
inc.	100	750	1750	18					
F-CW	40	20000	3150	79	2.08	164	1.50	118	0.22
F-PL	40	20000	800	20	5.86	117	2.87	57	0.14
F-PL/AQ	40	20000	1900	48	3.07	146	1.54	73	0.18
HP Hg	400	24000	21000	53					
HP MH	400	20000	40000	100	2.26	226	1.28	128	0.29
HP Na	400	24000	50000	125	2.13	266	0.63	79	0.31
HP Na	1000	24000	140000	140	2.13	298	0.63	88	0.35
MLX NaNd	400	10000	55000	138	2.25	309	1.78	245	0.42
MLX CsPr	300	10000	33000	110	2.35	259	2.34	257	0.38

Three spectral weighting functions are of interest in evaluating the visible radiation produced by these lamps. These weighting functions are related to the photopic lumen (plm), the scotopic lumen (slm) and the Relative Action for the photosynthetic component of plant growth (RA). The photopic lumen is the most

commonly used lumen and is associated with the color-sensitive cones of the human retina. The scotopic lumen is associated with rods and night vision. The shapes of these weighting functions are shown in Figure 2. All three curves are arbitrarily defined to be 1 at 555 nm, which is the peak of the photopic lumen curve. Light at 555 nm is defined as having an efficacy of 683 plm/W and 683 slm/W.

The RA function in Figure 2 is that reported by McCree (1971) for the average field plant species, and has been normalized here so that RA=plm=slm for 555 nm radiation. Plants show less color discrimination than does the human eye. The RA response is the broadest of the three curves, and is higher in the red where there are more quanta of light per unit of energy. McCree shows, however, that over the 400 to 700 nm range a uniform quantum efficiency does not fit the data much better than does a uniform energy efficiency. The main point to be made with Figure 2 is that lamps developed for general lighting are not necessarily optimal for plant growth.

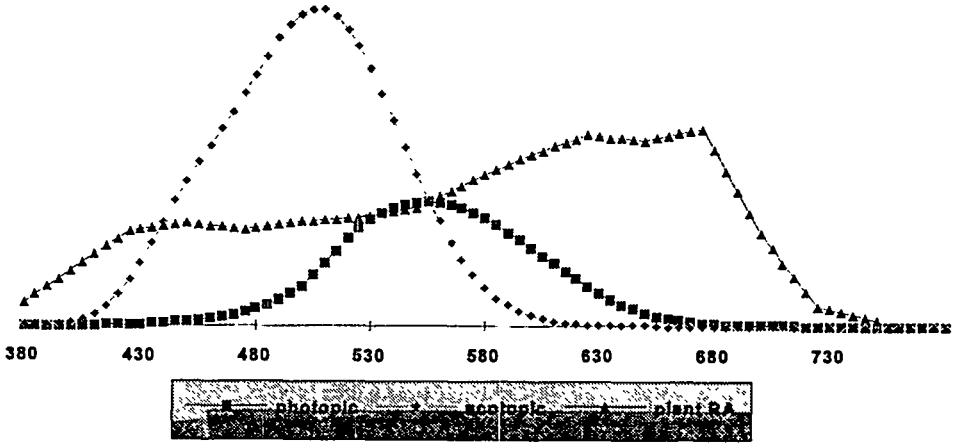

Fig. 2 Spectral weighting functions

Two different measures of power are indicated in Table 2. W represents the total Watts entering the lamp electrically. Wv represents the number of Watts leaving the lamp as visible radiation (380-760 nm). The visible efficiency ratio (Wv/W) shows what fraction of the total power leaves the lamp as visible radiation . The balance leaves primarily as infrared radiation, some emitted by the discharge, but most emitted by various solid components in the lamp assembly. Among the commercial lamp types, the high pressure Na lamps have the best Wv/W ratios.

Spectra

The fluorescent lamp offers enormous opportunity for spectral variation merely through changes in the phosphor. The spectra of three commonly used GE fluorescent lamps are shown in Figures 3-5. Each involves a completely different phosphor system. Figure 3 shows the spectrum of the standard cool white fluorescent lamp. This lamp is commonly found in indoor commercial applications. The spectra shown in Figures 4 and 5 are the result of combining phosphors which have emissions in the far red and blue regions of the spectrum so as to concentrate power near the two peaks in the RA curve shown in Figure 2. These spectra are deficient in green, and make objects appear purple, which is desirable in some circumstances. Table 2 shows that these lamp types have very different RA/W, plm/W and slm/W efficiencies.

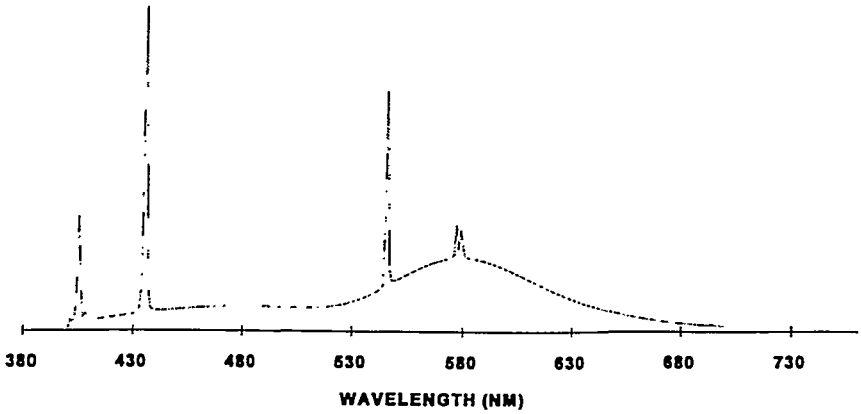

Fig. 3 F-CW Spectrum

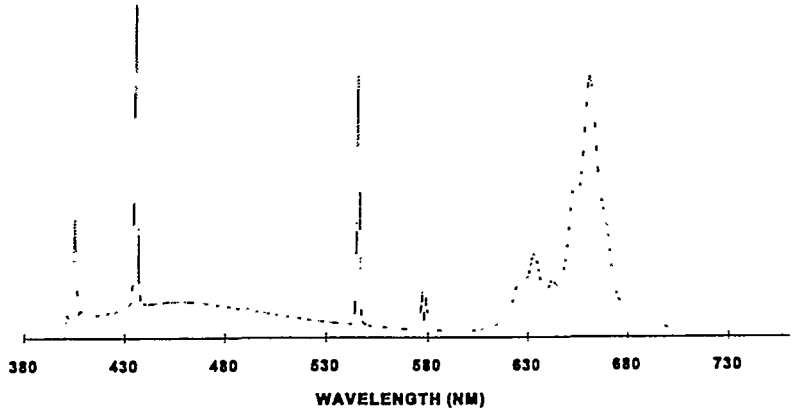

Fig. 4 F-PL Spectrum

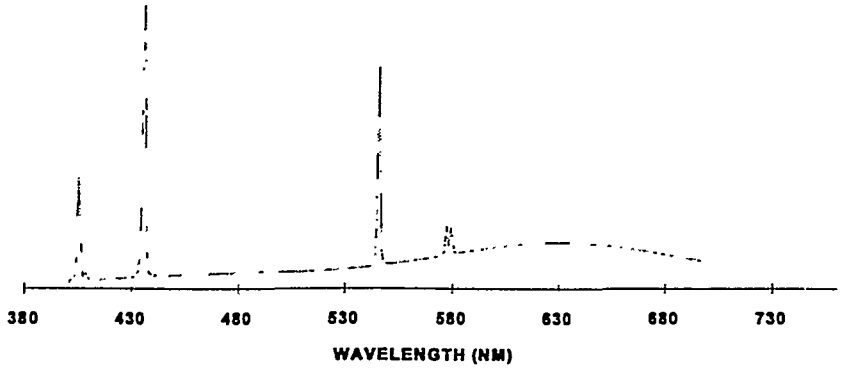

Fig. 5 F-PL/AG Spectrum

The high pressure lamp types are more attractive than fluorescent lamps for many plant growth applications due to their somewhat higher efficiencies, and their ability to provide more light per fixture. The two most important types for plant growth have the spectra shown in Figures 6-7. The high pressure MH spectrum shown in Figure 6 contains prominent Na, Sc and Hg lines which are reasonably well distributed throughout the visible spectrum. MH spectra based on other chemistries are also possible. Many examples are shown in the paper of Reiling (1964). The high pressure Na spectrum shown in Figure 7 contains only Na lines, and is dominated by the self reversed Na resonance line at 589 nm. Table 2 shows the high pressure Na lamp to be more efficient for plant growth, as measured by RA/W, than any of the other conventional lamp types.

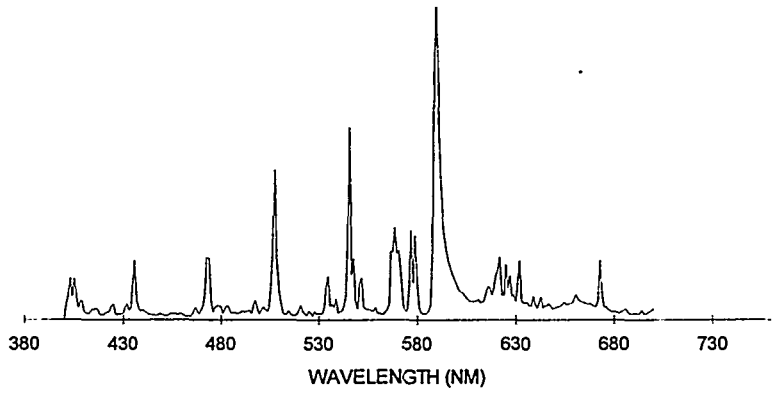

Fig. 6 HP MH Spectrum

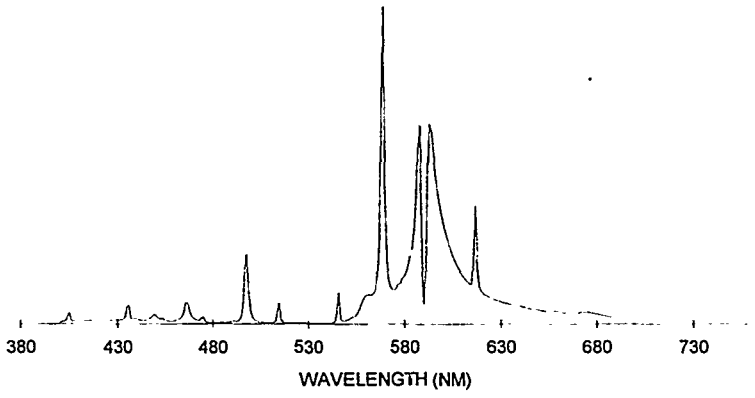

Fig. 7 HP Na Spectrum

Electrodeless High Pressure Lamps

New electrodeless discharge technology being developed at GE, but not now commercially available, offers considerable promise for plant growth. This technology involves a metal halide discharge operating in a fused quartz arctube without electrodes or Hg. Power is applied by an inductive exciter operating at 13.56 MHz. The lamp configuration is similar to that described by Dakin et al. (1992). Without electrodes, a wider range of halides can be used, and wall blackening associated with tungsten transport is avoided. Two of the many possible halide doses are NaI plus NdI_3 and CsI plus PrI_3. Ratings and spectra achievable with these doses are indicated by the MLX entries in Table 2, and Figures 8 and 9. The CsPr spectrum is populated by myriad Pr atomic lines, with little or no contribution from Cs. The NaNd spectrum has a similar contribution from Nd atomic lines plus the strong Na lines seen earlier in Figure 7. The NaNd system is seen to be more efficient than high pressure Na systems by all measures, and to provide more blue radiation as well.

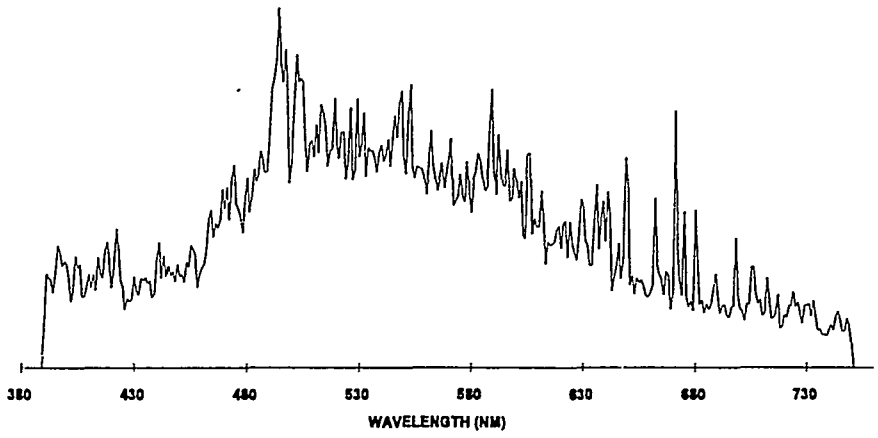

Fig. 8. MLX CsPr Spectrum

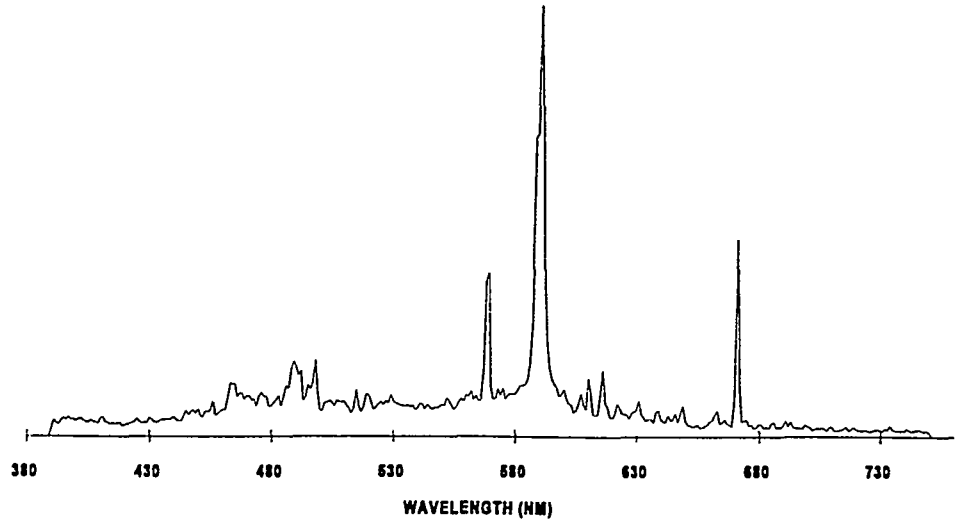

Fig. 9. MLX NaNd Spectrum

ADVANCES

For more than a century, technological advances have enabled the electric lighting industry to steadily introduce better products. That trend continues today. In the incandescent, fluorescent and high pressure categories, new products are available with significant performance advantages over the more familiar types indicated in Table 2. We will quickly review some of the technological advances which are making these new products possible.

Materials

Materials have long had center stage in lighting advances. This is due to fundamental life-performance tradeoffs related to material operating temperatures. A landmark historical advance was the development of translucent polycrystalline Al_2O_3, which made the high pressure Na lamp possible. A more recent advance is fluorescent lamp phosphors capable of operating at higher temperatures. Another is high temperature dichroic films capable of trapping infrared radiation inside an incandescent lamp while allowing visible radiation to escape.

Ballasting and Electronics

Discharge lamps require ballasts, shown schematically in Figure 1, to limit and control the current which they draw from the electric mains. These ballasts have traditionally been passive electromagnetic devices made of copper and iron, the simplest example being a series inductor. Recent advances in power semiconductors and control circuitry have enabled the development of cost effective electronic ballasts. These typically operate at high frequency, and are smaller, lighter and more efficient than their electromagnetic predecessors. The electronics also enable simple control features such as dimming, and more specialized control features related to idiosyncrasies of the discharge lamps. As shown by Osteen (1979), for instance, the blue emission from the high pressure Na lamp can be enhanced by operating on a pulsing ballast with suitable frequency and duty cycle. Electronic ballasting is quite common in new fluorescent installations, and is beginning to appear for low power high pressure lamp types.

New Lamp Types

A number of new discharge lamp types have appeared in recent years. These have been made possible by new technology, and encouraged by market forces such as energy conservation. The most conspicuous new types are the compact fluorescent lamps with integral ballasts. These are direct replacements for screw-in incandescent lamps, offering the cost and energy savings inherent to fluorescent lighting without the need to install new fixtures. Compact fluorescent lamps with integral ballasts represent a tour de force of new technology, relying on advances in phosphors, electronics, high speed manufacturing, and more. Other new discharge lamp types include a proliferation of low wattage high pressure Na and MH lamps.

More relevant to plant growth are new high pressure Na types with higher efficiency, brought about by increasing the Xe pressure. Other high pressure Na types of possible interest in plant growth operate at higher Na pressure to provide more blue radiation, but at the expense of reduced overall efficiency.

CONCLUSIONS

The lighting industry provides a wide range of commercial discharge lamp types, each offering a unique combination of wattage, efficiency and spectral power distribution. Only a small fraction of the available lamp types have been indicated here. Most of these lamps have been developed for general lighting, where the costs of technological advance are justified by large markets for better products. Many of these same lamps are applicable to plant growth, however, where the spectral requirements are somewhat different than those for human vision. Of particular interest in lighting for plant growth are new fluorescent lamp phosphor systems, ongoing advances in the high pressure Na lamp, and the introduction of new types such as the electrodeless high pressure lamp.

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FLUORESCENT AND HIGH INTENSITY DISCHARGE LAMP USE IN CHAMBERS AND GREENHOUSES

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INTRODUCTION

Fluorescent and High Intensity Discharge lamps have opened up great opportunities for researchers to study plant growth under controlled environment conditions and for commercial growers to increase plant production during low/light periods. Specific technical qualities of fluorescent and HID lamps have been critically reviewed by Dr. James Dakin. I will direct my remarks to fluorescent and high intensity discharge (HID) lamps in growth chambers, growth rooms, and greenhouses. I will discuss the advantages and disadvantages of using each lamp in growth chambers, growth rooms and greenhouses.

Growth Chambers are small (3m x 4/m and smaller) walk-in or reach-in enclosures with programmable, accurate temperature, relative humidity (RH) and irradiance control over wide ranges. The intent of growth chambers was to replicate sunlight conditions and transfer research results directly to the greenhouse or outside. It was quickly realized sunlight and outside conditions could not be mimicked. We now appreciate most of the reasons, which include spectral quality, irradiation level and long wave differences. Today, it is recognized that it is of principal importance to provide radiation environments which can be repeated, so experimental plants can be compared over time, among chambers and among locations. Growth chambers are also used to study irradiance and spectral fluxes.

Growth Rooms are usually large rooms (larger than 3m x 4m) with only lamp irradiance, but providing relatively limited ranges of environmental control (i.e., 10 to 30 C temperature, 50 to 90% RH and ambient to 1000 ppm CO2), and commonly independent of outside conditions. The narrower range of environmental conditions (as compared to growth chambers) reduces construction costs without a great loss of accuracy of control. Irradiance requirements for growth rooms are similar to those of growth chambers, i.e. standardized spectral quality and uniform irradiance in the growing area. Growth rooms are also used for growing a large number of plants in a uniform standard environment condition, such as commonly required for Plant Science teaching, Plant Breeding, Entomology and Plant Pathology research. Growth rooms are also used in commercial horticulture for tissue culture, seed germination (plugs) and seedling growth.

Greenhouses are designed to allow maximum sunlight penetration through the structure. Initially greenhouses were used to extend the growing season. Then as heating systems, and cooling systems improved, they were used year round. Low light during the winter months reduced plant growth, but with the advent of efficient lamps (HID and fluorescent) it became possible to increase growth to rates close to that in summer months. Supplementary lighting is used during low light periods of the year and anytime to ensure consistent total daily irradiance for research plants.

FLUORESCENT-GROWTH CHAMBERS

Assets:

1. Cool White fluorescent (CWF) lamps have been and are the standard lamps used in growth chambers. Much of the experimental growth chamber results reported in the literature is based on CWF grown plants.
2. CWF lamps have the greatest moles of PPF output efficiency of all fluorescent lamps.
3. Spectral distribution of the CWF lamp is reasonable. Other fluorescent lamps warm white, daylight, etc. have different spectra and some of them have spectra closer to sunlight, but the total mole output of PPF is reduced.
4. Photon levels in chambers of up to 600 umol $m^{-2}s^{-1}$ can be achieved.

Liabilities:

1. CWF and most other fluorescent lamp are not identical to sunlight. One difficulty trying to mimic sunlight is the solar intensity varies from location to location and is constantly changing.
2. Fluorescent lamps have a relatively short lamp life (5,000 to 10,000 hrs.), compared to HID lamps.
3. Must use VHO fluorescent lamps to obtain useful levels of PPF.
4. Fluorescent lamps have a rather rapid decay rate. We have recorded a loss as much as 30 umol $m^{-2}s^{-1}$ in a week. The output of the lamp decays 75% over the life of the lamp. Replace 1/3 of the lamps every 3 or 4 months to maintain more uniform PPF.
5. The decay rate for new lamps is particularly rapid. Therefore, lamps should be operated for 100 hours before use in a research study.
6. PPF should be measured weekly.
7. The plant growing bench has to be adjusted up or down to maintain a desired PPF level at the top of the plant canopy.
8. Temperature of the lamp is critical to obtain maximum PPF output and longevity (an air temperature of 20° C is best, permitting optimum lamp bulb surface temperature of about 40° C). Therefore, the light cap area in a growth chamber should have good temperature control. If the temperature of the light cap varies, temperature of the lamp will vary and PPF output will vary.
9. Changes in line voltage will shorten lamp life.
10. PPF levels higher than 600 umol $m^{-2}s^{-1}$ are difficult to obtain.
11. Special plant grow lamps emit less PPF and are not recommended for use in growth chambers.
12. PPF levels close to the walls of the chamber are significantly lower than in the rest of the chambers. Each chamber should have PPF levels measured and plotted. Care should be taken to grow plants in known PPF locations. The growing area should be blocked to obtain effective experimental design.

FLUORESCENT - GROWTH ROOMS

Assets:

1. The assets are the same as for growth chambers.
2. If lack of height is a problem in the growth room, fluorescent lamps must be used to ensure uniform PPF. For example, rooms used for tissue culture or germination require fluorescent lamp, where the material is grown on closely-spaced shelves.

Liabilities:

1. Liabilities are the same as listed for the growth chambers.
2. For large rooms, fluorescent lamps may not be appropriate, because the installation of the barrier may be difficult. The barrier is needed to maintain the optimum temperature around the lamps.

FLUORESCENT - GREENHOUSES

Assets:

1. Assets are the same as for the growth chamber.
2. Lamps are easy to install.

Liabilities:

1. Most liabilities are the same as listed for the growth chambers.
2. Lamps cause excessive shade on a greenhouse bench.
3. Lamps need to be positioned close to the plant material (less than 1 meter) to provide useful levels of PPF.
4. Fixtures may be exposed to dripping water or water sprays and, therefore appropriate precautions should be taken (ground fault interrupters).

HID - GROWTH CHAMBERS

Assets:

1. HID lamps are required to attain PPF levels above 500 umol $m^{-2}s^{-1}$. Up to 1500 umol $m^{-2}s^{-1}$ can be achieved with HID lamps.
2. HID lamps have long lamp life. (30,000 hours for High Pressure Sodium lamps and 15,000 for Metal Halide lamps)
3. HID lamps have a high efficiency of PPF output, compared to other lamps.
4. Metal halide lamps have spectra satisfactory for plant growth without other sources.
5. Spectra from HPS lamps appear satisfactory at high PPF (>700 umol $m^{-2}s^{-1}$) but at lower

PPF the spectra from HPS lamps may be deficient in blue for many plant species.

6. Dimming ballasts can be used to change and control irradiance output. A 30% reduction can be used with HPS, without changing the spectra. Greater re-ductions may change spectral emissions and may turn the lamp off. There is up to a 10 minute delay in restarting of HID lamps. They can only be restarted at 100% of full power and then dimmed.

Liabilities:

1. Longwave radiation is a problem when HID lamps are installed to provide high PPF levels. Barriers and/or water can be used to reduce this long wave irradiance (3,000 nm and above). A barrier must be cooled with air and water passed through a heat exchanger, to remove the heat.
2. Plant material cannot be grown close to HID lamps, or heat damage will occur (no closer than 1 meter).
3. Uniform of PPF on the growing surface is difficult to obtain. Computer programs are available for HID lamp installations to insure uniform irradiance.

HID - GROWTH ROOMS

Assets:

1. Same assets as for growth chambers.
2. High irradiance levels are usually desired (500 to 1,000 umol $m^{-2}s^{-1}$) and can be achieved with HID lamps.
3. To produce a umol $m^{-2}s^{-1}$, it is more efficient to use HID lamps.
4. HPS lamps produce more mol m^{-2} per electric input than metal halide lamps. Metal halide has a better general spectra of PPF, than HPS which peaks at 550 to 660 nm.

Liabilities:

1. Same liabilities as for growth chambers.
2. Heat load from long wave radiation is high at high PPF and requires considerable cooling capacity.
3. Barriers to reduce long wave radiation may be difficult to install in large rooms. Water cooled lamps may be a better solution for heat removal, which in turn could reduce the size of the mechanical refrigeration.

HID - GREENHOUSES

Assets:

1. Same assets as for growth chambers.
2. HPS lamps are best, because of long lamp life, up to 30,000 hours, a small decrease in output of PPF over the life of the lamp, and the best efficiency of PPF for power used. (Low levels of blue wavelengths are satisfied by levels from sunlight).
3. Heat can be an asset during cold winter nights and on a normal winters night may supply 25% of the heating requirement.
4. With a supplemental lighting level of 200 umol $m^{-2}s^{-1}$, 26 mol m^{-2} day^{-1} can be achieved in most greenhouses in the US during the darkest months of the year by the combination of natural and supplementary light.
5. PPF uniformity (less than 15% variation) can be achieved with efficient luminaries and proper installation.
6. Computer programs are available to determine proper luminare installation for uniform irradiance.

Liabilities:

1. Same liabilities as for growth chambers.
2. Limit lamp installation to 200 umol $m^{-2}s^{-1}$ PPF or heat from the lamps and shade from the luminaries become too great.
3. Low levels of PPF (less than 50 umol $m^{-2}s^{-1}$) will present a problem to obtain uniform PPF.
4. Plants should be at least 1 meter below the lamps or long wave radiation will cause burn (heat) problems.
5. Ballasts (some models) can be remote from the lamps and luminaries to reduce the live load on the greenhouse structure and reduce shading of the plants.
6. Heat from the lamps can 'over heat' the greenhouses during mild outside temperature (above 0° C) and will cause exhaust fans to cool.

SHORT REPORT

MANAGEMENT OF FLUORESCENT LAMPS IN CONTROLLED ENVIRONMENT CHAMBERS

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Management of fluorescent lights is recommended to:

[a] maintain uniformity of light intensity over time and

[b] permit reproducibility of lighting conditions during experimental replications. (chamber x chamber) (chamber x time).

At the McGill Phytotron, the lighting intensity can be controlled to desired level because any individual pair of the 40 lamps in each chamber can be set to be 'on' at any particular time.

Lamps are evenly divided into four lamp groups of differing hours of use. One-fourth of the lamps are replaced each 1500 hours of use. Thus at any time the lamps in the chamber will have the following range in hours of use:

25% tubes	25% tubes	25% tubes	25% tubes
0-1500	1500-3000	3000-4500	4500-6000

This replacement procedure has provided the following history of use for providing PPF in one of the chambers.

	Jan. 16 Replacement		April 16 Replacement		July 20 Replacement	
	Before	After	Before	After	Before	After
Group A	4600	4600	6200	0	1480	1480
Group B	3300	3300	4750	4750	6250	0
Group C	1650	1650	3010	3010	4650	4650
Group D	6200	0	1600	1600	3250	3250
PPF (μmol $m^{-2}s^{-1}$)	515	560	530	610	540	580

Tube burning hours for each level are logged by the chamber control microprocessor but can also be manually tracked by numbering tube-pairs and calculating age (photoperiod x days). Intensities should be measured at the start and weekly over the entire course of an experiment to obtain averaged vs. initial PPF readings.

A lamp canopy service history is maintained for each experiment permitting accurate replication of lighting conditions for subsequent replicate trials.

SHORT REPORT

DIMMING OF METAL HALIDE LAMPS

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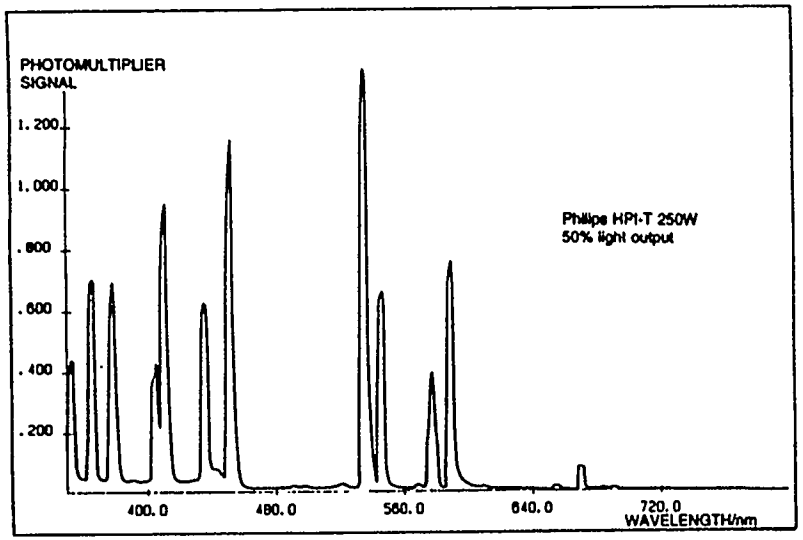
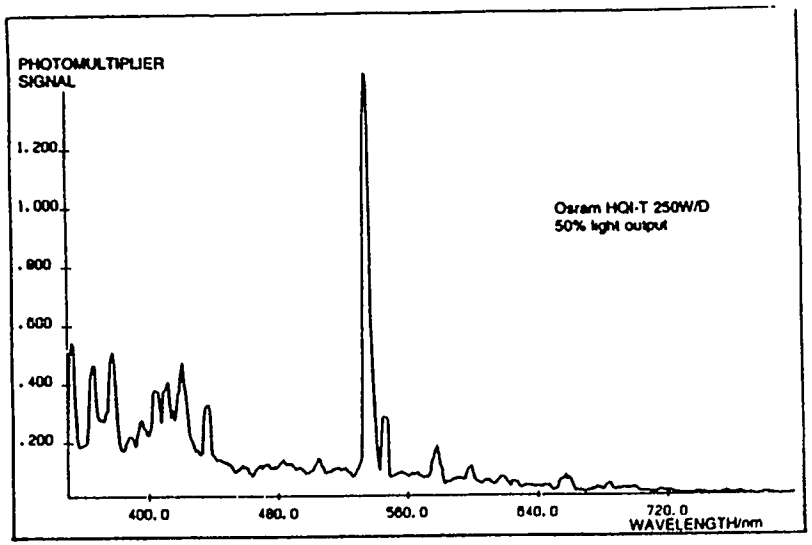
We ran some tests on the effect of dimming of metal halide (MH) lamps upon the stability and the spectral quality of the light output. Lamps used were a new Philips lamp HPI-T 250W, a similar Philips lamp with a few thousand burning hours and a new Osram lamp HQI-T 250W/D. The ballast was a BBC type DJ 250/2KS, the starter a BAS TORGI type MZN 250 SE and the dimmer an Elstrom Control System type ERHQ-T 250. Power was derived from a Philips stabilizer, type PE 1602.

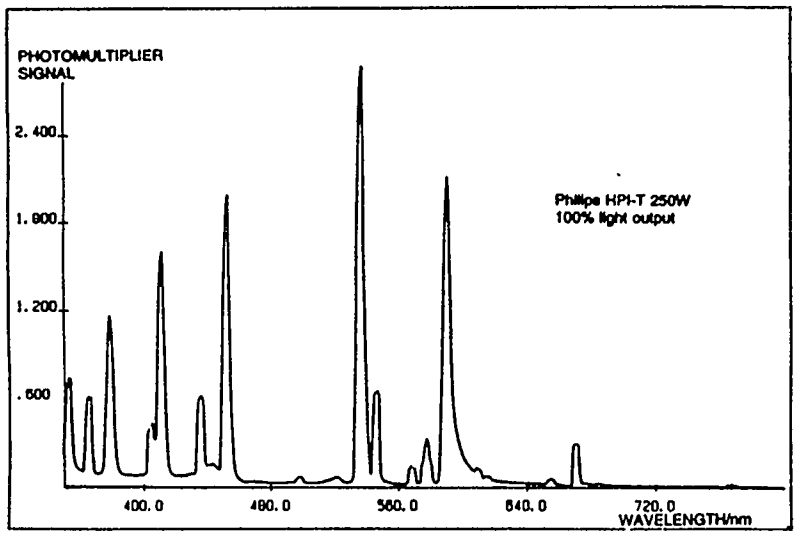
Lamp output was monitored with a PAR meter. Spectra were taken at 100% and at 50% output as measured with the PAR meter. Lamps were allowed to stabilize at any setting for 30 minutes before measurements were made. Lamp current at 100% and 50% was found to be 3.0 A and 2.6 A respectively for the Osram lamp, and 2.2 A and 1.5 A respectively for the Philips lamps.

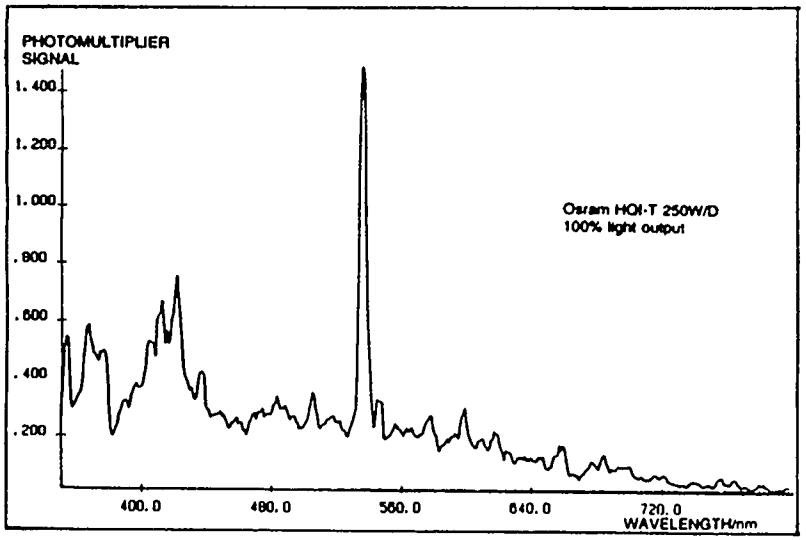
Lamp manufacturers advise against dimming for fear of poor stability and intolerable changes of the spectrum. However, none of the lamps showed a decrease in stability, no flicker or wandering of the discharge, and the changes of the spectrum were not negligible, but certainly not dramatic. Lamps of either manufacture retain their white color, relative peak heights of spectral lines did shift, but no gaps in the spectrum occurred. Spectra taken at 50% with 30 minutes intervals coincided. Differences between the new and the older Philips lamp were noticeable, but not really significant.

The figures show spectra for the new Philips and Osram lamps in a horizontal burning position at 50% and 100% light output. These are direct recordings of the photomultiplier (Hamamatsu R 636) signals in a monochromator system with a spectral bandwidth of 1.25 nm (FWHM), measured in 1 nm intervals.









Spectra of MH lamps at 50% and 100% light output

SHORT REPORT

ENHANCEMENT OF EFFICIENCY IN THE USE OF LIGHT FOR CULTIVATION OF PLANTS IN CONTROLLED ECOLOGICAL SYSTEMS

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The problems of plant cultivation with the use of artificial lighting are related to energetics and, first of all, to the lack of effective sources for photosynthesis, secondly to the necessity to supply a system with a considerable power in the form of light energy and to remove transformed thermal energy, and finally to economic considerations. These problems are solved by three ways: by the choice of effective radiation sources, design approaches, and technological methods of cultivation. We shall consider the first two ways.

Analysis of the characteristics of available light sources (Table 1) shows that filament lamps have a low efficiency coefficient and high infrared radiation (IR). Metal halide lamps have a high efficiency coefficient (up to 38%), a continuous spectrum and a short life. Besides, their control scheme is rather complicated. Fluorescent high-pressure lamps have a low efficiency coefficient and a large size of the luminous body which interfers with the redistribution of their radiant flow. Compact KL 7-11 lamps have good prospects. They are characterized by a high surface radiation density and a small size permitting the redistribution of their radiant flow. However they have not been tested for their use in space. Fluorescent low-pressure lamps and sodium high-pressure lamps also appear to be promising. The main characteristics of fluorescent lamps and sodium high-pressure lamps are presented in Table 2. All these lamps are characterized by a high surface radiation density providing a radiation level sufficient for plant growth and development. It is known from ground-based experiments that the cultivation of plants requires a radiation level of no less than 70 W PAR/m^2 with a PAR/IR ratio of no less than 1:4. This means that for an area of 1.0 m^2, 88 lamps would have to be installed utilizing 0.7 kW of electrical energy. When using 11 W compact lamps, 40 lamps would be needed with a power demand of 0.55 kW.

Special 8 W white fluorescent lamps were designed for space plant growth units and also used as light sources for general use on the ground: SD 1-4 (1 lamp), SD 1-5 M (1 lamp), SD 1-7 (2 lamps) and PSB (6 lamps). The light device ARNIKA with a sodium high-pressure lamp, DNaT-70, was designed for space experiments.

Under ground-based conditions we carried out an experiment to estimate the efficiency of light devices SD 2-7, PSB (with white and red- and blue-colored lamps in the ratio of 3:2:1). In a mixed spectrum the productivity of lettuce was found to be increased by 20-25%. Also, some changes in the biochemical composition of plants were noted. The productivity of plants upon equalization of light power under DnaT-70 lamps corresponded to the growth with a mixed spectrum and significantly exceeded that under lamps with a continuous spectrum.

TABLE 1. Some characteristics of lamps for irradiation.

Class of lamps	Power range (W)	Life (h)	PAR:IR (400-700:700-1200)	Notes
Filament	unlimited	up to 2000	1:7	
Fluorescent				
Low-pressure	4-150	3000-15,000	1:0.05	used in space
High-pressure	80-2000	15,000	1:1	investigations
Metal halide	250-2000	200-2000	1:0.7	
Sodium high-pressure	70-1000	up to 15,000	1:0.4	prepared for the use in space investigations

TABLE 2. Main characteristics of Fluorescent lamps.

Type of lamps	Power, W	Size, mm	Power in the PAR zone,W	Superficial rediation density	Notes
LB4-2	4	16x160	0.6	90	
Fluorescent LB8-6	8	16x298	1.4	115	used in space investigations
L38	8	16x298	1.6	130	no analogs
LS8	8	16x298	1.2	100	no analogs
LK8	8	16x298	1.4	115	no analogs
KL/TBS	7	135x32x20	1.3	150	not tested in
KL/TBY	11	235x32x20	2.5	190	for space investigations

The first lighted unit used for plant cultivation under space flight conditions, Oasis-1, was placed aboard the first orbital station Salyut. the electric power demand of this apparatus was 30 W. Three SD 1-4 light devices with white fluorescent lamps were used. Nine plants provided with 6 cm^2 each, were placed within an irradiated area of 400 cm^2. The rate of the luminous flow reached 25±5 W PAR/m^2. Later on, modified light devices SD 1-5 M and SD 1-7 were used in Svetoblok, Fiton, Malakhit and in modified Oasis-1 AM aboard the orbital stations Salyut and Mir. Using white fluorescent lamps, LB 8-6, in the growth unit, Svet, aboard the station Mir, the

power in the PAR region was increased up to 30±10 W/m^2 due to a more compact arrangement of lamps (6 lamps per 500 cm^2). This required the use of a heat removal system, thus the total energy in the vegetation chamber was increased. Fluorescent lamps were used in the American PGU. Light diodes have been used in the University of Wisconsin Astroculture flight unit.

With the above-mentioned devices, fundamental results in the field of space biology were obtained directly related to the development of maned space flights, particularly to the possibility of creation of biological life-support systems. A fundamental possibility of growth and development of plants under microgravitation conditions, including the stage of seed production, was demonstrated (Merkis, Laurinavichus, 1980; Mashinsky, Nechitailo et al., 1992; Nechitailo, Mashinsky, 1993). At the same time, the problem of lighting efficiency remains. As early as the middle seventies we began constructing a chamber to provide one astronaut with a daily ration of vitamins and a part of the vegetable ration, to improve the psychological comfort of astronauts, and to develop studies on the use under microgravitation conditions of higher plants as an element of the life-support system. The device was named KAMIN (by the first letters of the family names of the authors - Konshin, Alexander Mashinsky and Nechitailo).

Plants grown in Kamin are assumed to produce 20 g of dry biomass daily for 1.0 m^2 area under the following conditions: carbon dioxide at 0.3±0.05%, oxygen at 18±3%; air humidity at 80±15%; temperature at 20±5°C (the temperature difference between the vegetation and root zones should be no less than 2-5°C), irradiation at 100±20 W PAR/m^2. The basis of the device is a cylinder with a vegetation unit on its inner surface. The cylinder is able to rotate on bearings relative to the growth chamber body and the lighting unit, which is located excentrically in the cylinder, thus providing for even illumination of plants of different age in the units. The plants are grown in units by the conveyor method (each unit contains plants of different age).

We returned to the idea of using the new design units for improving illumination conditions when developing a modified Svetoblok-2 together with a group of U.S. scientists from the University of Utah. The leader from the U.S. side was Professor F. Salisbury. As a result of the joint work of the American and Russian scientists, a model was constructed to be used in joint Russian-American space research programs. The idea initially consisted in placing lamps vertically in an ellipse focus which formed a light-reflecting surface. In the other focus it was planned to place plants. Thus, the whole light energy reflected from the ellipse surface would remain in the vegetation zone. The data indicate that the given technological approach permits an enhancement of lighting efficiency providing for photosynthesis. Unfortunately, it should be stated that this work has not yet received further development as a cooperative Russian-American project for joint investigations aboard orbital stations. Therefore the Russian specialists offer to other interested scientists to continue this joint activity.

SHORT REPORT

SYSTEMS OF ARTIFICIAL LIGHTING AT THE PHYTOTRON OF PLANT BREEDING AND GENETIC INSTITUTE (ODESSA).

Adolf Chernozubov

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At the Odessa Phytotron we have installed over 50 climatic chambers and cabinets made by various companies of the United States, Canada, Germany and U.S.S.R. They employ different light sources including Sylvania fluorescent lamps of various types, fluorescent lamps produced in the former Soviet Union with a special luminophore, ordinary tungsten lamps, xenon, mercury, mercury-iodide, sodium, etc. Our objective in lighting is that the intensity distribution over the wave lengths should be maximal in the photosynthetically active part of the spectrum and minimal in the IR part to avoid plant sterilization.

Phytotrons are extremely energy consuming entities, and the large part of their energy consumption falls into the lighting category in our electric bills. Therefore, we are in a constant search of the processes to reduce energy, for example, we use a mirroring polychlorovinyl film as light deflector, we create combined light sources, we have even employed movie projection lamps in combination with monochromators and attempted the use of fiber glass optics. However, the main way to increase effectiveness would be the development of new types of light sources, which would come close to the threshold of 150 to 200 lumens per watt.

Over the years we were constantly improving our systems of artificial lighting, since we had good contacts with several producers and inventors in Russia. However, with the economic crisis unfolding, our Phytotron is having a difficult time keeping the equipment updated.

However, I should point out here, that our Phytotron is the only operating plant breeding Phytotron in the territory of the former Soviet Union. We will certainly do our best to keep it running and will continue our fruitful experiments. We are open for collaboration and welcome anybody who wants to deal with us on a basis of mutual cooperation.

SHORT REPORT

MARTORVÁSÁR PHYTOTRON

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H-2462 Martonvásár P.O.B. 19, Hungary

Lighting in the Martorvásár Phytotron plant growth units is as follow:

24 units - Cool white and Gro-lux fluorescent 1:1 or Cool white and incandescent lamps 3:1.

24 units - Metal halide lamps

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XENON LIGHTING ADJUSTED TO PLANT REQUIREMENTS

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INTRODUCTION

When electricity started to replace the flame techniques for lighting the discharge between two carbon electrodes was the first electric light discovered in 1809. Fifty years later the electric heating of carbon filaments started a competitive lighting technique. Both types of lighting are still competing with each other (Neumann 1977). The preference at the time being depends on the applicability and economy of the particular brand. The discharge techniques, however, due to economic and spectral improvements seem to be still promising in the long run (Meyer and Nienhuis 1988).

Xenon arc lamps were introduced to lighting about 50 years ago (Schulz, 1947,Larche 1955) when temperature radiators dominated the lighting technique and discharge lamps had just started to be developed for a wider market. Both of these lamp types were limited in power, in lifetime, and in colour rendering. Progress in glass production and handling techniques had reached a level permitting the construction of high pressure bulbs which are necessary for an increased gas filling. Xenon is the heaviest stable noble gas and has the lowest ionization threshold (12.1 eV) of the noble gases. It promised a considerable improvement of luminous efficacy combined with a smooth spectrum at gas pressures of 105-107 Pa.

While most discharge lamps e.g. mercury, sodium, or metal halide lamps emit a more or less pronounced line spectrum, the radiation output of xenon is dominated by a smooth continuum Schäfer 1969, Popp 1977), resulting from the recombination between electrons and positively charged xenon ions. As the recombination process involves the population of excited xenon states which thereupon relax to the ground state, some weak lines in the visible part and strong lines in the near infrared region are also observable. Due to the favourable coincidence of some atomic parameters of xenon, the continuum is centered around the green spectral range (550 nm) and thus a good approximation of the natural sun spectrum is achieved.

Xenon lamps are available as low and high power lamps with relatively high efficiency and a relatively long lifetime up to several thousand hours. Different construction types of short-arc and long-arc lamps permit a good adaptation to various applications in projection and illumination techniques without substantial changes of the spectral quality. Hence, the xenon lamp was the best choice for professional technical purposes where high power at simultaneously good spectral quality of the light was required.

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*Paper presented by H. D. Payer

However, technical development does not stand still. Between the luminous efficacy of xenon lamps of 25-50 lm/W and the theoretical limit for 'white light' of 250 lm/W is still much room for improvement. The present development mainly favours other lamp types, like metal halide lamps and fluorescent lamps for commercial lighting purposes (Kaufmann and Christensen 1984).

The following sections deal with some of the properties of xenon lamps relevant to plant illumination; particularly the spectral aspects, the temporal characteristics of the emission, and finally the economy of xenon lamps will be addressed. Due to radiation exceeding the natural global radiation in both the ultraviolet (UV) and the infrared (IR) regions, filter techniques have to be included into the discussion referring to the requirements of plant illumination. Most of the presented results were obtained by investigations in the GSF phytotron (constructed by Heraeus-Vötsch, Balingen according to Payer et al. 1986 and 1993) or in the closed Phytocell chambers of the University of Erlangen (constructed by BBC York, Mannheim, according to a design by Hartmann and Kaufmann 1990). As our experiences are restricted to area plant illumination rather than spot lights our discussion will concentrate on low pressure long-arc xenon lamps which are commonly used for such plant illuminations. As the spectral properties of short-arc lamps do not differ much from those of long-arc lamps most of our conclusions will be valid for high pressure xenon lamps too. These lamps often serve as light sources for small sun simulators and for monochromators which are used for action spectroscopy of plant responses.

MATERIALS AND METHODS

The Light Sources: Lamp and Filter Techniques

Two long arc xenon lamps, 4500 W each (NXE 4500, Heraeus Hanau) and the corresponding electric devices and instructions were provided by Heraeus Original Hanau. The lamp house, its heat absorber, and ventilation instructions were provided by Heraeus Vötsch Balingen (according to the design for the GSF phytotron, Payer et al. 1986, adapted from Boxhammer 1981). The front cover consisted of 2 mm fused quartz slides. The reflector is formed by cold light mirrors (Schott, Mainz). The complete luminairy consisted of two xenon lamps 80 cm apart, mounted 180 cm above plant level. It was integrated into the lamp ceiling of a recently developed sun simulator (Seckmeyer and Payer 1993). Optionally a water filter for IR filtering (Warrington et al. 1978) and glass filters for UV or IR absorption are available. The residual ceiling and walls of the lamp compartment are cladded with highly reflecting panels of anodised aluminium. Particularly for the comparison of the lighting efficiency the xenon lighting system of the Phytocell chambers at the University of Erlangen was evaluated (Hartmann and Kaufmann 1990). The Phytocells at Erlangen are equipped with two long arc xenon lamps (Osram XQO, 10000 W each) installed at a distance of 80 cm from each other and 120cm above the plant level. Cold mirrors type 213 (Schott, Mainz) serve as light reflectors, the IR rejection is performd by coated glass filters type 112 (Schott, Mainz) . Two 6 mm layers of security glass SPRIDUR are used to separate the light compartment from the experimental space.

Measurements

General lighting parameters were measured with integrating instruments. Total radiation was

determined with a pyranometer (Kipp + Zonen CM 11, 300 - 2500 nm). Illuminance and photosynthetic active radiation were measured with sensor heads made by Licor (Luxmeter LI 210) and (Quantum counter LI 190, 400 - 700 nm) PRC Krochmann (Luxmeter 110). UV-B radiation was recorded with a Robertson-Berger-Meter (Biometer 501, Solar Light). For spectral measurements spectroradiometers were used. Light, respectively radiation was collected by a cosine adapted diffusor and coupled into the monochromators, residing outside the chamber, by means of a 2 m quartz fiber bundle. All sensors were placed directly into the plant compartment at a distance of 180 cm below the lamp.

As the whole spectrum measured from 250 to 1350 nm cannot be covered with a single monochromator/detector combination, the spectral range was divided into the following four parts with adequate overlapping of each other:

A) 250 to 500 nm: A double monochromator (Bentham M300HR/2) with two gratings of 2400 grooves/mm and a photomultiplier (EMI 9558BQ) as detector were used. Its spectral resolution was adjusted to 1 nm, the detection limit was 0.01 mW/m2 nm

B) 400 to 850 nm: A single monochromator (Bentham M300HR) with a grating of 1200 grooves/mm and a photomultiplier (EMI 9558BB) as detector were used. Its spectral resolution was 5 nm, the detection limit better than 0.01 mW/m2 nm

C) 750 to 1100 nm: Monochromator: same as B). The detector was a silicon diode, the detection limit was approx. 1 mW/m2 nm

D) 900 to 1350 nm: Monochromator: same as B). The detector was an uncooled lead sulphide cell. The detection limit was approx. 20 mW/m2 nm

Calibrations were performed by using a calibrated deuterium lamp ($k < 280$ nm) and a calibrated 100 W halogen lamp for the remaining spectral range (PTB Braunschweig). Spectral irradiances for the unfiltered radiation (UV to IR transparent quartz slides served for protection) and the water filtered radiation were measured directly. Irradiances for other filter combinations were derived from those using the spectral transmission data of the individual filter materials.

The electric power consumption was read from electricity meters and included the energy for ballast. The energy for cooling was not included. These measurements formed the basis for an estimation of the lighting efficiency of our lamp assembly.

The optical measurements at the Erlangen Phytocell included a spectral radiometric device described by Kaufmann and Hartmann (1990), a pyranometer, PAR-meter, UV-radiometer,and photometric analyses as described by Hartmann and Kaufmann (1990). Additionally, a digital luxmeter (Mavolux, Gossen) was used. All sensors had a cosine response.

The temporal pulsations of the xenon emission were measured with the monochromator/photomultipier combination B, as described above, connected to a digital storage oscilloscope.

RESULTS AND DISCUSSION

Spectral aspects

The radiation penetrating the quartz envelope of a xenon lamp shows an almost flat part with little line structure in the visible range and a pronounced line structure in the IR spectrum (Figure 1). The short-wave limit at approx. 200 nm and the long-wave tail up to 2500 nm (Kaufmann and Christensen 1984) were not included in our plant related investigations. They are described in the literature. The irradiance in the IR exceeds the irradiance of natural global IR radiation by an order of magnitude. The heat resulting from excess IR absorption by biological tissues will lead to rapid destruction. Excess short-wave UV radiation will also be deleterious to living systems. Xenon lighting, therefore, requires specially tailored filters which, protect living systems from these spectral irradiances.

The criteria for filter selection are, however, not readily met by the available filter systems which, therefore, do not completely fit the experimental requirements for plant illumination. The criteria can be summarized as follows:

A) Spectral balance. The excess radiation should be removed with negligible losses of the required useful radiation which is defined by an energetic and spectral balance close to natural conditions.

B) Long term stability. The mechanical and optical properties of the filter material should have a long-term stability which depends on scientific considerations, cost, and duration of an experiment.

There are several glass or plastic filters transmitting at least part of the required radiation. Figures 2 and 3 show typical results of such glass filtered xenon radiation. The first system employs IR absorbing glass (KG1, Schott), the other systems make use of glass with a heat reflecting coating. All systems eliminate most or all of the short wave UV radiation and provide a good transmittance in the visible range (Schott filter 112 and 113). The KG1 glass, which exhibits a UV-B transmission superior to the other filters, shows an increasing IR absorption with an increasing wavelength. In order to remove the absorbed energy an effective cooling by air or water is necessary. In the case of heat reflecting layers IR is reflected to other materials from which heat can be removed more readily than from glass. The main purpose of all these filters is the eliminiation of the strong peaks in the near IR. Besides glass filters water is known as a good heat absorbant. Since water filters need a container, the spectral properties of both water and its containment have to be taken into account (Figure 4).

Due to economic aspects large water layers rely on containment materials other than fused quartz. They do absorb a great deal of the UV radiation as already demonstrated in Figures 2-4. The residual IR-absorption of water filters can be concluded from Figure 4, where the spectral transmittance of 2 cm and 20 cm glass contained water layers are compared. The absorption of water in the near IR (800-950 nm) is not very effective regardless of the layer thickness whereas longer wavelengths are readily absorbed.

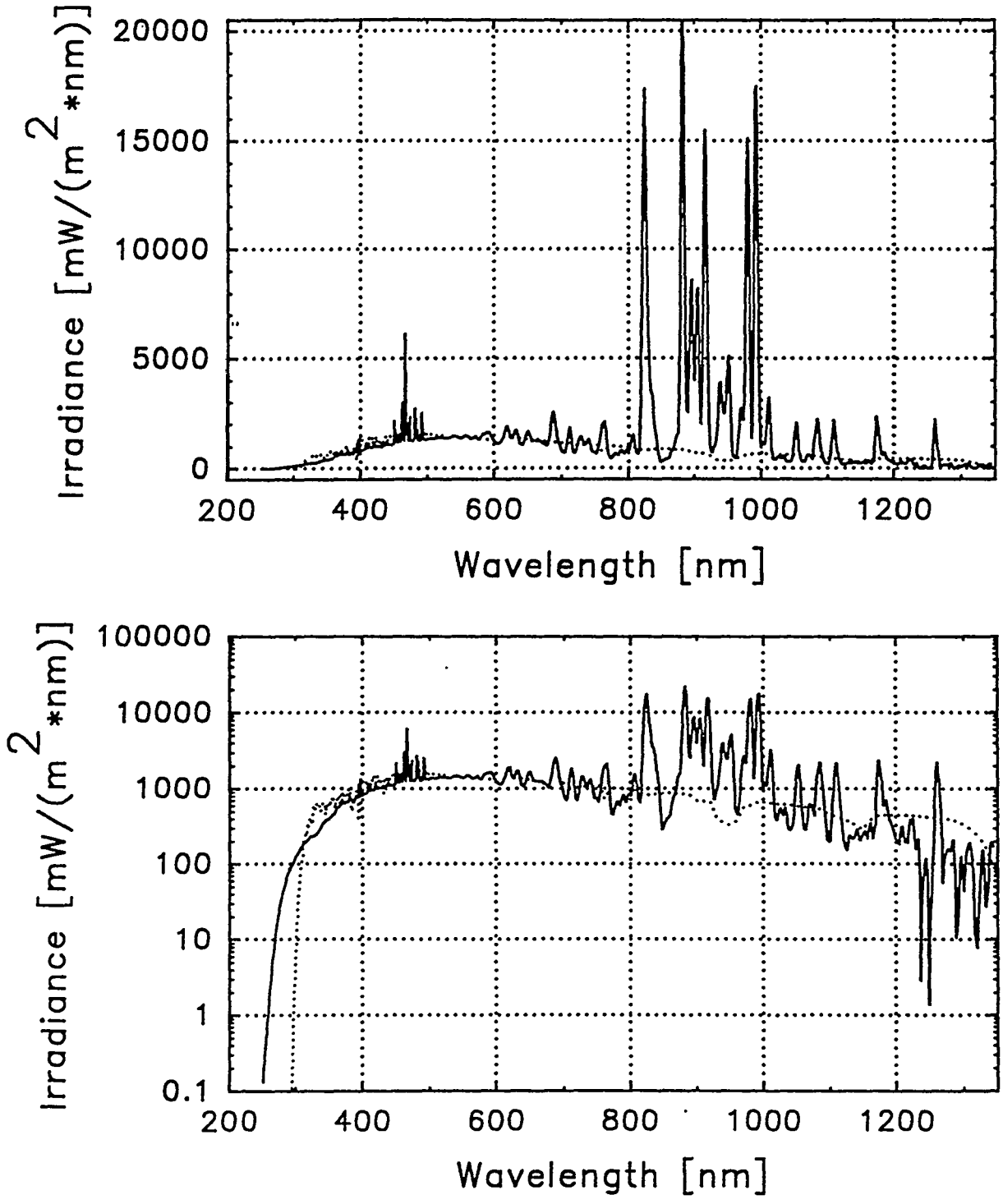

Fig. 1. Spectral irradiance of the unfiltered radiation of a long arc xenon lamp. The data are adjusted to 1940 µmol/(m2 s). The dotted line indicates the spectral irradiance of global radiation for a sun elevation of 60 degrees and an ozone value of 320 DU according to model calculations.
Fig. 1a (top). Linear plot
Fig. 1b (bottom). Log plot.

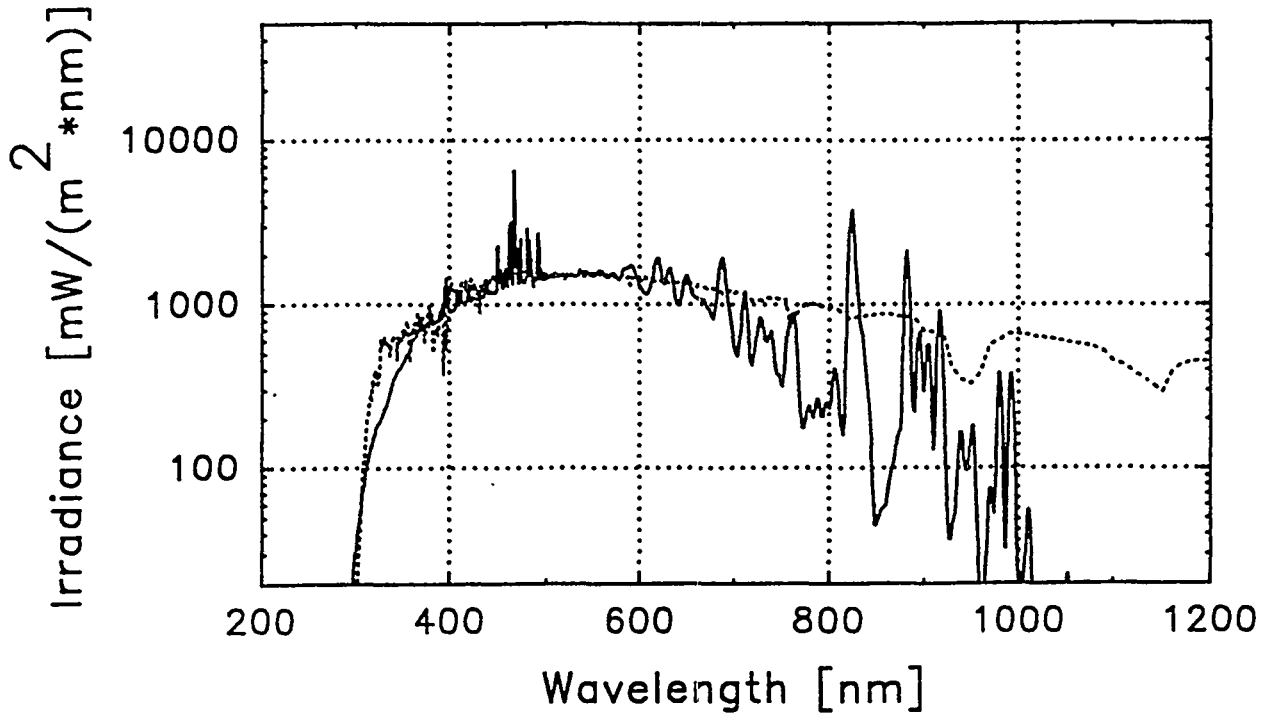

Fig. 2. Spectral irradiance of xenon radiation, filtered by an IR absorbing Schott glass KG 1. Further explanation see Figure 1.

With regard to our above stated criteria for filter properties we compare all presented filter systems applied to xenon light according to the spectral balance of the transmitted radiation. As reference for natural conditions the global radiation is calculated according to a model of Seckmeyer and Thiel (unpublished) based on data of Green (1983) for a 60 degree sun elevation, the approximate maximum available in Central Europe and an ozone column of 320 Dobson units. For comparison the spectral irradiances obtained from calculated global radiation and differently filtered xenon radiation (Figure 1) are adjusted to an equal photosynthetic active radiation (PAR) of 1940 μmol m-2 s-1. Spectral subsets of the UV, the visible, and the IR ranges are presented in Table 1. The weighted visible and UV ranges. Illuminance and erythemal weighting according to CIE are added for comparison.

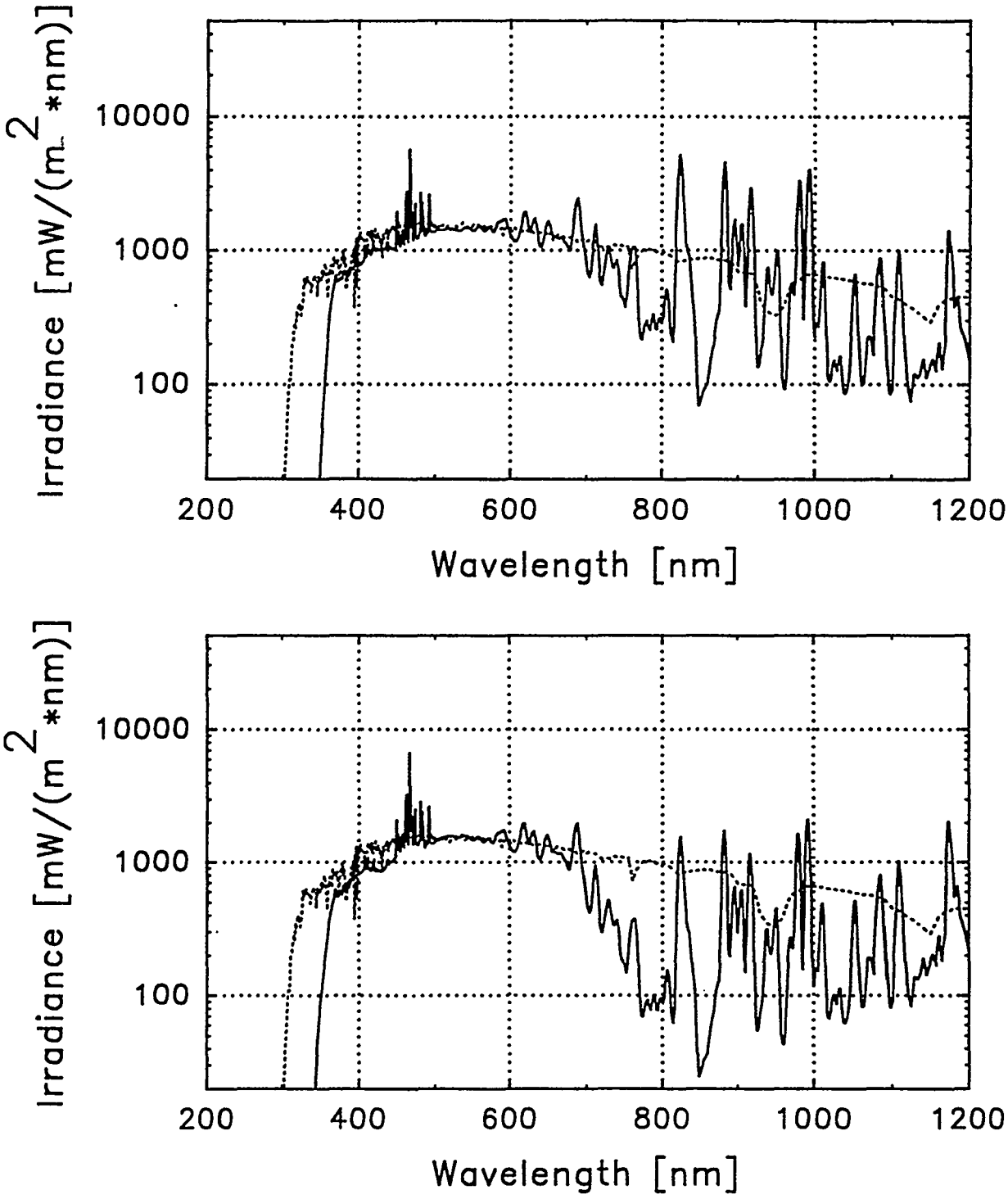

Fig. 3. Spectral irradiance of a xenon radiation, filtered by heat reflecting glass.
Fig. 3a (top). Schott type 112 filter.
Fig. 3b (bottom). Schott type 113 filter. For further explanations see Figure 1

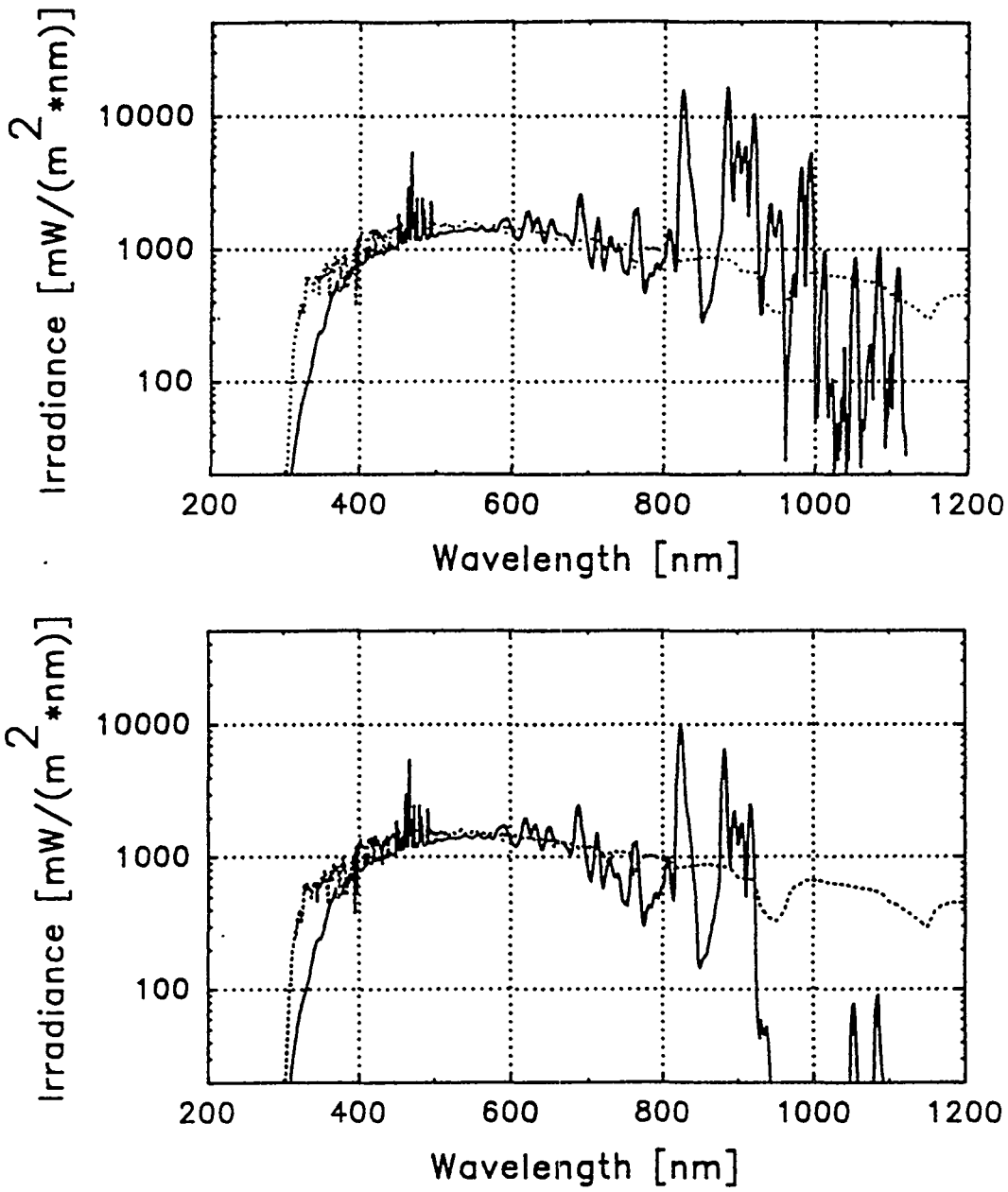

Fig. 4. Spectral irradiance of a xenon radiation, filtered by water contained in Tempax glass (Schott).
Fig. 4a (top). Water layer of 2 cm
Fig. 4b (bottom). Water layer of 20 cm. For further explanations see Figure 1.

The data from Table 1 demonstrate that within the visible and photosynthetically effective spectral ranges a good approximation of integral values can be obtained by careful design of the filter system. However, the phytochrome effective far red range (around 730 nm) seems to be not sufficiently available (KG1 and 113) without accepting excess IR (filter 112 and water layers). Thus our first criteria to match the spectrum closely to natural conditions may not be met fully. If excess IR is intolerable the far-red gap, caused by the transmission characteristic of the IR filters, can be filled by an independent irradiation system providing part of the

required phytochrome effective radiance separately from the xenon system. As long as excess IR is acceptable the best spectral balance is achieved by glass contained water layers of sufficient thickness.

TABLE 1: Spectral Irrandiances of Differently Filtered Xenon Lighting Systems in Percent of Global Radiation

	Solar 60° global radiation absolute	Xenon [percent of solar radiation]					
			IR reflecting glass		IR abs.	Tempax + Water	
		unfiltered	112	113	KG1	2cm	20cm
250-1350 nm	971 W/m²	**172**	82	67	63	124	77
250-280 nm	—	(0.31 W/m²)	—	—	—	—	—
280-320 nm	3.0 W/m²	**167**	**<0.1**	**<0.1**	64	**17**	**17**
320-400 nm	53.8 W/m²	79	50	52	85	60	61
600-700 nm	132 W/m²	108	107	100	96	112	111
700-800 nm	104 W/m²	98	61	**28**	**49**	93	68
800-900 nm	85.6 W/m²	**500**	124	**42**	75	**450**	**228**
900-1000 nm	53.3 W/m²	**920**	**189**	88	**36**	**440**	63
Erythema	3.35 MED/h	585	4	4	150	30	31
Illuminance	109 klux	96	98	103	102	96	97

The spectra were normalized to 1940 μmol/(m²·s) of PAR and related to the respective spectral range of the global radiation. The resulting percentages of the spectral ranges are in bold figures if the deviation from the global radiation is more than 50%.

The accumulated spectral irradiances of Table 1 reveal a good elimination of the excess short wave UV range by all filter systems. Most filters except of the KG1 glass do not only eliminate the UVC range but also the UVB range which may be essential for many plant responses. Taking into account the continuous shift of the UV absorbance which results from glass ageing by short-wave UV irradiation, long term stability of the UVB irradiance cannot be achieved by current irradiation techniques (Döhring et al. 1994). Hence, the second criteria for photobiological experiments cannot be met sufficiently for this spectral range. The best choice in our opinion is cutting off the UV range < 320 nm from the xenon lamp irradiation and supplementing the UVB range if necessary by an independent irradiation system (Seckmeyer and Payer 1993).

Temporal Variations of Xenon Light

The optical output of an electrical lamp is correlated to the frequency of zero crossing (100/120 per second) of the applied AC voltage (50/60 Hz) (Figure 5). In the case of incandescent lamps, quartz halogene lamps included, the light oscillations are strongly damped due to the heat capacity of the tungsten filament. These lamps do not completly extinguish during each zero crossing of the applied voltage and the optical ripple is, therefore, small.

The plasma of a xenon discharge can follow much more rapidly to the instantaneous change of the input voltage. This is the reason why xenon flash tubes have such a firm standing in flash photography and time resolved experiments down to the microsecond range.

Xenon lamps connected to AC power systems do have a pronounced flicker even if not visually perceptable. Figure 5a shows an oscilloscope recording of the 100 Hz pulsations of a 4500 W xenon long arc lamp. The ratio between maximum and mean irradiance is approx. 2 and is much higher during the ignition transient.

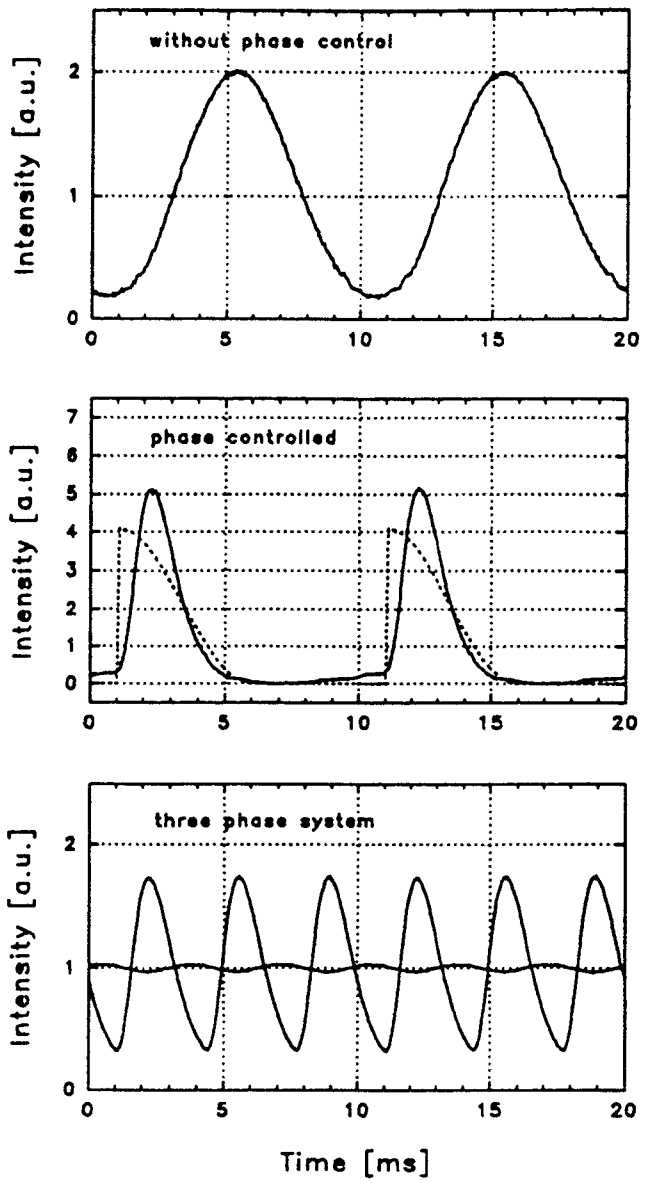

Fig. 5. Light ripple of an AC operated xenon lamp under different modes of operation
Fig. 5a (top). Single phase operation without phase control Imax/Imean = 2.
Fig. 5b (middle). Single phase operation with phase control (solid line), Imax/Imean = 5. The dotted line shows schematically the phase control of the applied AC power.
Fig. 5c (bottom). Three phase operation with phase control (large ripple) and without phase control (low ripple). Imax/Imean = 1.7 and 1.1 respectively.

An electronic phase control, as it is used for continuous dimming of the lamp output even increases the maximum to mean ratio to more than 5 (Figure 5b). This electronic device switches on a certain variable portion of each half period of the input sine voltage (Figure 5b). The light output of the xenon lamp virtually mirrors the electrical input power resulting in a strong ripple.

Neither AC powered lamps nor lamps operated with phase controlled voltage showed any significant spectral dependence of the lamp output. This is not surprising, as in either case lamps are operated at rather moderate current densities (< 100 A/cm^2). Dramatic spectral changes in xenon discharges, mainly an increase of irradiance in the blue, can only be expected at current densities well above 1000 A/cm^2 (Goncz and Newell 1966).

Thus, the temporal analysis shows that in both types of operation modes a biological system is subject to a strongly varying irradiance. The oscillation contrast and the duration and frequence of the dark periods are approximately of the same magnitude as Kok had found to be effective during his flash light studies on photosynthesis (Kok et al. 1959, Seckmeyer and Payer 1988). As a consequence xenon lamps should be ideally driven by direct current. This mode, however, results in a reduced lifetime as compared to AC driven xenon lamps. The pulsations of AC powered lamp systems can also be drastically reduced by operating three lamps (or a multiple thereof) on a three phase mains system. This mode of operation results in a very steady luminous flux (Figure 5c). Damping is, however, hardly achieved if the lamps are phase controlled (Figure 5).

Economical Aspects

Although the economy of plant lighting depends very much on the purpose and conditions of application (Meyer and Nienhuis 1988, Neumann 1977, Kauer and Schedler 1986) some aspects have to be discussed in order to judge the value of xenon lamps. Four main criteria listed in Table 2 pay regard to the different lamp properties: Lifetime, luminous efficiency (defined as the ratio between luminous flux and the electrical power input), luminance, and spectral properties. All efforts of lighting technology right from its invention in the last century were put into these four aspects.

Lifetimes of xenon lamps which vary from 50 to 3000 hrs have to be well considered under economical aspects. Most other lamp types, particularly those of a high luminous efficiency provide much longer life times.

Metal halide lamps have with regard to the luminous efficiency an advantage of a factor 4 as compared to long arc xenon lamps (Table 2). This also holds approximately for the PAR region. The main reason is the strong excess IR of xenon radiation. However, it must be considered that metal halide lighting requires several additional measures, e.g. supplemental quartz halogen lamps, to adjust the spectral region to plant requirements. These additional measures reduce the advantage to a factor 2 to 3. This estimation agrees well with our comparative measurements of illuminance and total irradiance performed in the Erlangen Phytocell chambers with xenon lighting and in the GSF sun simulator, equipped with metal halide and other lamps (Seckmeyer and Payer 1993). As the IR output of metal halide lamps is

much lower, an effective heat control can be achieved by economic glass or water filters. Xenon lamps require more sophisticated and expensive systems of optical filters and cooling techniques to remove the strong excess IR energy.

TABLE 2: Efficiency of Some Common Light Sources

	lifetime [h]	luminous efficiency [lm/W]*	luminous flux [1000 lm]	spectral properties and color temperature
Carbon filaments (Edison)	300	2	0.100	continuous, 2000 K
Tungsten double coil	1000	13	1	continuous, 2800 K
Quartz–halogen incandescent	2000	40	40	black body, 3300 K
Hg fluorescent low pressure	10000	95	16	oligochrome
Hg high pressure	8000	60	5000	oligochrome
Me–halide	5000	105	1200	polychrome, 6000 K
Na–low pressure	10000	220	200	monochrome
Na–high pressure	14000	130	130	oligochrome
Xe short–arc (XBO)	2000	50	1500	
Xe long–arc (XQO)	3000	25	500	continuous +
Xe long–arc max	?	30	4000	polychrome, > 6000K
Xe long–arc (XBF) water cooled	1000	34	225	

*Luminous efficiency is defined as luminous flux related to the total electrical power input

Despite the relatively low lighting efficiency xenon arcs reach highest artificial luminance concentrated to a single lamp and compare in this respect best with sunlight. Therefore, xenon lamps are unique, for instance, as a light source of projectors and monochromator systems. Furthermore, xenon lamps do practically not need a warming-up time but the full illuminance is available immediately.

Although the economy of lighting is mainly based on the sensitivity of the human eye, this evaluation holds roughly true for plant requirements, too. Spectral aspects seem to deserve highest priority for both visual and botanical applications. For instance, lamps with a few lines are not sufficiently balanced to meet the photobiological requirements of plants but may be sufficient to support growth and to illuminate technical objects at low cost. Only xenon lamps and some metal halide lamps provide a spectral distribution which is comparable to sunlight. The advantage of metal halide lamps is their economical adaptability to biological applications, while xenon lamps provide an almost constant smooth spectral output close to sunlight over a wide range of power. If, for particular plant experiments, spectral variations are needed this can only be achieved by a sophisticated combination of several lamp types which can be operated individually (Payer et al. 1993).

CONCLUSIONS

The high luminous flux and spectral properties of xenon lamps would provide an ideal luminairy for plant lighting if not excess IR radiation poses several problems for an application: the required filter systems reduce the irradiance at spectral regions of particular importance for plant development. Most of the economical drawbacks of xenon lamps are

related to the difficult handling of that excess IR energy. Furthermore, the temporal variationof the xenon output depending on the oscillations of the applied AC voltage has to be considered for the plant development. However, xenon lamps outperform other lighting systems with respect to spectral stability, immediate response, and maximum luminance. Therefore , despite considerable competition by other lighting techniques, xenon lamps provide a very useful tool for special purposes. In plant lighting however, they seem to play a less important role as other lamp and lighting developments can meet these particular requirements at lower costs.

ACKNOWLEDGEMENTS

We gratefully acknowledge the detailed support and advice by Prof. K.M. Hartmann and Ms.Mollwo at the Botanical Department of the University of Erlangen who provided information and equipment necessary for the comparative studies. The mutual independent reproduction of optical arrangements and data at Erlangen and Munich provided the trustworthiness of the presented results. We are further indepted to both Heraeus Vötsch Balingen and Heraeus Industrietechnik Hanau who provided the basic hardware and software on xenon luminairies free of charge. Particularly the provision of scientific material by Dr. P.March, Hereaus Industrietechnik is highly appreciated. Last but not least we thank our technical staff, D.Arthofer, H.Egger, P.Kary, W.Kratzl, P.Martin, J.A.Meier and B.Rieger who contributed all their efforts to a successful completion of our investigations.

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EFFICIENT, FULL-SPECTRUM, LONG-LIVED, NON-TOXIC MICROWAVE LAMP FOR PLANT GROWTH *

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INTRODUCTION

Fusion Systems Corporation has developed a mercury-free, low infra-red, efficient microwave lamp using a benign sulfur based fill optimized for visible light. Our literature search and discussions with researchers directed us to enhance the bulbs red output. We have demonstrated a photosynthetic efficacy of over 2 micro-moles per microwave joule which corresponds to over 1.3 micro-moles per joule at the power main. Recent work has shown we can make additional increases in overall system efficiency. During the next two years, we expect to demonstrate a system capable of producing more than 1.5 micro-moles/joule measured at the power main with significantly less IR than alternative lamp systems.

BACKGROUND

The results described are from NASA SBIR* funded work. We determined optimal plant growth light requirements via a literature search and researcher input. We surveyed candidate lamp fill materials to be used in combination with sulfur and explored several methods of increasing photosynthetic efficacy. Following is a description of the lamp's potential and the work done without disclosing proprietary information.

Advantages of Sulfur Lamp Technology

Why sulfur lamp technology? The sulfur bulb technology stems from 22 years of research and development work on microwave powered mercury based electrodeless light sources at Fusion. We summarize the properties of this new electrodeless sulfur light source:

- Spectral Stability — Non-reactive fill materials and the absence of electrodes lead to lamps with virtually no shift in spectrum over their life.
- Long Life — Life tested to nearly 10,000 hours. No evident failure mode internal to the lamp envelope discovered to date ("infinite" bulb life). System life is now limited by magnetrons which with development could be doubled to 20,000 hours or more.

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*Based on work supported by NASASmall Business Innovation Research (SBIR) Phase I Contract NAS10-11978.

- Very High Efficacy — The source has been tested at above 2 micro-moles per microwave joule, bare bulb*. We expect improvements from this value.

- Continuous Red/Green/ Blue Output — There are no large spikes in the spectral distribution. See Figure 1.

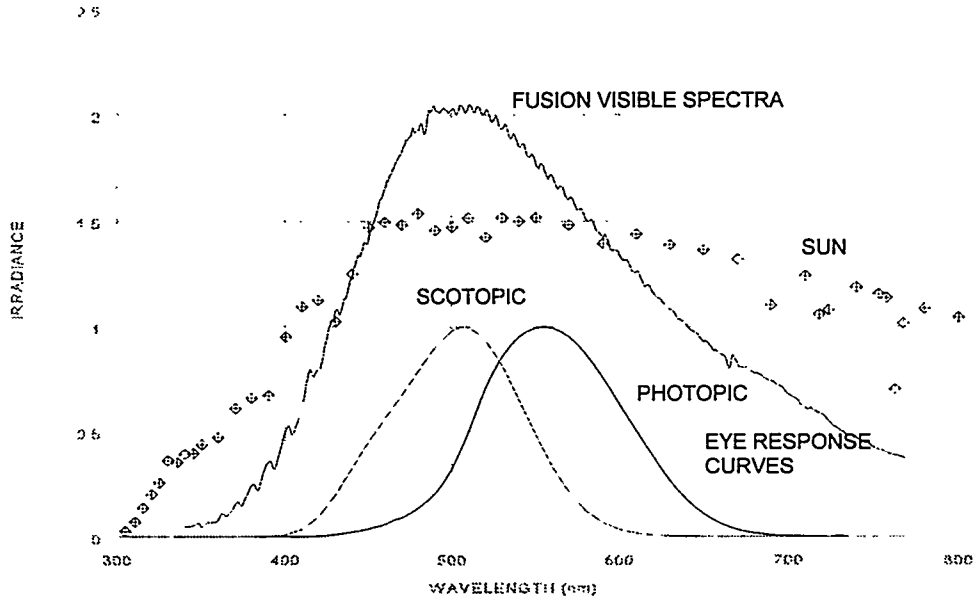

Fig. 1. Spectral Irradiance of 6700° CCT bulb (upper solid curve) with solar spectra (discrete points -- CIE Pub. 85, Table II). Lower curves are scotopic and photopic eye responses for comparison only.

- Fill Gas — The bulb is non-toxic, mercury-free, and safe -- low pressure when not operating.

- Excellent Maintenance — We estimate bulb light output at 10,000 hours will be 95 percent of initial output. This is referred to as "maintenance."

- Stops/ Starts — Stops and starts do not affect an electrodeless bulb's lifetime. As an example, comparable Fusion UV bulbs are warranted for 100,000 cycles and have achieved 400,000 in tests.

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*Bare bulb means the output measured using bulb input power without ballast or fixture losses included. This method of expressing efficacy is usual within the lighting industry. Unless otherwise stated we will use efficacy at the power main to mean bare bulb with ballast, but without a lamp fixture (reflector, etc.)

- Rapid Start — Cold start is significantly shorter than conventional HID lamps.
- Operating Range — Packages in the range 2,000 to 6,000 micro-moles per meter squared per second of PAR are potentially practical.
- Low UV and IR — See Figure 2. We expect to make further improvements

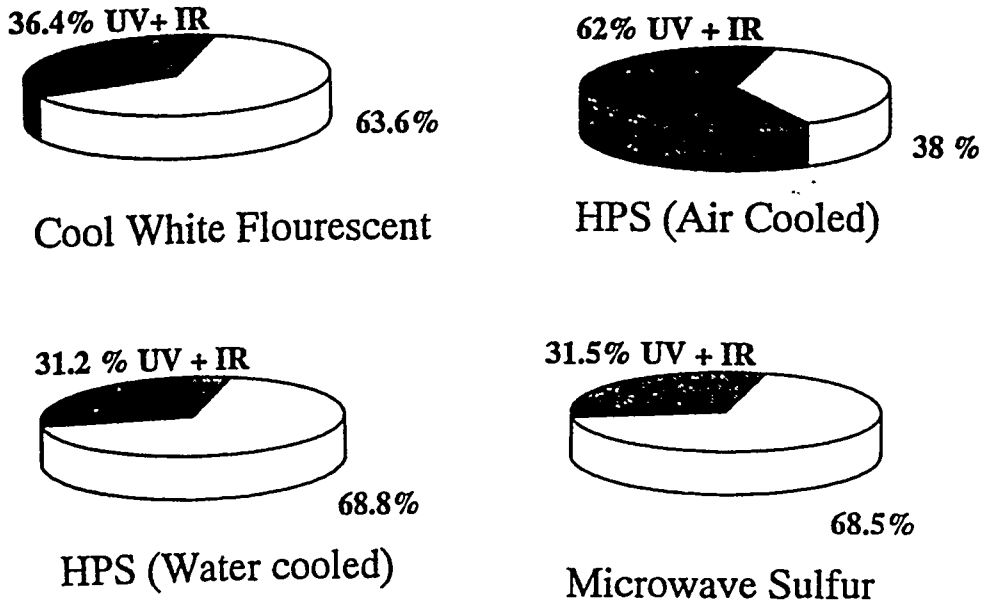

Fig. 2. 400 to 800 nm radiation versus UV + IR radiation (percent power output) or various lamps. From data adapted from Both et. al. (1994).

Sulfur Electrodeless Lamp Technology Overview

Like all HID lamps, visible light from sulfur bulbs comes from a hot gas or plasma within a transparent envelope or bulb. The plasma is heated in conventional lamps by a current between special metal electrodes. These electrodes can be a significant deleterious factor for bulb life and maintenance of output. The sulfur bulb's plasma is heated by microwave energy interacting with the material within a quartz spherical bulb -- no electrodes. The sulfur bulb is extremely simple in concept, just a quartz envelope, noble gas, and sulfur. These materials do not react with each other. See Figure 3. To this mixture, we have added other materials on a trial basis. This simplicity and the absence of chemical reactions is the reason for the sulfur bulb's long-life and excellent output maintenance.

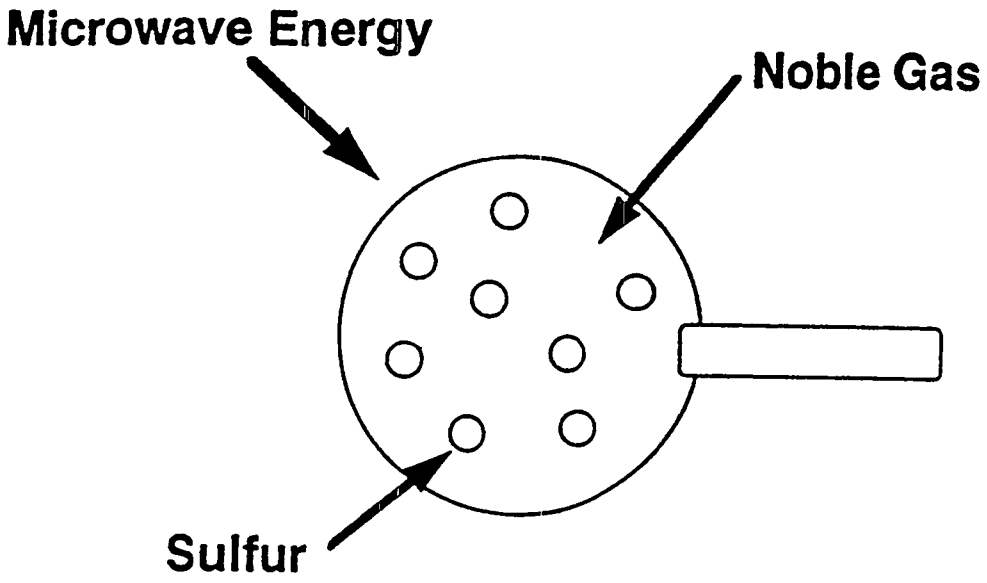

Fig. 3. Microwave Electrodeless Quartz Sulfur Bulb.

The microwave energy for the sulfur bulb is generated by a magnetron, similar if not identical to those found in microwave ovens. The magnetron is powered by direct current electricity from a power supply, which receives its energy from the alternating current electrical power mains. Figure 4 is a schematic of the lamp. Not shown in the figure is the magnetron to bulb coupling means.

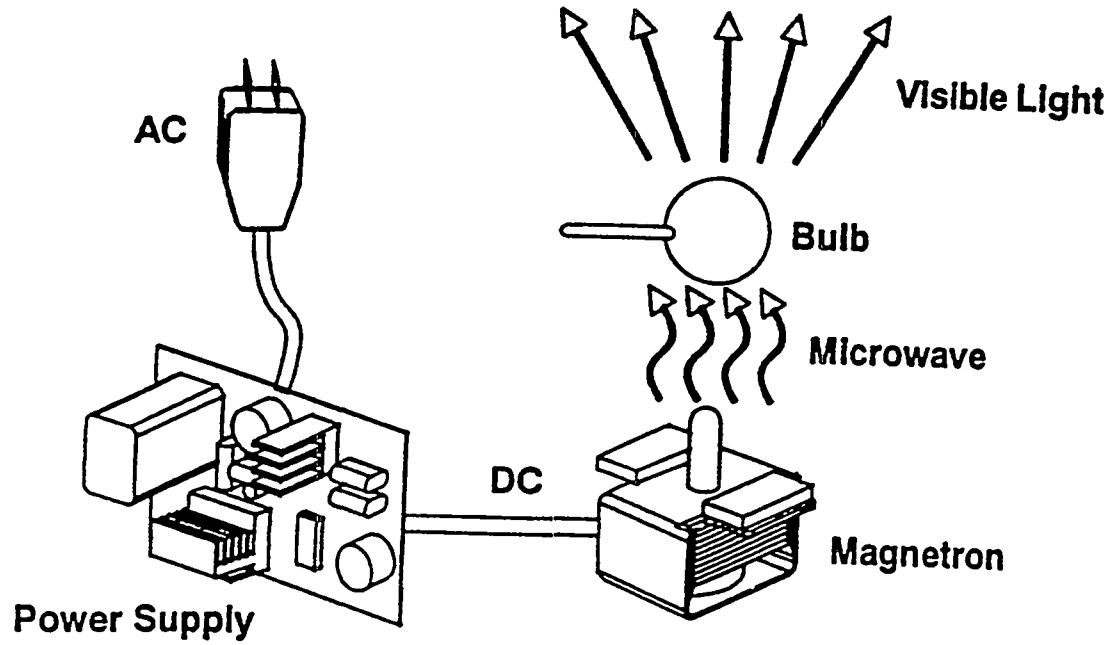

Fig. 4. Microwave Electrodeless Lamp Schematic.

Figure 5 is a cross-section of a lamp head showing the microwave coupling to the bulb. Surrounding the bulb is a microwave containment screen and outside the screen is a reflector.

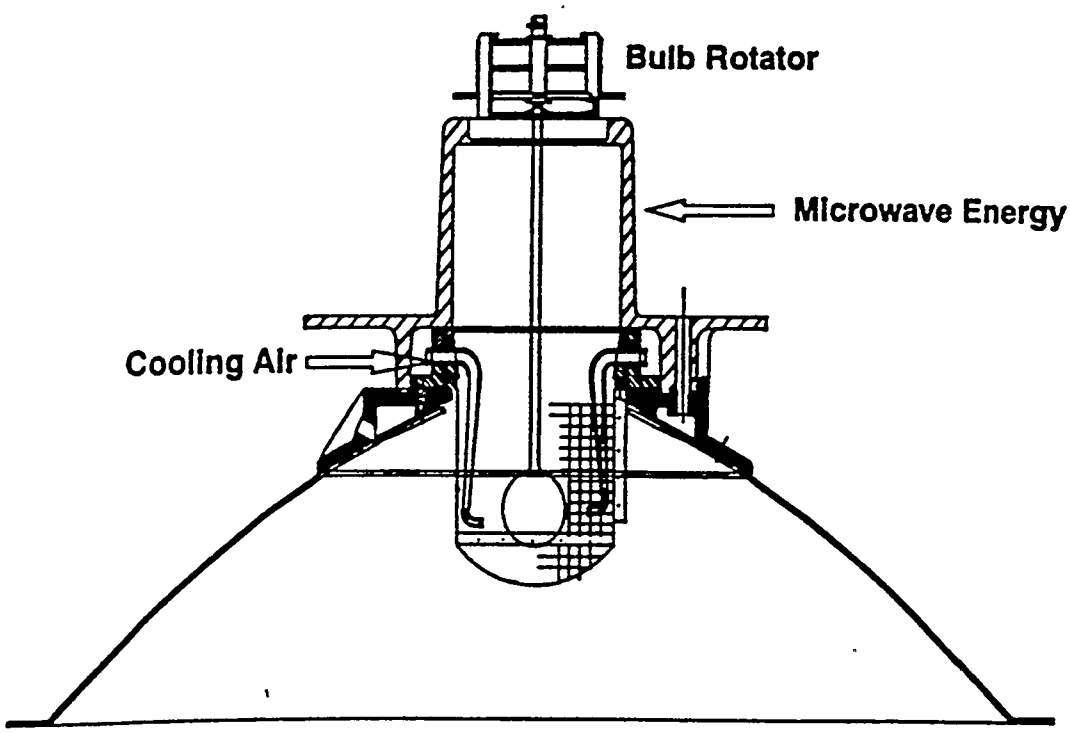

Fig. 5. Microwave Electrodeless Lamp showing Bulb Coupling.

A recent and complete review of RF and microwave electrodeless lamps for lighting with an extensive citation list was authored by Wharmby (1993). The basic paper on the sulfur lamp technology was presented by Dolan *et al.* (1992).

Potential Applications

Commercial applications for Fusion's plant growth lighting innovation are in three areas: experimental plant growth chambers, enclosed artificially-lighted plant growth factories, and supplementary early season lighting for commercial nurseries and farms. Spectrum, efficacy, cost, life, and infra-red content are key factors which will determine market success. Each market area weights the factors differently.

Experimental plant growth chambers. Plant growth chambers are essentially sophisticated, lighted, walk-in refrigerators designed to maintain a constant temperature and humidity. Control of carbon dioxide and other gases can be important. Low infra-red emission, output and wavelength stability, and adequate photosynthetic radiation are key criteria to plant growth researchers. Lamp life, efficacy, and cost are less important. We have found an improved spectra would be welcome by researchers.

Experimental growth chambers are used at colleges and universities, bio-technology firms, in government, and research laboratories.

Enclosed artificially-lighted plant growth factories. Phytofarms of America may be the only US firm to grow lettuce and other greens hydroponically totally under artificial light commercially (water cooled high pressure sodium) in the US for a period of time. See Field (1988). Phytofarms is no longer operating. One critical factor in shutting down was the cost of

electricity. For artificially lighted plant growth factories, the cost per quanta delivered to the plant is the most critical factor. At the present time no source appears to have the efficacy to allow plant growth factories to flourish in the US. Apparently such growth farms are successful in Japan. Low infra-red content and cost per unit dry weight grown are key factors in this market.

Supplementary early season lighting. The largest near term potential market is supplementary lighting for early season plant growth. In this market, initial cost of equipment and operating costs are primary. High pressure sodium has adequate spectra and initial and operating costs for many situations. According to a limited sample of commercial growers, infra-red from high pressure sodium lamps is not a problem and may be helpful as the supplementary lighting helps keep the ground warm during December through February.

OPTIMAL PLANT GROWTH SPECTRA

When starting this work, the authors decided to obtain input on the optimal plant growth spectra so lamp objectives could be properly set. We choose to do this by examining the literature and talking with key plant growth researchers.

Summary

Our literature search and researchers' comments* suggest an optimal plant growth spectral energy distribution for photosynthesis and most photomorphogenic processes: 10% of the energy in the blue region of the spectrum, preferably at about 440 to 460 nanometers, and 90% of the energy in the red region of the spectrum with approximately 75% in the region between 600 and 700 nanometers, and less than 25% of the red energy in the far-red from 700 to 800 nanometers. UV radiation below 360 nanometers wavelength has been shown to have deleterious affects on plant morphology, and infrared radiation past 800 nanometers doesn't contribute to plant growth and can be harmful at high levels (McCree 1984).

We also learned photosynthetic radiation, the number of photons between 400 and 700 nanometers, expressed in micro-moles, is a good initial metric for the output of plant growth bulbs. This metric is simple, widely used, and sufficiently close to the well known McCree (1972) relative quantum yield curve as to be quite useful.

Researcher Comments

The total energy of the radiation input to the plants has two separate criteria, where for most plants (except wheat and certain other seed grasses), a "blue" energy input of 30 to 35 micro-moles per meter squared per second has been suggested as the minimum needed for decent plant growth, and 70 to 75 micro-moles M^{-2} sec^{-1} has demonstrated better performance (Sager). Total energy has been postulated as optimized at approximately 600 micro-moles M^{-2} sec^{-1}. By controlling the total energy output to that level, direct comparisons can be made between the

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*Researchers supplying comments are listed following references.

Fusion visible system and fluorescent, metal halide and high pressure sodium lamps. The reason is fluorescent lamps are limited to approximately that range and many researchers have concluded plant growth performance for fluorescent illuminated systems is acceptable (Downs).

There were also some comments from researchers as to the reasoning they used in selecting a particular spectral distribution. Robert J. Downs said the residual radiation energy following transmission through a single soybean leaf is almost completely quenched below 700 nanometers, thus indicating the green and blue radiation is absorbed or reflected by the topmost leaves in the foliage. Thus in order to get sufficient leaf mass, red radiation between 600 and 800 nanometers is very important, as only that radiation contributes to photosynthesis in the leaves below the top-cover foliage.

Downs also expressed the opinion the Fusion spectrum of Figure 1 is too blue. A flatter distribution would be better.

Frank Salisbury suggested the [sulfur] spectra would be considered "ideal" as it presently exists for researchers working in the areas of plant environmental and pollution research, as the researchers would be able to model solar equivalent response and have the ability to rapidly study such topics as ozone depletion, greenhouse gas effects, volatile hydrocarbon pollution, acid rain effects and other environmental variables as well as their impact on plant growth, morphology and physiology. Salisbury also stated for many wheat-like plants, the red output from high pressure sodium works extremely well, and those types of plants seem to have little need or requirement for the 10% blue radiation as defined by other researchers.

Theodore Tibbitts indicated a differing view. He suggested the bulk of the radiation would be most useful if the radiation distribution were partitioned into 10% in the blue near 450 nanometers, and 90% in the region between 550 and 680 nanometers. He believes this would be an optimal spectra for nearly all commercial applications. He suggested the spectra would be best if it was strongly peaked near 600 nanometers with a rapid fall to zero above 800 nanometers and below 300 nanometers.

Two of Fusion's lamps are being used by the USDA, Climate Stress Laboratory by Dr. Steven J. Britz and his co-workers in plant growth studies. Dr. Britz, writes "I doubt that a single spectrum will be optimal under all conditions. Much will depend on the species or genetic variety being used." His general conclusion, however, is in line with other researchers -- 90 % of quanta in the red, 10 % in the blue. A key point in Britz's communication is "... our interest in the [Fusion sulfur] lamp is based primarily on its ability to simulate sunlight more accurately with respect to spectral quality and irradiance ..."

Tibbitts' note reminds us the photomorphology for most plants has a strong far-red response at approximately 730 nanometers, which is one of the themes of Kasperbauer's paper on phytochrome regulation (Kasperbauer 1992). With a strong control on radiation within the red and far-red, plant morphology can be highly regulated. Fusion's present spectral output for the sulfur bulb is slightly higher in the red to far-red ratio in comparison to solar radiation, which helps explain Britz's finding of a phytochrome photoequilibrium distribution of 0.76 for the sulfur bulb system as compared to 0.72 for solar radiation (Britz *et al.* 1994). Thus the present

spectra should have a tendency to have elevated growth of plant dry matter and a reduced photomorphological response, enabling the morphology to be controlled by addition of "far-red" light at approximately 730 nanometers.

Galland's review (1992) can be regarded as a cautionary note for any assumptions or statements regarding previous blue-light research and plant physiology and photomorphology.

At a meeting at Fusion Systems Corporation (June 4,1992), Jerry Deitzer pointed out the importance of radiation in the 700 to 800 nanometer region. He also stated "... [for commercial growers] photons per watt is the key." At the same meeting, Robert Langhans suggested a key advantage of the Fusion lamp in plant growth chamber studies was the low amount of far infrared.

CANDIDATE LAMP FILLS

We examined a number of candidate lamp fills and designs. For our purpose here, we describe two.

The fills which included LiI do show an additional red component. Typical is Figure 6. However, we have to pay a large price for the "increase" in the red. First, heat conduction losses hurt the efficiency due to the low weight (high conductivity) of lithium. Second, the iodine absorbs blue and green light. Lithium could be introduced into the fill via Li_2S which has a reasonable vapor pressure, but heat conduction losses still remain a concern. We have not exhausted the work with lithium and are hopeful.

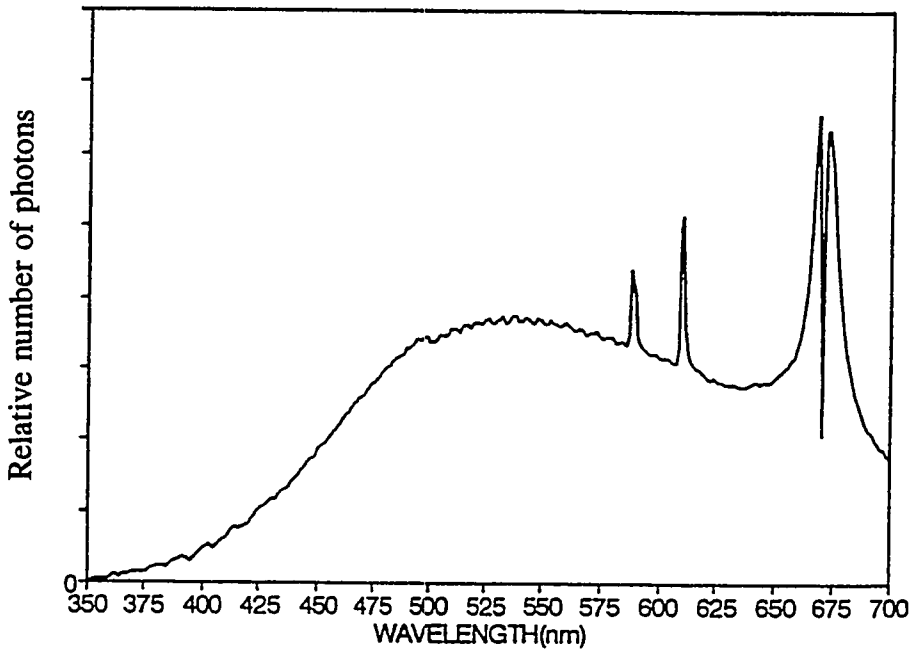

Fig. 6. Sulfur/lithium in the range 400-700 namometers. The ordinate is proportional to the number of photons per second.

Sulfur with X, a proprietary material, is shown in Figure 7 compared with the sun. The most prominent novel characteristic of the bulb fill is the close match to the solar spectrum. The color stability of this lamp is excellent, and no external filtering is needed to match solar spectrum. While the photosynthetic efficacy of the source is good, it falls below other possible choices. See Table I.

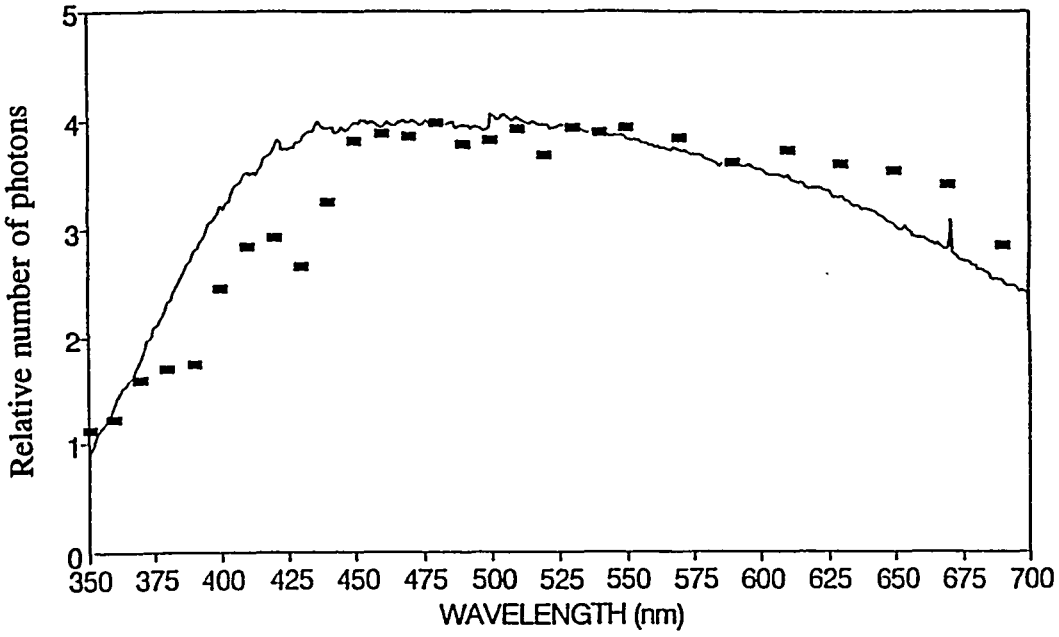

Fig. 7. Sulfur plux X in (continuous line) compared with the sun (discrete points). The ordinate is proportional to the number of photons per second.

RESULTS

We first list our bare bulb results and then compare the best to a practical configuration.

Bare Bulb Results

We tested several sulfur combinations (sulfur plus other materials) and alternative designs in an attempt to increase the red output and increase the photons available for photosynthesis. Table I summarizes a few of the different fill/designs tested and their bare bulb photosynthetic efficacy. Sulfur alone (lamp of Figure 1) is shown for comparison along with the theoretical maximum assuming a uniform distribution of photons between 400 and 700 nanometers.

TABLE 1 Photosynthetic Efficacy of Fusion Test Bulbs.

Fill	micro-moles/RF joule	Comments
Standard comparison bulb (sulfur + argon)	1.75	First sulfur lamp system.
Sulfur + LiI	1.01	Runs hot.
Sulfur + X* + argon	1.41	Solar-like spectra.
Sulfur + argon (modified design).	Above 2.0	Will be subject of next NASA SBIR contract.
Theory: Constant number of photons per unit wave length, 100% efficiency	4.6	All energy in 400 to 700 nm band with photons distributed uniformly, no other loss in system.

*Proprietary material. Patent applied for.

Practical Growth Chamber Results

It should be kept in mind the efficacy values given in Table I are bare bulb numbers without light-directing fixtures, and do not include power supply losses. Actual values on plants will be significantly lower. With that in mind, we compare our numbers with the values published by Barta *et al.* (1992) in Table II, below. Barta *et al.* numbers reflect experience in "typical growth rooms and cabinets" and, as such, are lower than would be expected with bare lamps. We added the fourth line to reflect what might be expected from the 2 plus micro-mole per joule lamp of Table I.

TABLE 2 Data from Barta *et al.* (1992), abridged with added sulfur lamp.

Photosynthetic Radiation Source	Electrical Efficacy (micro-moles/joule) at plant level
High Pressure Sodium (HPS)	1.00 - 1.52
DH-TS GaAlAs LED	0.20 - 0.91
Cool White Fluorescent	0.13 - 0.75
Fusion sulfur lamp Efficacy > (2 X .65 X .70) *	> 0.91

* Efficacy > greater than 2 micro-moles times 0.65 power supply efficiency times 0.70 fixture efficiency.

Discussion

The high pressure sodium (HPS) values up to 1.52 of Table 2 seem high. Using the same 0.70 fixture efficiency as above, a ballast efficiency of 0.88, and the conversion divider of 82 from Thimijan et al. (1983), we get for a 1000 watt HPS bulb:

	140 lumens per watt / 82 --> 1.71 micro-moles/joule new bare HPS bulb
times	0.88 ballast efficacy
times	0.70 fixture efficacy
equals	1.05 micro-moles per joule for the HPS lamp at plant level.

Actually, given the relative size of the sources, one would expect the sulfur lamp fixture to be of greater optical efficiency. Thus, we conclude the present sulfur lamp photosynthetic efficacy is nearly that of the HPS and note the sulfur lamp does not require water cooling.

We expect additional improvement during our next NASA SBIR contract resulting in a system efficacy greater than HPS.

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LIGHT EMITTING DIODES AS A PLANT LIGHTING SOURCE

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INTRODUCTION

Electroluminescence in solid materials is defined as the generation of light by the passage of an electric current through a body of solid material under an applied electric field. A specific type of electroluminescence, first noted by Lossew in 1923, involves the generation of photons when electrons are passed through a *p-n* junction of certain solid materials (junction of a *n*-type semiconductor, an electron donor, and a *p*-type semiconductor, an electron acceptor) (cited in Bergh and Dean, 1976). Development efforts to translate these observations into visible light emitting devices, however, was not undertaken until the 1950s. The term, light emitting diode (LEDs), was first used in a report by Wolfe, et al., in 1955 (cited by Williams and Hall, 1978).

The development of this light emitting semiconductor technology dates back less than 30 years. During this period of time, the LED has evolved from a rare and expensive light generating device to one of the most widely used electronic components. The most popular applications of the LED are as indicators or as optoelectronic switches. However, several recent advances in LED technology have made possible the utilization of LEDs for applications that require a high photon flux, such as for plant lighting in controlled environments. The new generation of LEDs based on a gallium aluminum arsenide (GaAlAS) semiconductor material fabricated as a double heterostructure on a transparent substrate has opened up many new applications for these LEDs (Cook et al., 1987).

CHARACTERISTICS AND PERFORMANCE

The following desirable characteristics of LEDs were listed by Williams and Hall, 1978:

- Long life
- Small size and weight
- Ruggedness
- Good temperature stability
- Low drive voltage
- Fast switching times
- Low noise optical switches
- Compatible with integrated circuits
- Tailored wavelength of light emission
- Cold light (minimum heating)

It is obvious that a number of these characteristics are of considerable importance in selecting a light source for plant lighting in a controlled environment facility. Of particular importance is the characteristic that light is generated by an LED at a rate far greater than the corresponding thermal radiation predicted by the bulk temperature of the device as defined by Plank's radiation law . This is in sharp contrast to other light sources, such as an incandescent or high intensity

discharge lamp. This is not to imply that the LED does not heat up because not all electrons are converted into photons and such electrons are retained and result in increasing the temperature of the LED.

Power Conversion (Quantum) Efficiency

Since the quantum efficiency of many LEDs is in the range of 1 to 3 percent, it is not surprising that considerable skepticism prevails that an LED could be used for applications that require a high photon output. This is particularly true of many of the commercially available LEDs in the blue, green, yellow and orange region of the spectrum. However, the recently introduced red light emitting LEDs and the new blue light emitting LED exhibit much higher power conversion efficiencies. For example, external quantum efficiencies of some of the high output GaAlAs LED devices fabricated in the early stages of this technology development effort were reported to be around 18 percent at 300° K and 50 percent at 90° K (Cook et, al., 1987). It may be appropriate to point out that a significant number of photons generated by the LED are in fact reflected back into the device and never emitted outside the LED. Thus, internal quantum efficiencies are much higher and efforts have been made to reduce the difference between the internal and external quantum efficiencies normally found in most LEDs, which is basically an optical and materials problem.

The quantum efficiency of the high output GaAlAs LED is dependent on several important considerations. A frequently overlooked factor is that the quality of the semiconductor alloy has a major impact on the external quantum efficiency of this device. Fabrication of the superthick GaAlAs layer having a transparent substrate with a high degree of consistency and reliability is difficult and expensive. Any compromise in these fabrication procedures results in an LED with low quantum efficiencies and output flux. Therefore, effective use of the GaAlAs LED as a plant lighting source is dependent on devices that are fabricated in such a way as to achieve the highest possible external quantum efficiencies.

The temperature of a *p-n* junction of a diode is a function of input power, ambient temperature, heat sink efficiency, and operation mode (continuous or pulsed). Increases in the temperature of the *p-n* junction result in decreased internal quantum efficiencies (Fukuda, 1991). Therefore, external quantum efficiencies are inversely related to the device operating temperatures as reported by Barta, et al. 1992., and drive current shown in Figure 1a and b.

When being used as a plant lighting source, it is often desirable to operate LEDs at as high a forward current as possible to obtain a high photon flux. Since the LED *p-n* junction temperature increases in proportion to the drive current, removal of heat at the active layer of the LED is critical to maintaining LED performance. Unfortunately, the conductive heat transfer rate of the epoxy used for the encapsulation of typical commercially available LEDs is low. The relative power conversion of a typical GaAlAs LED decreases as the forward drive current is increased (Figure 1a). For example, at the manufacturers suggested maximum rating of 50 mA of forward current, the relative power conversion (quantum efficiency) is approximately 75 percent of that when the device is operated at a forward current of 10 mA. When the device is operated at 100 mA forward current, the relative power conversion decreases to 55 percent of that when the device is operated at a forward current of 10 mA. Thus, increasing the forward drive current of a typical epoxy encapsulated LED increases the photon output but significantly reduces the quantum efficiency.

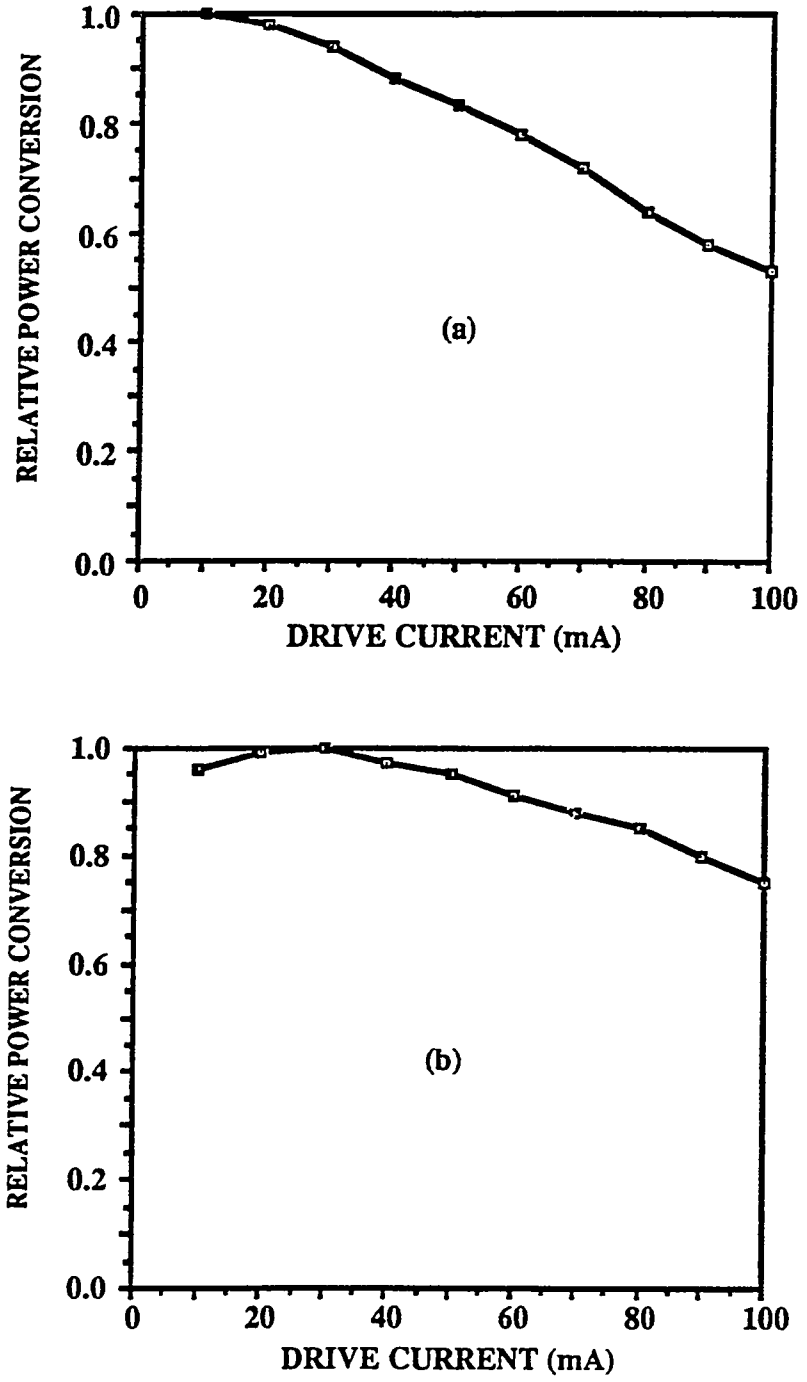

Fig. 1. Relative power conversion of a GaAlAs LED, with a peak emission at 670 nm (a) LED encapsulated in epoxy resin,(b) LED mounted on a proprietary heat dissipation device. (Data from Quantum Devices, Inc.)

On the other hand, when the semiconductor material is mounted in a way that increases the conductive heat-transfer rate over that of an epoxy encapsulated LED, the power conversion when the LED is driven at 50 mA of forward current is approximately 95 percent of that when the LED is driven at its maximum power conversion point of 30 mA forward drive current

(Figure 1b). Even at 100 mA of forward drive current, the LED retains approximately 80 percent of the maximum relative power conversion efficiency. These data clearly demonstrate that if the GaAlAs LED is to be used as a light source requiring a high photon flux, the semiconductor material must be mounted in such a way that the conductive heat-transfer rate maintains the LED at or near the ambient temperature of the environment in which it is operating. Maintaining the LED operating temperature as close as possible to that of normal room temperatures (~300° K) results in the added benefits of prolonging the life and maintaining the photon output during the life of the LED. The LED mounting approach used in the QBeam™ lighting system (Quantum Devices, Inc., Barneveld, WI 53507) utilizes high conductive heat-transfer mounting material which enables the light unit to generate a photon flux exceeding 2000 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

Spectral Composition of the Emitted Light

The peak wavelength of the light emitted by an LED is controlled by the composition of the semiconductor material of the LED, and to a much lesser extent by the operating temperature of the LED. Semiconductor materials are available that have peak emissions ranging from the blue to the infra-red regions of the radiant energy spectrum, the spectral region of most interest for use in plant lighting. For example, the GaAlAs semiconductor can be fabricated so as to have a peak emission over the spectral range of 630 to 930 nm. The most widely available GaAlAs LEDs exhibit a peak wavelength around 660 nm with the spectral energy distribution as shown in Figure 2. An important point is that the peak spectral output of the GaAlAs LED can be fabricated to coincide with the maximum absorption of chlorophyll in the red region of the spectrum. This is an obvious advantage of the LED as a plant lighting source compared to other currently used light sources.

An LED that emits in the blue region of the spectrum is another important component of an LED plant lighting system to the extent that this radiant energy relates to photomorphogenic plant responses. The spectral energy distribution of a recently introduced blue light emitting LED is shown in Figure 3. The semiconductor material of this LED is reported to include alloys of GaN, InGaN, and AlGaN (Anon., 1994). The photon output of this blue light emitting LED is considerably less than that of the red light emitting LED but at least two orders of magnitude higher than any other commercially available blue light emitting LED.

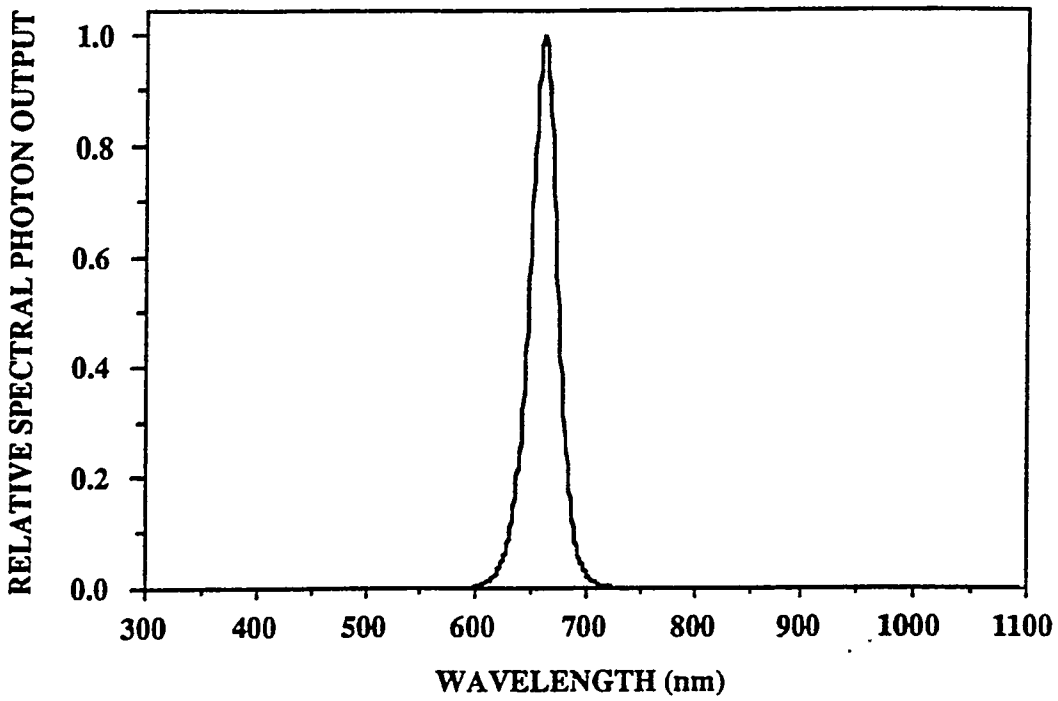

Fig. 2. Spectral photon distribution of a gallium-aluminum-arsenide (GaAlAs) light emitting diode (LED) having a peak emission at ~660nm.

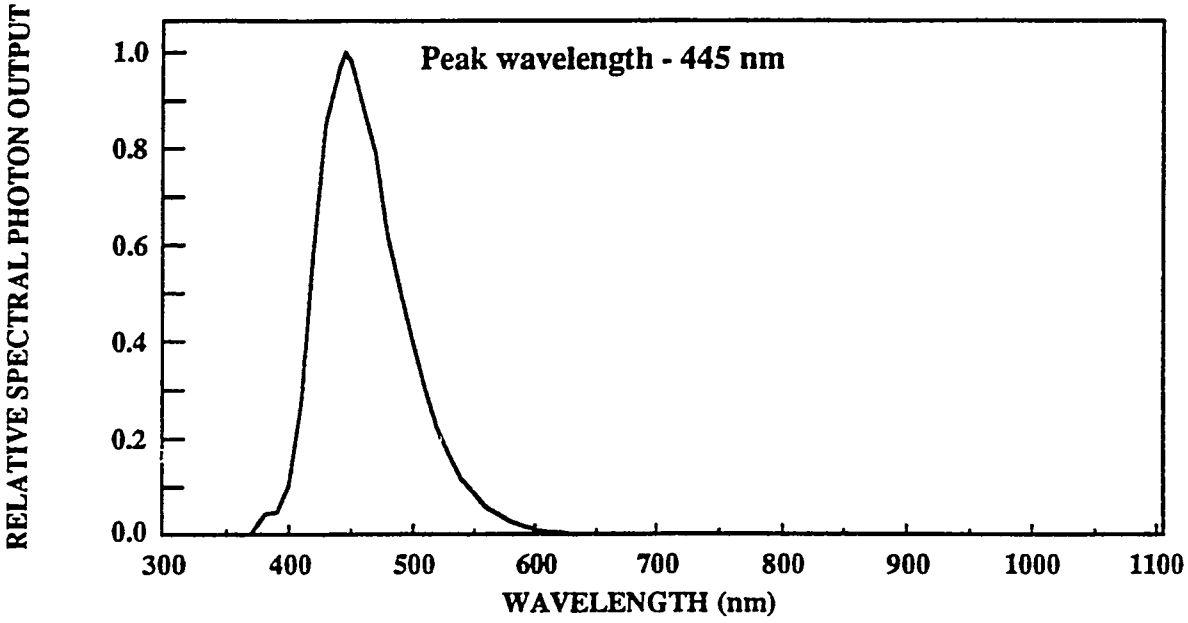

Fig. 3. Spectral photon distribution of a complex gallium-nitride (GaN, InGaN, AlGaN) light emitting diode (LED) having a peak emission at ~445 nm.

The LEDs that emit in the green, yellow, and orange region of the spectrum are based on GaAs, GaP, and/or GaAsP semiconductor materials. The spectral energy distribution of these LEDs varies, depending on the specific composition of the semiconductor. The photon output of these LEDs is rather low and consequently they are of questionable utility in a plant lighting system. Developmental efforts are in progress on these materials and it may be possible that LEDs emitting light in these spectral regions with a higher photon flux will be available in the future.

There is some interest, mostly outside the plant lighting area, in an LED that would emit "white" light. Any such LED would be based on fabrication techniques using multiple semiconductor materials, or chips, rather than one semiconductor material capable of emitting "white" light. Availability of the high output blue light emitting material should facilitate the fabrication of "white" light emitting LEDs at photon flux levels of 50 to 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

PLANT RESPONSES

A plant lighting system for controlled environments must provide plants with an adequate flux of photosynthetically active radiation, plus providing photons in the spectral regions that are involved in the photomorphogenic and phototropic responses that result in normal plant growth and development. Use of light sources that emit photons over a broad spectral range generally meet these two lighting requirements. Since the LEDs emit over specific spectral regions, they must be carefully selected so that the levels of photsynthetically active and photomorphogenic and phototropic radiation meet these plant requirements. This does not imply, however, that the LED plant lighting system must provide photons over the entire spectral region of known plant response, namely 380 to 750 nm.

Photosynthesis

Conversion of electrical energy to light energy and the quantum requirement of photosynthesis of a given lamp, are the critical criteria for selection of a light source to provide the photosynthetically active radiation of a plant lighting system. Tennessen et al. (1994a), compared the photosynthetic rates of kudzu (*Pueraria lobata* [Willd] Ohwi.) leaves when the photons were supplied by a xenon lamp or by LEDs with a peak emission in the range of 650 to 664 nm (depending on the intensity of irradiation) over the range of 0 to 1400 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Their results show a typical photosynthetic response curve. At high levels of photon flux, above 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and ambient levels of carbon dioxide, the rate of photosynthesis was lower for the kudzu leaves irradiated by the LEDs compared to leaves irradiated by a xenon lamp (Figure 4). However, the photosynthetic response to light intensity was virtually identical for the two light sources when the measurements were made in at elevated levels of carbon dioxide, 175 Pa (Figure 5). These data reflect the potential limitation on photosynthesis by stomatal conductance at low levels of p CO_2 related to stomatal response to red light which will be discussed later. Photosynthetic response of kudzu leaves to increasing concentrations of internal CO_2 partial pressures and at a light intensity of 1000 $\mu mol \cdot m^{-2} \cdot s^{-1}$, was found by Tennessen et, al. (1994a) to be the same whether the photons were provided by a xenon arc lamp or LED lamps (Figure 6).

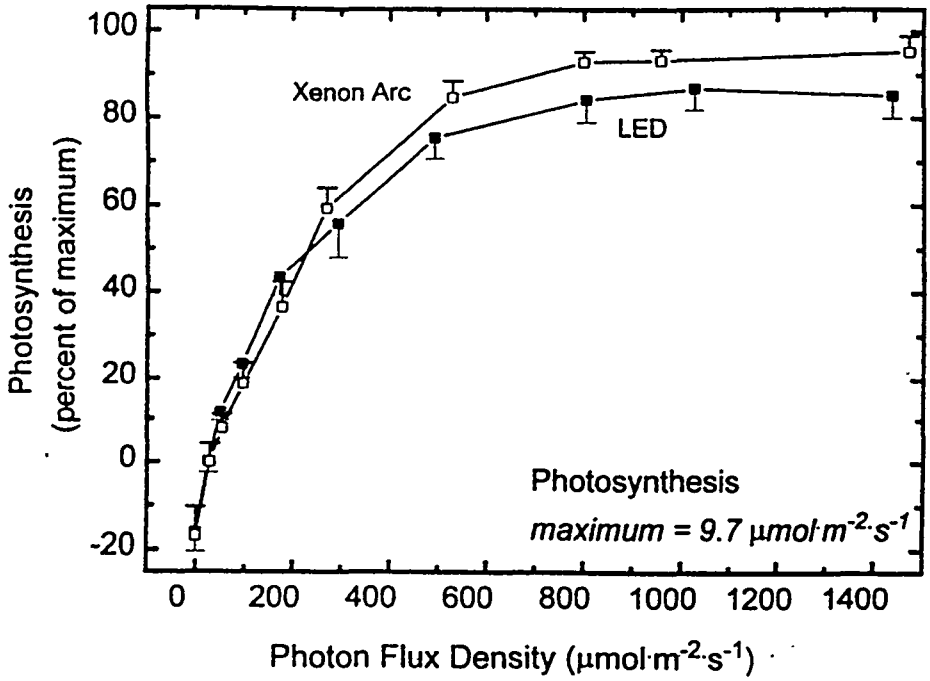

Fig. 4. Net photosynthesis of kudzu leaves, as a percent of maximum in white light, as a response to light intensity from a xenon are lamp (open symbols) and a light emitting diode with a peak emission at ~660 nm (closed symbols), and at a CO_2partial pressure of 35 Pa. (Tennessen et, al., 1994a).

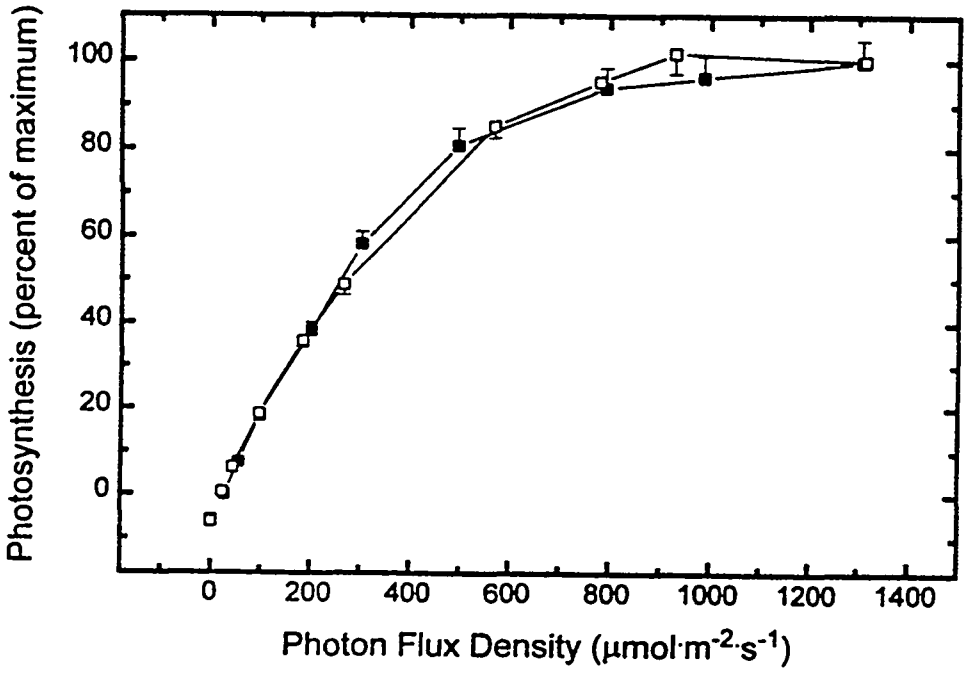

Fig. 5. Net photosynthesis of kudzu leaves, as a percent of maximum in white light, as a response to light intensity from a xenon arc lamp (open symbols) and a light emitting diode with a peak emission at ~660 nm (closed symbols), and at a CO_2 partial pressure of 175 Pa. (Tennessen et, al., 1994a).

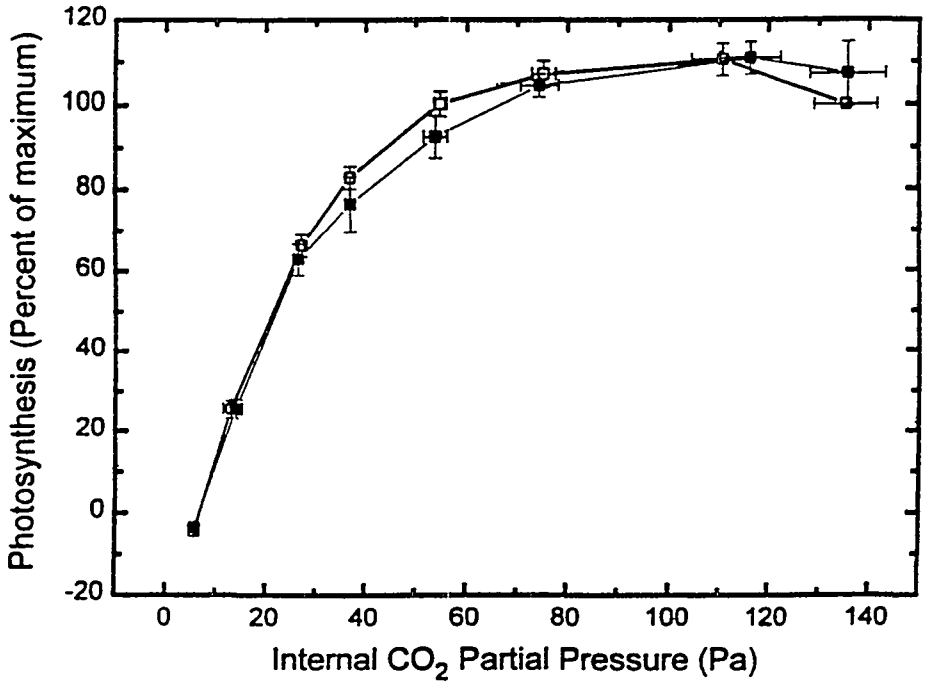

Fig. 6. Net photosynthesis of kudzu leaves, as a percent of maximum, in response to various levels of internal CO_2 pressure and 1000 μmol $m^{-2}s^{-1}$ of light from a xenon arc lamp (open symbols) and a light emitting diode (LED) with a peak emission at ~660 nm (solid symbols). (Tennessen et, al., 1994a).

Tennessen, et al. (1994b), have reported that photosynthesis of tomato (*Lycopersicon esculentum* Mill.) leaves in 2 kPa O_2 (2 %) and 35 Pa CO_2, was nearly linear within the photon flux range of 0 to 50 μmol $m^{-2}s^{-1}$ from LEDs with a maximum emission at 658 nm. The quantum requirement was 10.3 ± 0.6 mol photons mol^{-1} carbon with LEDs having a peak emission at 658 nm, and was not statistically different from the quantum requirement using an LED light sources having peak emissions of 667 and 677 nm. The quantum requirement using an LED light source with a peak emission of 690 nm was 12.3 ± 0.6 and increased to 18.6 ± 0.6 with LEDs having a peak emission at 698 nm. As a comparison, tomato leaves irradiated with cool white fluorescent lamps exhibited a photon requirement of 12.0 ± 0.6 mol photons · mol^{-1} carbon in 2 kPa O_2 (Figure 7).

Also shown in Figure 7 are amounts of electrical energy required for the LED lamps having different peak emissions to produce a photon flux of 50 μmol $m^{-2}s^{-1}$. The lowest amount of electrical power (mW) required to fix a μmol of carbon was obtained using LEDs with peak emission in the range of 668 to 675 nm. These observations reflect the increased power conversion efficiency of the GaAlAs LED as the peak emission is increased over the range of 650 to 800 nm. Obviously, photosynthesis is drastically reduced when the percentage of photons beyond 700 nm increases.

These data clearly illustrate that the GaAlAs LED can be an effective source of photosynthetically active radiation. The quantum requirement and electrical energy required to fix a quantity of carbon is less for the LED lamp than for a cool-white fluorescent lamp. In addition, the LED lamps can be a very effective photon source for photosynthetic research to study electron transport, carbon metabolism, and trace gas emission. As technology improvements are made so that the discrete conventional LED is replaced by a monolithic array of diodes, LEDs will become a feasible plant lighting source for controlled environment plant growing facilities.

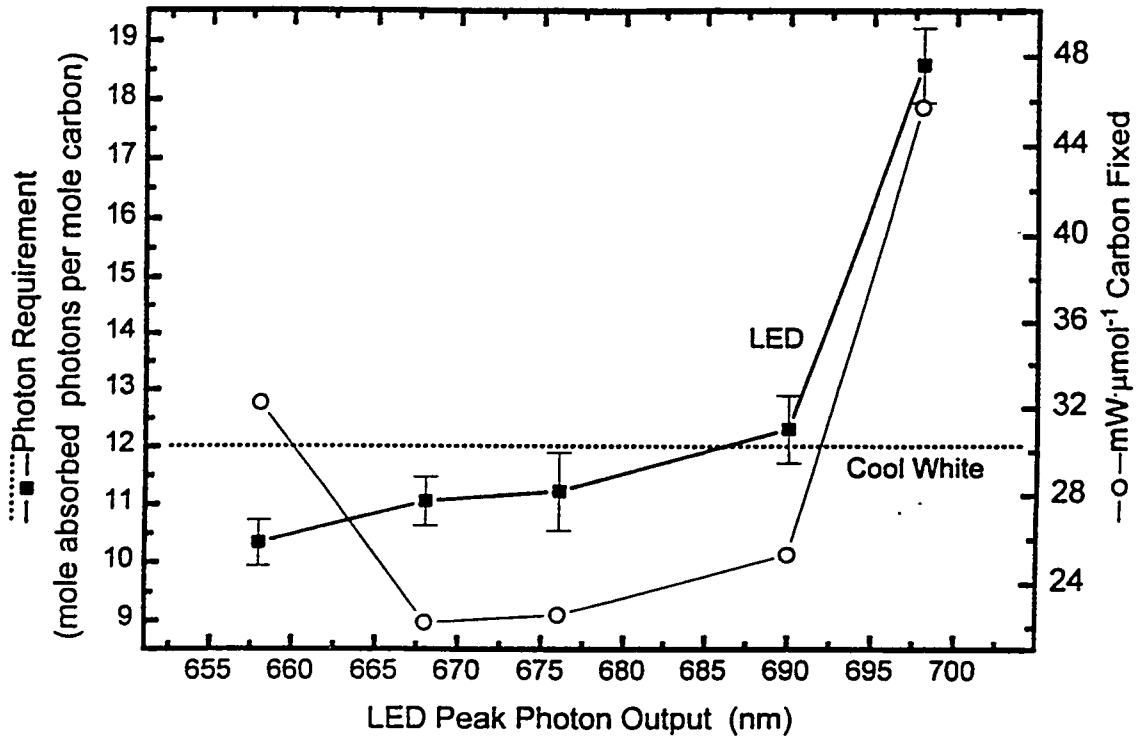

Fig. 7. Quantum requirement of photosynthesis and LED electrical conversion efficiency as affected by spectral quality of light provided by light emitting diodes (LEDs) (solid symbols) or by a cool-white fluorescent lamp at irradiance levels of 50 μmol $m^{-2}s^{-1}$. Electrical conversion efficiency (open symbols) is calculated as mWμmol $carbon^{-1}$, based on the product of mWμmol $photons^{-1}$ and quantum requirement. (Tennessen et, al., 1994b).

Pulsed Lighting

The switching characteristics of LED are desirable for applications requiring pulsed light. The LED can be pulsed at frequencies as high as 100 MHz. We have measured near instantaneous irradiance levels of as much as 5000 μmol·m^{-2}·s^{-1} from LEDs pulsed at KHz frequencies. The LED is an ideal lighting device to study comparative photosynthetic rates under pulsed and continuous irradiation. There are indications in the literature that plants may more efficiently utilize light if it was provided to the leaf as an intense pulse rather than as a continuous flux. However, Tennessen et al.,(1994b), have observed that photosynthetic rates of tomato leaves were equivalent when the light was provided as a pulse of 5000 μmol·m^{-2}·s^{-1} when on 1 % of the time (1.5 μs on and 148.5 μ s off) compared with a continuous photon flux of 50 μmol·m^{-2}·s^{-1} (Figure 8). All the comparative light treatments shown in Figure 8 provided the same level of photons integrated over an equivalent time period. Thus, electron transport of the photosynthetic apparatus appears to act as an integrator of photon flux pulses. The general observation that photosynthetic rates of leaves declines with increasing light levels appears to be a consequence of limitations from downstream reactions and not an inherent limitation of the primary photochemistry of electron transport as may have been previously hypothesized.

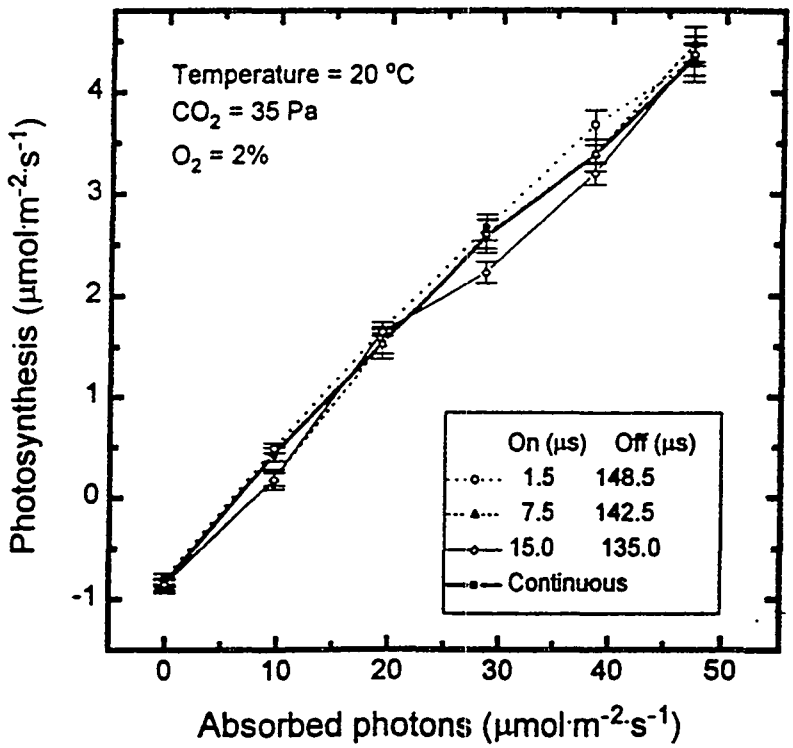

Fig. 8. Photosynthetic response of tomato leaves to increasing amounts of absorbed photons provided in pulsed segments of 1.5, 7.5, and 15 µs during a cycle time of 150 µs. The integrated photon flux of the pulse treatments were equal and the same as a continuous photon flux of 50 µmol $m^{-2}s^{-1}$. (Tennessen et, al., 1994a).

Photomorphogenic Responses

Radiant energy in the blue spectral region has been shown to affect the morphological characteristics of a number of plant organs. Early in the evaluation of the red light LEDs, it was observed that lettuce (*Lactuca sativa* L.) and other dicotyledonous plants developed excessive hypocotyl elongation, stem elongation, leaf extension, and reduced chlorophyll when grown under red light emitting LEDs as the sole source of irradiation. These abnormal morphological characteristics were eliminated and normal plant development occurred when light from the LEDs was supplemented with blue light from fluorescent lamps (Bula, et al., 1991).

Chlorophyll synthesis and chloroplast development appear to be affected when seedlings are grown under red light only. No critical data are available that provide an explanation of these observations or the impact these plant responses may have on seedling growth and development. These general observations indicate that supplementation of red light with a small quantity of blue photons would eliminate such effects and result in normal seedling development.

Hypocotyl elongation of lettuce seedlings appears to be a very sensitive indicator of the amount of blue photons required to support normal photomorphogenic plant development. Using hypocotyl elongation as an indicator of plant response to the presence or absence of blue photons, Hoenecke, et al. (1992), reported normal lettuce seedling hypocotyl development when the red light from LEDs was supplemented with more than 30 µmol $m^{-2}s^{-1}$ of photons in the blue spectral region (Figure 9). The other interesting observation was that the hypocotyl elongation response was regulated by the flux of blue photons and not by the ratio of blue to red photons.

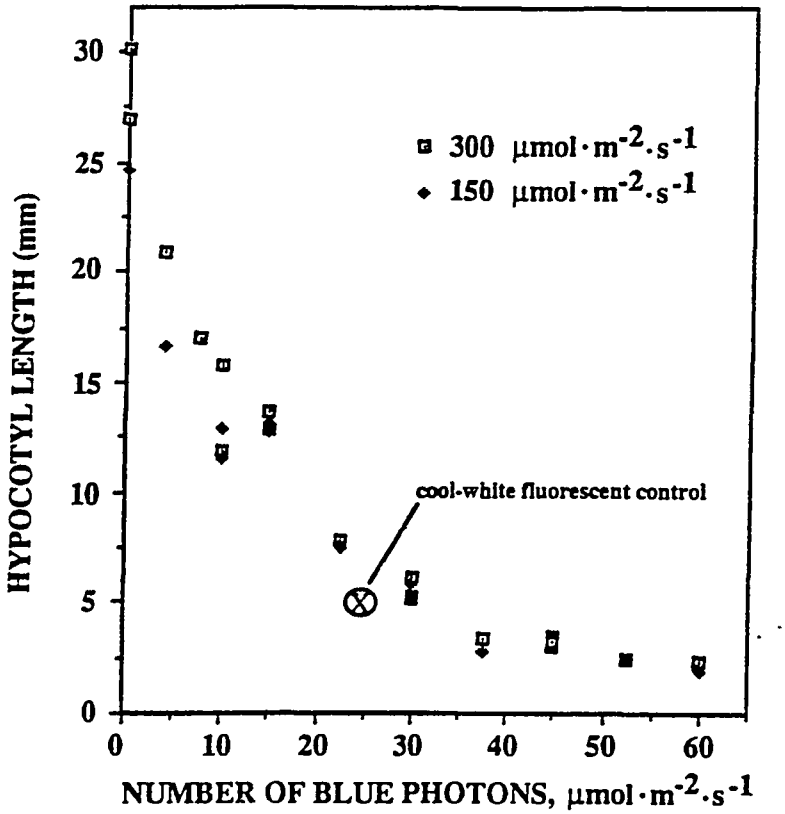

Fig. 9. Relationship between lettuce seedling hypocotyl length and flux of blue photons at two photosynthetic photon flux levels provided by light emitting diodes (LEDs) with a peak emission at ~660 nm and fluorescent lamps having a 246 phosphor that emits photons primarily between 435 and 470 nm. the cool white fluorescent response was at an irradiance level of 150 µmol $m^{-2}s^{-1}$ (Hoenecke, et al., 1992).

Flowering and seed development of several species of plants grown under a combination of red light emitting LEDs supplemented with 30 µmol$m^{-2}s^{-1}$ of blue light were similar to plants grown under light from cool-white fluorescent lamps. Thus, normal plant growth and development can be expected with most , if not all, plant species when grown under red light emitting LEDs as the source of photons for photosynthesis and supplemented with a small quantity of blue photons to meet the photomorphogenic requirements involved in normal growth, development, and maturation.

Stomatal Response

The classical observation that stomates open in light and close in the dark is an over simplification of stomatal response as it relates to stomatal conductance of CO_2 into the leaf. A number of internal and environmental conditions are involved in this critical plant response. From the standpoint of using red light emitting LEDs, Sharkey and Raschke, (1981), reported that stomatal opening was most responsive to light in the blue region of the spectrum, with a peak response being at approximately 450 to 460 nm (Figure 10). However, red photons provide sufficient signal for stomata to open so that the effects of low stomatal conductance under red light can only be overcome by increasing the concentration of CO_2 to higher than ambient levels (Tennessen, et al., 1994). We have recently determined that providing a low level of blue photons from blue light emitting LEDs increases stomatal conductance and has the same effect on photosynthetic rates as was the reported effect of high CO_2 concentrations (unpublished data).

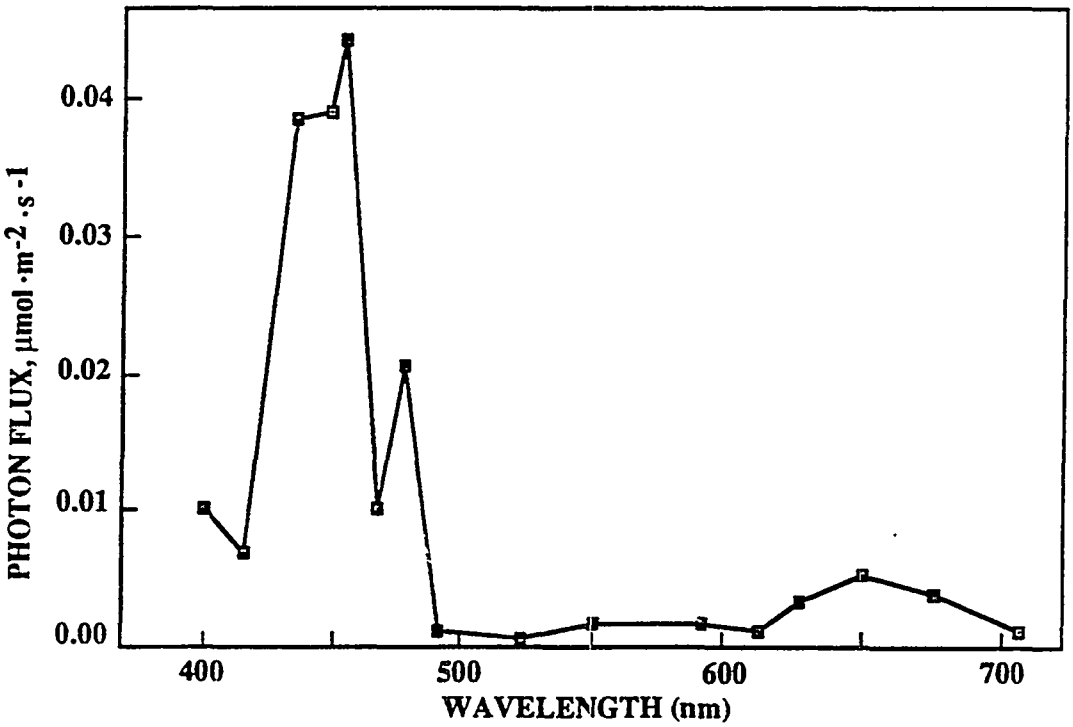

Fig. 10. Action spectrum of stomatal opening in the lower epidermis of leaves of *Xanthium strumarium*, indicated as the inverse of the photon flux required to produce a conductance of 15 cmol$m^{-2}s^{-1}$. (Sharkey and Rashke, 1981).

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LIGHTING APPLICATIONS

DISTRIBUTION

THE PHYSICS OF LIGHT DISTRIBUTION IN HOLLOW STRUCTURES

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INTRODUCTION

The purpose of this paper is to serve as an introduction, for non-physicists, to the subject of light distribution in hollow structures. The motivation for light distribution is the importance of getting the maximum value from available light. We all recognize that photons cost money (one photon costs about $\$10^{-25}$ to make) so we obviously want to try to make the maximum number of photons for a given cost. What is often overlooked, however, is that these photons have the highest value only if they are delivered to the right place in the correct quantity. This means that there is often substantial economic value in the high quality distribution of light. This problem is discussed from a very general perspective, in order to show the role of general optical films for manipulating light. The underlying physics at work in such films is described, and examples of common optical light deistribution films are provided.

THE DIFFICULTY OF LIGHT DISTRIBUTION

One might expect that since light travels very rapidly and efficiently in air, light distribution should be an easy matter. Surprisingly, it is this very property of light which makes it so difficult to control. Light rays spread fast in all directions, and it requires sophisticated optical engineering to "contain" light in a desired region and "channel" it so that it has the desired distribution at the final destination.

A different kind of problem results from the common opinion that light should be easy to understand, which probably arises because light is a visible part of our everyday lives. In reality, the behavior of light is often non-intuitive and generally quite different from the impression we get from our human visual perception system.

And not only is light confusing, but it is hard to measure as well! It is interesting to compare light to electricity in this regard. Although electricity is invisible, and unfamiliar to many of us, it is quite easy to measure. One can buy a voltmeter for about $100 that will measure a voltage to an accuracy of 1 part in 10,000. In contrast one must pay $1000 to buy an illuminance meter that can only measure to 1 part in 100. From this perspective, light is a thousand times harder to measure than electricity!

A simple example shows one way that the subject of light distribution can be confusing. Fig. 1 shows a device called an integrating sphere, which in this case is a hollow sphere with a white interior, containing at the center a light source which emits 10,000 lumens of light. The sphere interior area is 10 square meters, just to keep the numbers simple. It seems natural to estimate

that the luminous flux density, (that is, the illuminance), at the inside surface of this sphere would be simply given by

$$I = \frac{10{,}000 lumens}{10 m^2} = 1{,}000 lux \qquad (1)$$

In reality, there is a correction required due to the reflectivity of the inside surface of the sphere. In Fig. 1, the sphere interior has a surface reflectivity of 0.9, and this increases the illuminance at the interior of the sphere, because the light undergoes several reflections before being absorbed. In fact the actual illuminance is not even close to the above guess. It is actually 10 times larger, since the average light ray reflects 10 times! This is just one example out of many cases in which the behavior of light rays, while basically simple, is nevertheless non-intuitive.

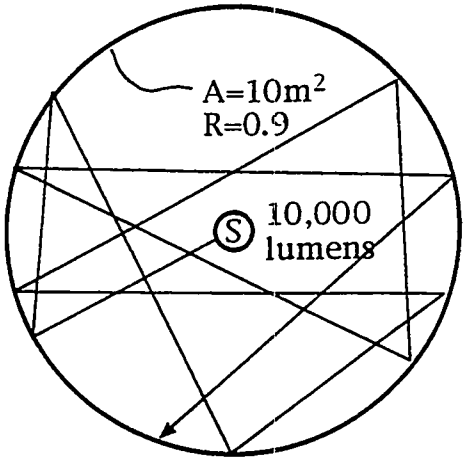

Fig. 1

A HIERARCHICAL VIEW OF LIGHT DISTRIBUTION

Fig. 2 is a general depiction of the light distribution problem. There is a structure filled predominantly with air, into which light is made available from either the sun or an artificial light source. The structure contains general surfaces which will be called "optical films" in the rest of this paper. These films interact with light rays, to guide them toward a "target" which represents the region where the light is wanted for some purpose.

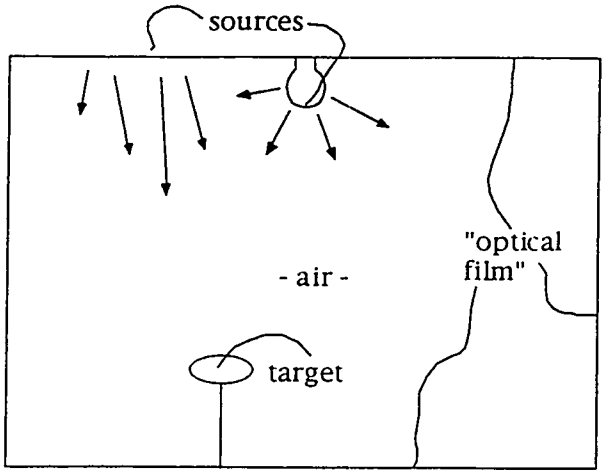

Fig. 2

It is helpful to view this situation on three hierarchical levels. The highest level is that shown in Fig. 2, and in more detail in Fig. 3, in which an example light ray undergoes numerous interactions with a variety of optical surfaces of arbitrary shape and optical characteristics. The circle in Fig. 3 shows an area of an optical surface which is small enough that the surface appears essentially flat within this circle, but which is large relative to the detailed structure of the surface itself. Typically, this circle might be a few millimeters in diameter.

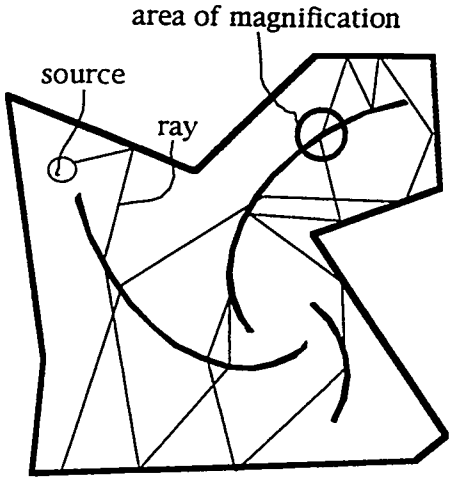

Fig. 3

Fig. 4 is a magnified view of the circle of Fig. 3, and represents the second hierarchical level of analysis. At this level, the optical surface can be seen in general to be a complex structure which interacts with light. The optical film contains interfaces between different media, and the optical behavior of the film is result of the light transmission properties of these media and the shape of the interfaces. Usually the behavior of the media are simple and the shape is complicated. At this level, the behavior of light is highly complex and non-intuitive.

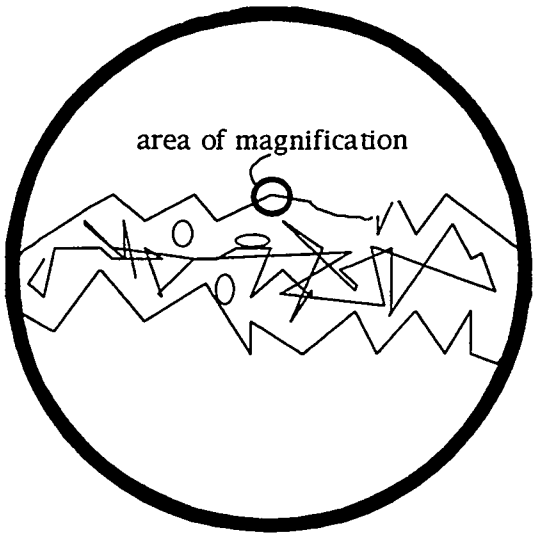

Fig. 4

Before moving on, it is important to note that this description of an optical film is very general. For example, it applies to all surfaces one might find in a room, outdoors, in a light fixture, and almost anywhere else.

The circle in Fig. 4 represents a view of a single optical interface in an optical film. The circle is small enough that the interface appears flat, but is large compared to a wavelength of light, so that it still makes sense to talk about light rays which travel in straight lines. For example, the diameter of this circle might be a bit less than a tenth of a millimeter.

Fig. 5 represents a magnified view of the circle in Fig. 4; this is the lowest level of the hierarchical analysis, and it is pleasing to find, as described below, that the behavior of light at this level is simple indeed.

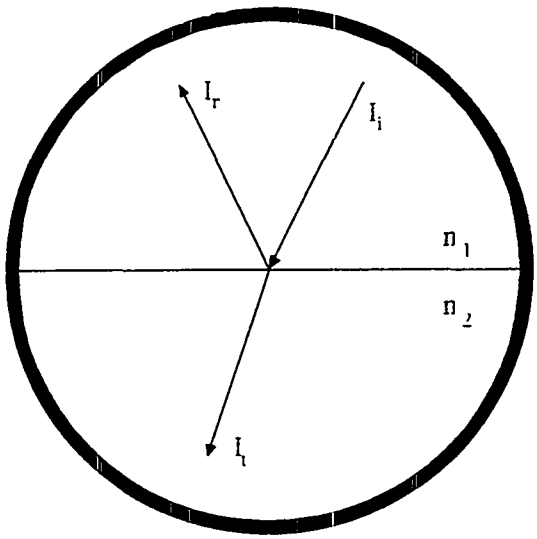

Fig. 5

THREE BASIC INTERACTIONS BETWEEN LIGHT AND MATTER

There are really just three cases one needs to understand, two involving interfaces, and one involving bulk transmission. Fig. 5 depicts one of the two interface cases, namely the interface between one dielectric material and another. The term dielectric basically means a material which is not metal and which is therefore quite clear at this size scale. Examples include glass, plastics, water, and air. For the purpose of this discussion, such non-metallic materials can be characterized by a number called the refractive index, usually denoted n. In the case of Fig. 5, the interface is between dielectric materials having different refractive index values of n_1 and n_2. An original light ray has an intensity I_i when it hits the interface, and as shown, some of the light energy reflects with intensity I_r, and some of the light energy is transmitted with intensity I_t. There are exact formulas that describe the relative intensity of the reflected and transmitted rays. but these are not needed in this discussion. The main thing that is important here is that there is

no energy loss at this interface. Another way of saying this is that:

$$I_i = I_t + I_r \qquad (2)$$

Usually, the reflected ray of Fig. 5 is much less intense than the transmitted ray. For example, this is the reason that we can see easily through a window, (although a slight reflection is also noticeable). However it is interesting to note that for some situations the reflected ray can be intense and the transmitted ray can be weak. In fact there is special case known as total internal reflection, in which there is no transmitted energy at all, and all of the light energy is reflected. This phenomenon is used in optical fibres, and also in certain hollow light guides, as will be discussed at the end of this paper.

Fig. 6 is on the same size scale as Fig. 5, and shows the second important interface case. This is the case of an interface between a dielectric material and a metal. At the size scale of Fig. 6 light travels a negligible distance in metal, and therefore only a reflected ray leaves the interface. The intensity of the reflected ray is given by the following formula:

$$I_r = RI_i \qquad (3)$$

where R is the reflectivity of the metal surface. The one really important thing about this case is that R can never be 1. That is, the reflected ray is always less intense than the incident ray, with the difference representing energy which is absorbed by the metal. R typically ranges from .7 to .95, and this means that any light distribution system in which light reflects off metal many times will be intrinsically inefficient. Incidentally, such dielectric/metal interfaces are common in everyday life - they are found in mirrors, and also on the surface of shiny metal objects.

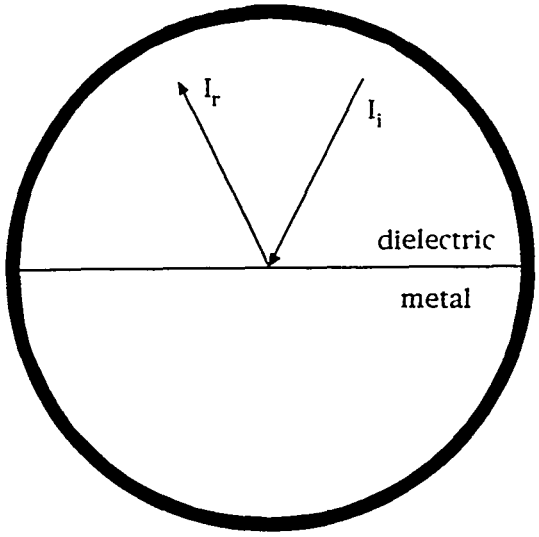

Fig. 6

Fig. 7 depicts the third important interaction between light and matter - the absorption of light as it travels through a dielectric medium. As mentioned earlier, the actual interface between two dielectric media is not absorptive. (The reason for this is that the interface itself has virtually zero thickness). However as a light ray travels through a dielectric material, some energy is absorbed. The fraction of energy lost per unit length is called the absorption coefficient, k. In solids, k can vary from as high as 10,000,000 per metre to as low as .01 per metre in certain materials, and is much lower in air. Also some materials may have dramatically different absorption coefficients for different wavelengths of light. It is this phenomenon which gives rise to color in optical surfaces.

The three phenomena described above - reflection/transmission at a dielectric/dielectric interface, incomplete reflection at a dielectric/metal interface, and absorption during transmission through a dielectric - are all that is necessary to understand the optical characteristics of the surfaces which are normally used in the controlled distribution of light. Of course applying these simple principles in order to determine the optical behavior of a given optical surface can be complicated, but is good to know that underlying the complexity is some simple physics.

Rather than theoretically predicting the behavior of an optical film, we often take a shortcut by going back to the second level of the hierarchy, and experimentally observing the optical behavior of a given film, as represented in Fig. 8. We can summarize the behavior of a film by describing the distribution of reflected and transmitted light intensity for any given direction of incident ray. This information is just a big data file for a computer to use to model the travel of light rays at the highest hierarchical level where we began.

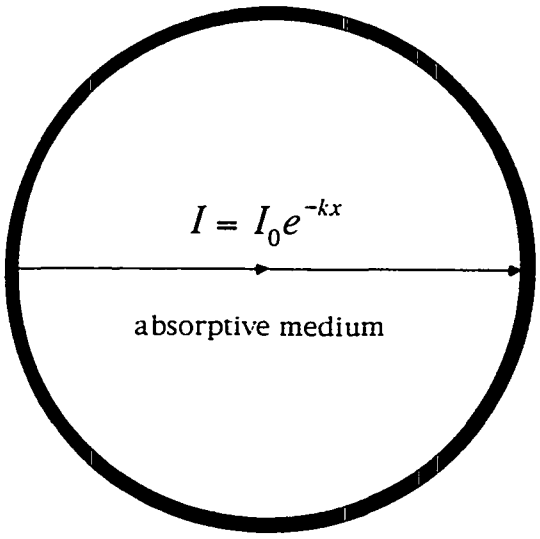

Fig. 7

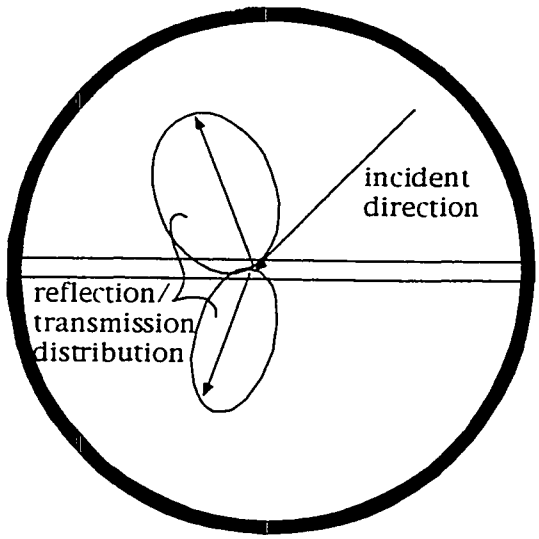

Fig. 8

EXAMPLES OF OPTICAL FILMS USED IN LIGHT DISTRIBUTION

The rest of this paper presents examples of common optical surface used in light distribution. The first, shown in Fig. 9, is a white surface such as paint, paper, cloth, snow, milk, etc. Such white materials consist entirely of dielectric/dielectric interfaces, usually formed by high refractive index particles or fibres in a matrix of low refractive index material, such as air or plastic. Each time a light ray interacts with such a particle, it is reflected or transmitted in a different direction than the incident one. The result is a "random walk" for the light ray, which results in most of the light energy re-emitting from the surface it entered originally. It is important to note that the ray is re-emitted with a random direction, independent of the incident ray direction, which can be useful, or undesirable, depending on the situation. White paints are usually not highly efficient - typical reflectivities are in the 70 to 80 percent range, but some special paints can exceed 90 percent. By the way, if the bulk absorptivity of the particles or of the matrix is wavelength dependent, the result is colored paint.

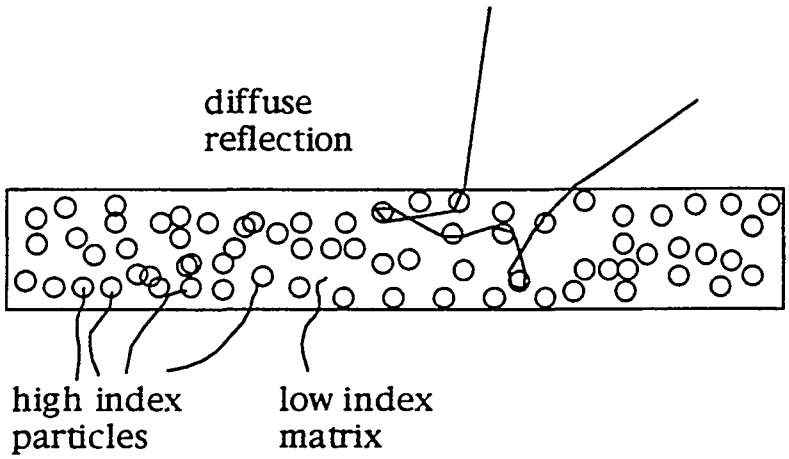

Fig. 9

Fig. 10 shows a useful film for reflecting light in a specular manner. Specular reflection means that the reflected ray travels in the same direction as the incident ray, except that the component of travel in the direction perpendicular to the surface is reversed. Such metalized films generally consist of a smooth substrate, such as polyester film, coated with a thin layer of metal, such as aluminum or silver, and further coated with a transparent cover to keep the metal smooth and to protect it from corrosion. Such films are very useful in some light guiding applications, but they suffer from the disadvantage of absorbing from 5 to 20 percent of the light with each reflection.

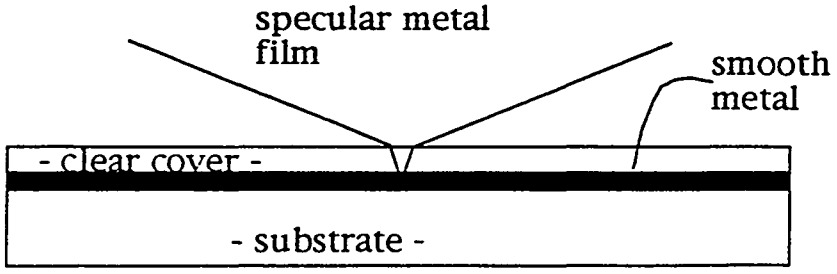

Fig. 10

Fig. 11 shows a fairly new and useful kind of general optical film, known as a textured dielectric film. The specific example shown in Fig. 11 is called Fresnel lens film. It consists of a thin dielectric sheet (often acrylic or polycarbonate resin), in which one or more of the surfaces has a prismatic structure which causes light to change direction. Such surfaces can obviously have a wide variety of shapes, and they can therefore do a variety of interesting things to the reflection and transmission characteristics of the film. Importantly, the dielectric material can be very non-absorptive. As a result such films reflect and/or transmit almost all incident energy, with virtually none lost to absorption.

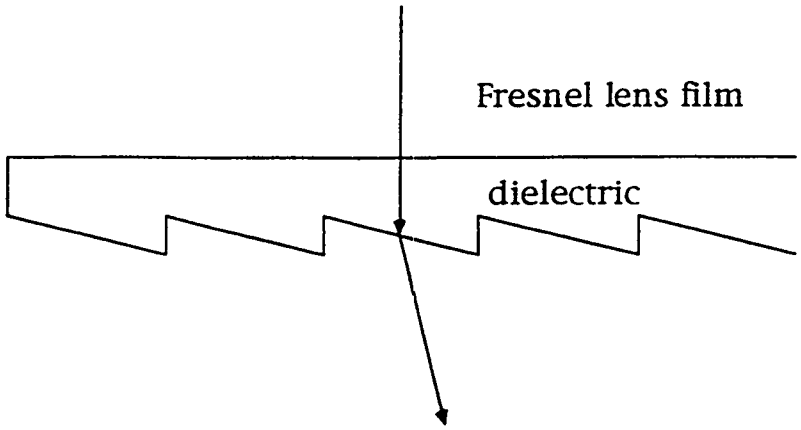

Fig. 11

Obviously there is a huge variety of such films, but in the interest of brevity, only one other example will be shown here, in Fig. 12. This film, known as prism light guide wall material, is very useful in light distribution. It has one flat surface, and one textured surface consisting of an array of linear right angle prisms inclined at 45 degrees to the flat surface. As shown, these prisms can reflect light by two total internal reflection steps, so the light is redirected back out of the surface from which it entered. Here we have a way for a film to reflect light much like a metal film, but without absorption.

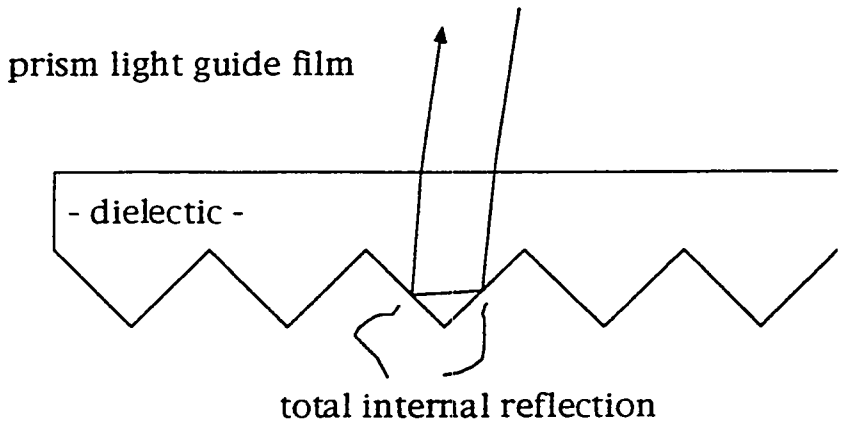

Fig. 12

This provides an important answer to the problem of channeling light in hollow structures with high efficiency. Fig. 13 shows a prism light guide - a tube whose walls are formed of prism light guide film, so that light rays entering one end can be piped down toward the other end.

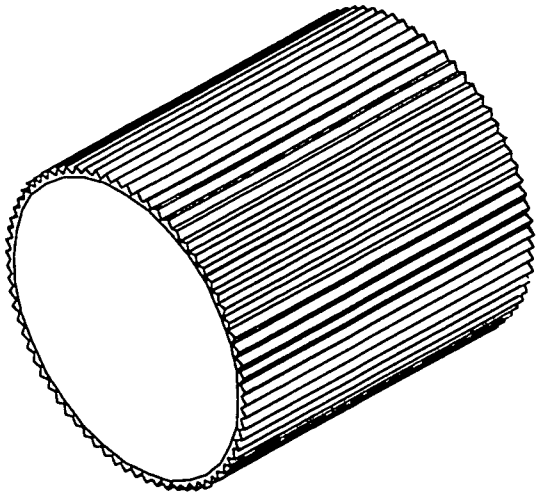

Fig. 13

CONCLUSION

By combining the prism light guide concept with the other kinds of optical films described above, it is possible to produce a wide variety of practical light distribution arrangement, on the highest level of the hierarchy where this paper began. Such arrangements are discussed elsewhere in detail; the intent of this paper has been to provide a greater familiarity with the underlying physics behind such work.

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 system 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.

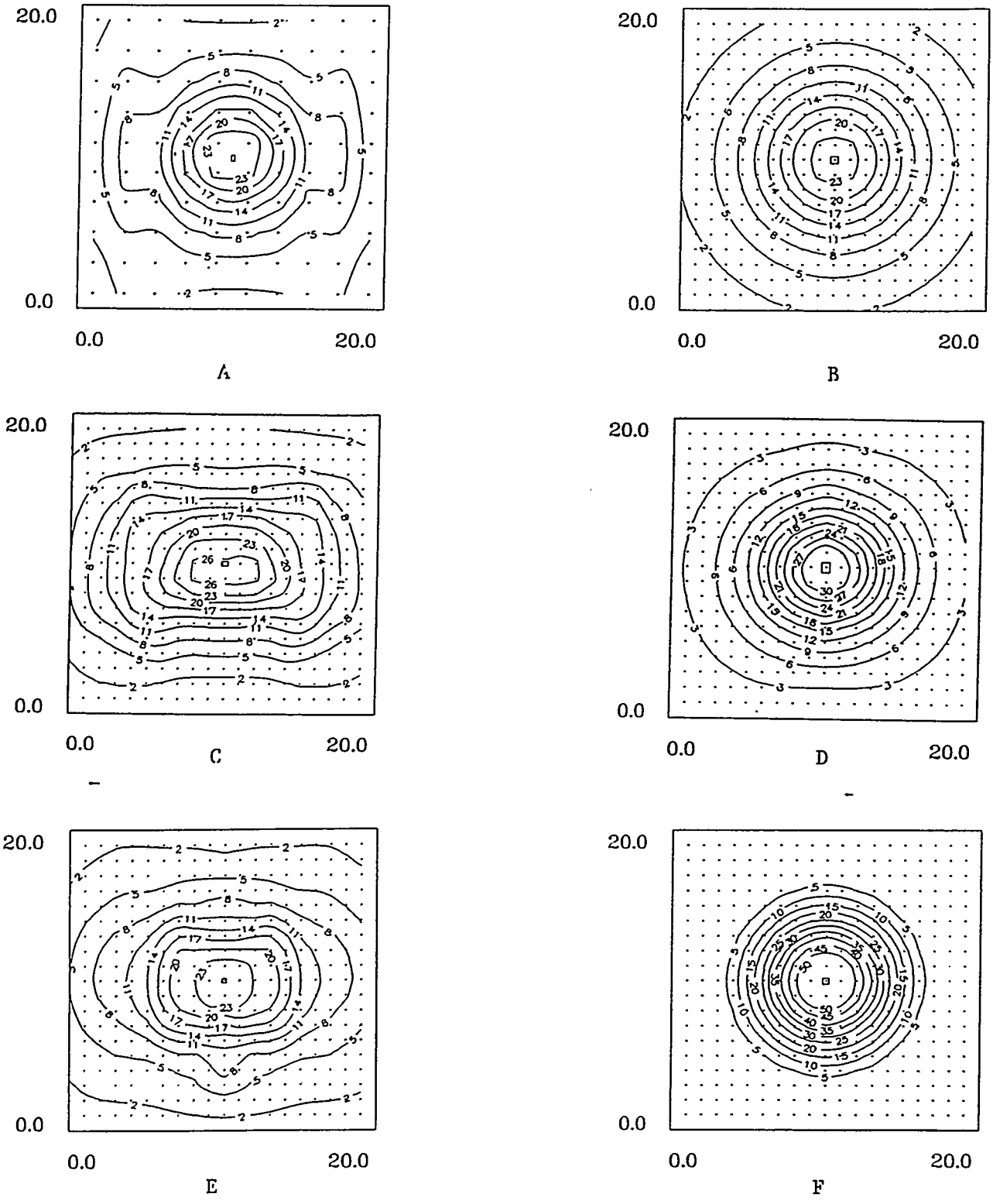
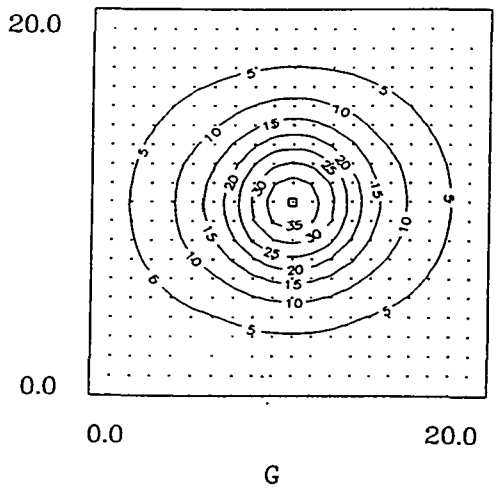


Fig. 1. PAR distribution patterns of eight 400 W HPS luminaires at a mounting height of 1.5m (5'). Contour lines are in $\mu molm^{-2}s^{-1}$, horizontal dimensions are in feet. Luminaire axis E-W, transverse axis N-S. Continued on next page.



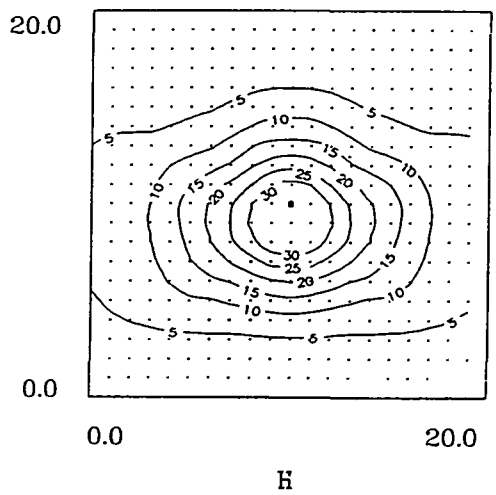


Fig. 1. Continued

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):

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

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):

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

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 $\mu molm^{-2}s^{-1}$ 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 $\mu molm^{-2}s^{-1}$ 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. $\mu molm^{-2}s^{-1}$	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.

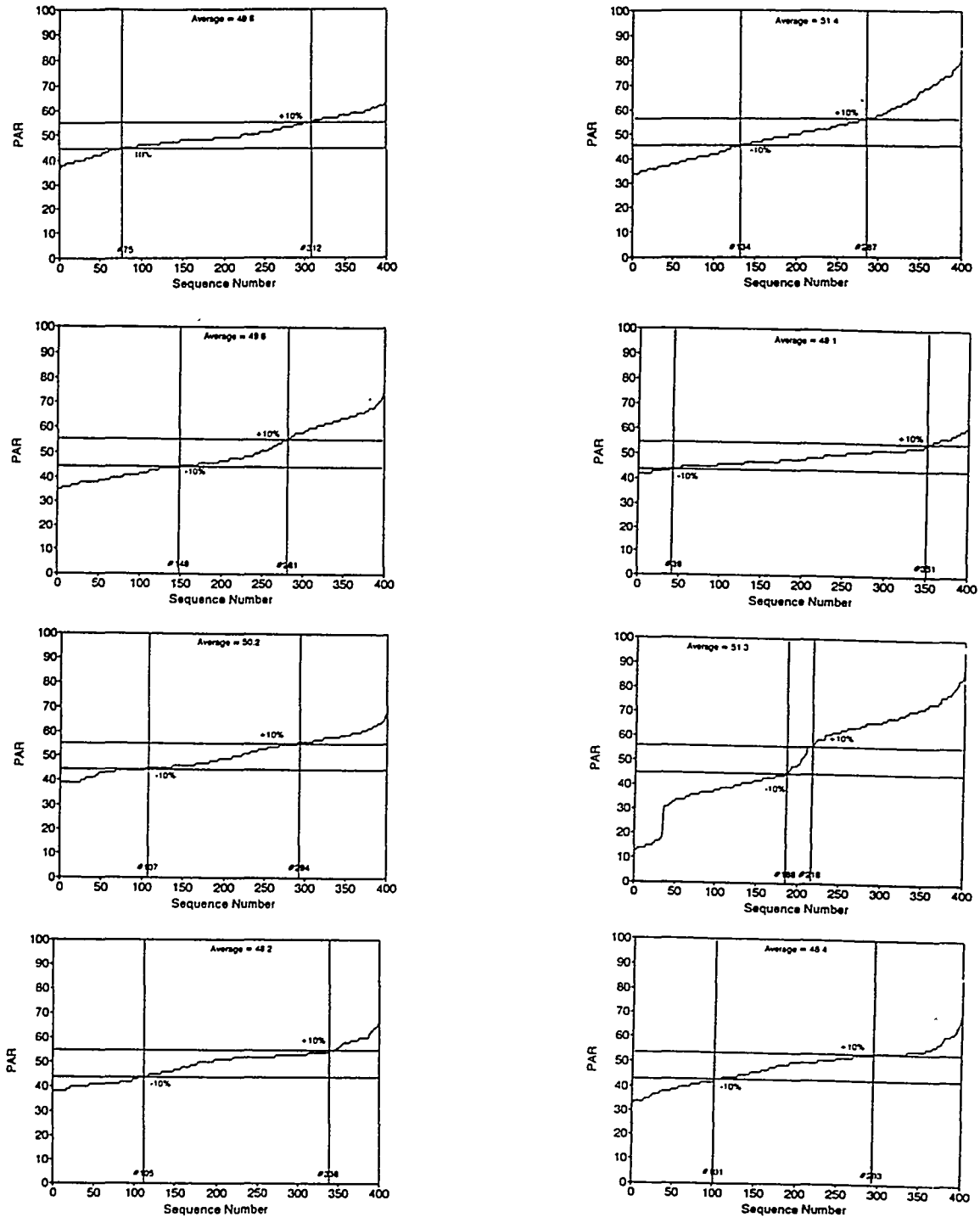


Fig. 2. Frequency graphs for Example 1, corresponding to the luminaires listed in Table 4.

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 $\mu molm^{-2}s^{-1}$, 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, $\mu molm^{-2}s^{-1}$	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 $\mu molm^{-2}s^{-1}$. These assumptions result in an average PAR level of 197 $\mu molm^{-2}s^{-1}$, 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, $\mu molm^{-2}s^{-1}$	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 $\mu molm^{-2}s^{-1}$) 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.

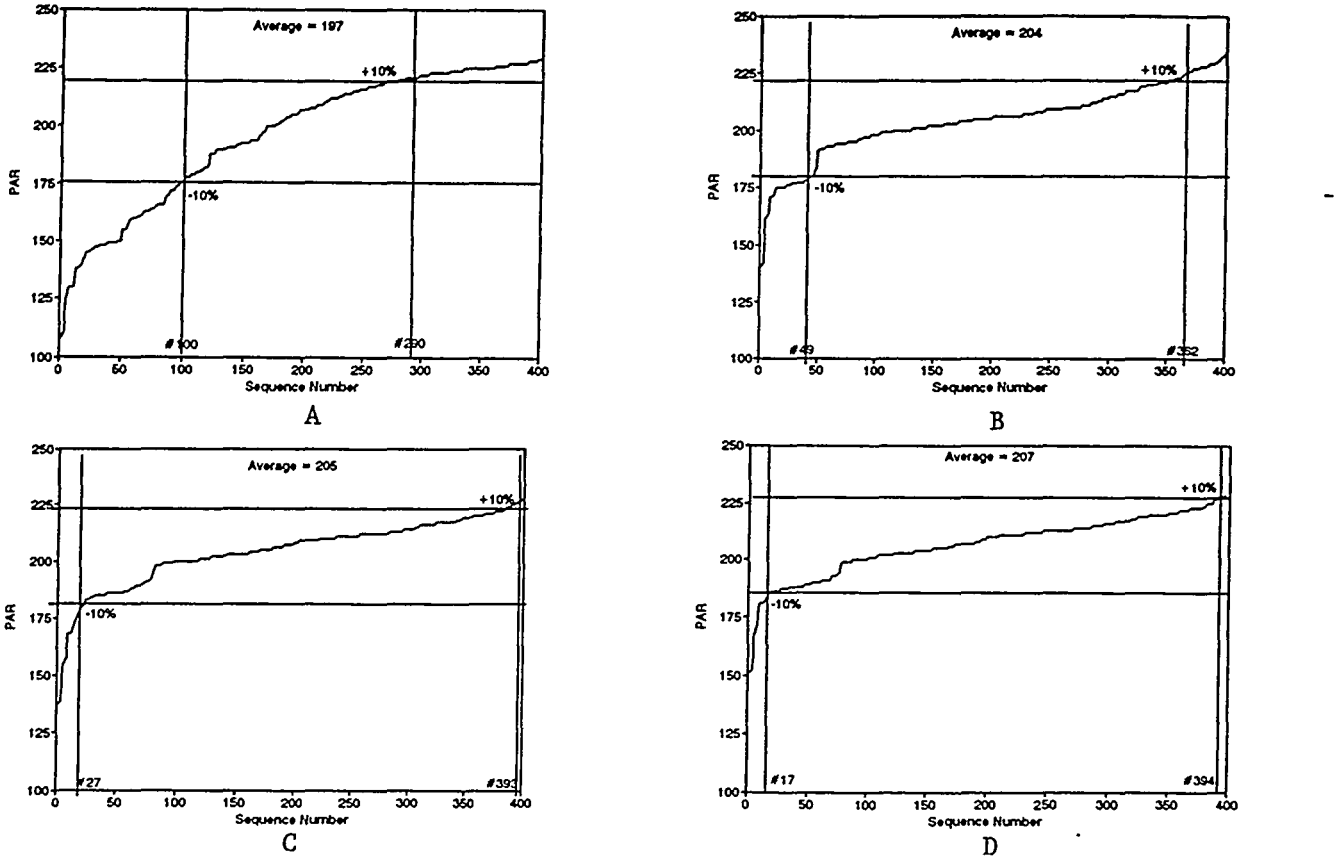


Fig. 3. Frequency graphs, Example 2: (a) base case, (b) change 1, (c) change 2, (d) change 3

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.

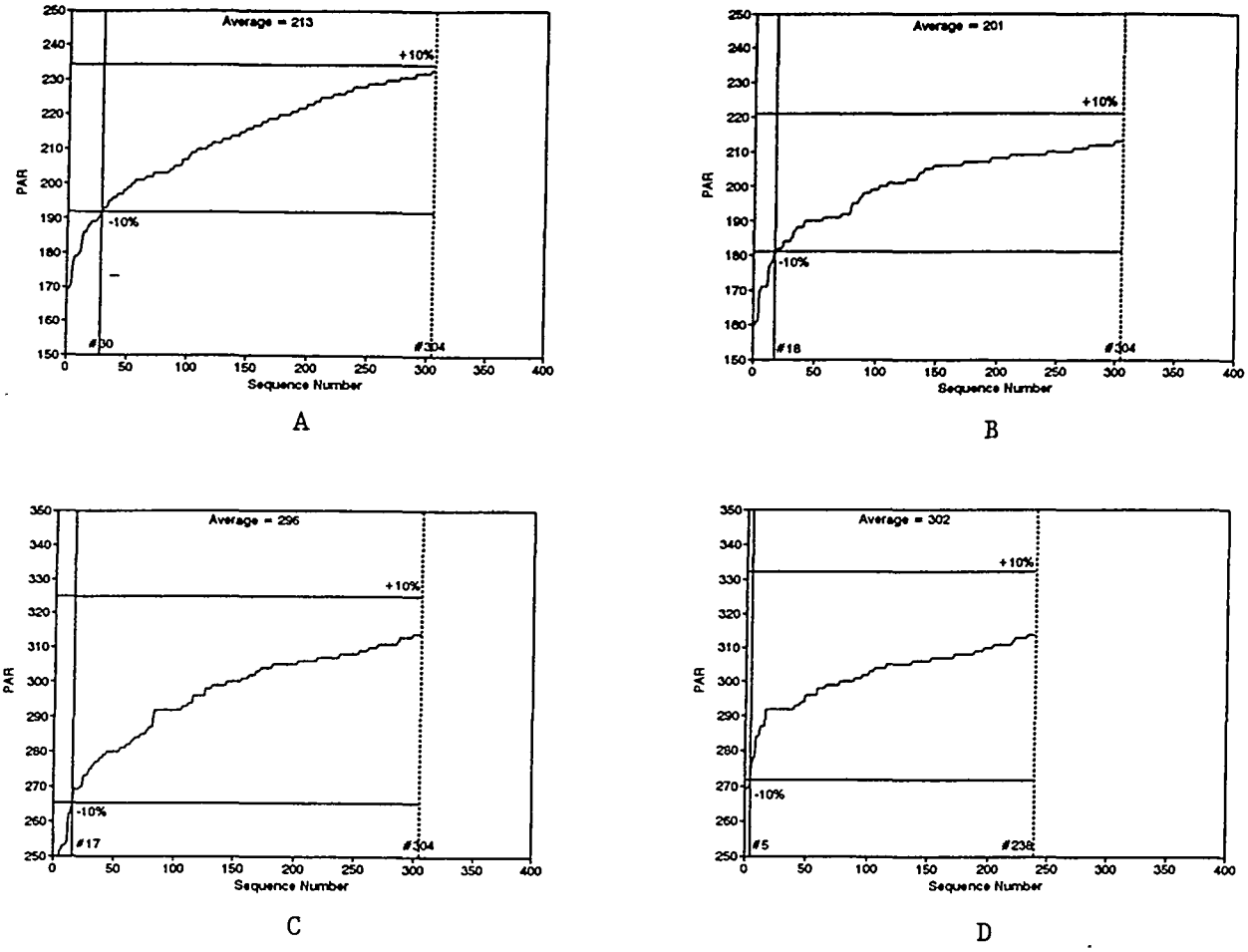


Fig. 4. Frequency graphs, Example 3: (a) base case, (b) change 1, (c) change 2, (d) change 3

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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SHORT REPORT

LUMINAIRE LAYOUT: DESIGN AND IMPLEMENTATION

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The following information was presented during the discussion regarding guidelines for PAR uniformity in greenhouses. The data shows a lighting uniformity analysis in a research greenhouse for rose production at the Cornell University campus. The luminaire layout was designed using the computer program Lumen-Micro (Lighting Technologies, Inc., Boulder, CO). A total of 48 luminaires (General Electric, model GHL Low Profile, 400 Watt HPS) were installed (Figure 1). After implementation of the design, accurate measurements were taken in the greenhouse and the uniformity analysis for both the design and implementation were compared (Table 1). A study of several supplemental lighting installations resulted in the following recommendations:

- Include only the actual growing area in the lighting uniformity analysis (i.e., exclude any areas, such as walkways, at the edges of the growing area).
- For growing areas up to 20 m^2: Take 4 measurements per m^2, i.e., one measurement in the center of each 0.25 m^2 (0.5 m by 0.5 m).
- For growing areas above 20 m^2: Take 1 measurement per m^2, i.e., one measurement in the center of each m^2 (1 m by 1 m).
- Use one of the Uniformity Criteria (Table 2) and frequency graphs (Figure 2) to compare lighting uniformity amongst designs.
- Design for a Uniformity Criterion of at least 0.75 (preferably at least 0.90) and the fraction within ± 15% of the average PAR value should be close to 1 (Figure 2).

TABLE 1. Lighting uniformity analysis for the rose greenhouse at Cornell.

	DESIGN		IMPLEMENTATION	
Average	107		97	
Average ± 15%	91 - 123		82 - 112	
Min - Max	49 - 159		28 - 167	
Standard Deviation	30		33	
Growing Area (m^2)	118		118	
Number of Data Points	220		128	
Number of Measurements m^{-2}	1.9		1.1	
Number of Luminaires	48		48	
Number of Luminaires m^{-2}	0.4		0.4	
		(Recommendation)		
Min/Avg	0.46	(≥0.80)	0.29	(≥0.80)
Min/Max	0.31	(≥0.70)	0.17	(≥0.70)
Uniformity Criterion 1	0.77	(≥0.75)	0.72	(≥0.75)
Uniformity Criterion 2	0.72	(≥0.75)	0.66	(≥0.75)

TABLE 2 Definitions of two Uniformity Criteria (UC)

UC 1	=	$1 - [(\Sigma\|Y_i - Y_{ave}\|)/(n * Y_{ave})]$	
UC 2	=	$1 - CV =$	$1 - [\sqrt{(\Sigma(Y_i - Y_{ave})^2/(n - 1))}]/Y_{ave}$
where: Y_i	=	PAR reading at location i	
	Y_{ave}	=	Average PAR reading over the growing area
	n	=	Number of PAR readings over the growing area
	CV	=	Coefficient of variation

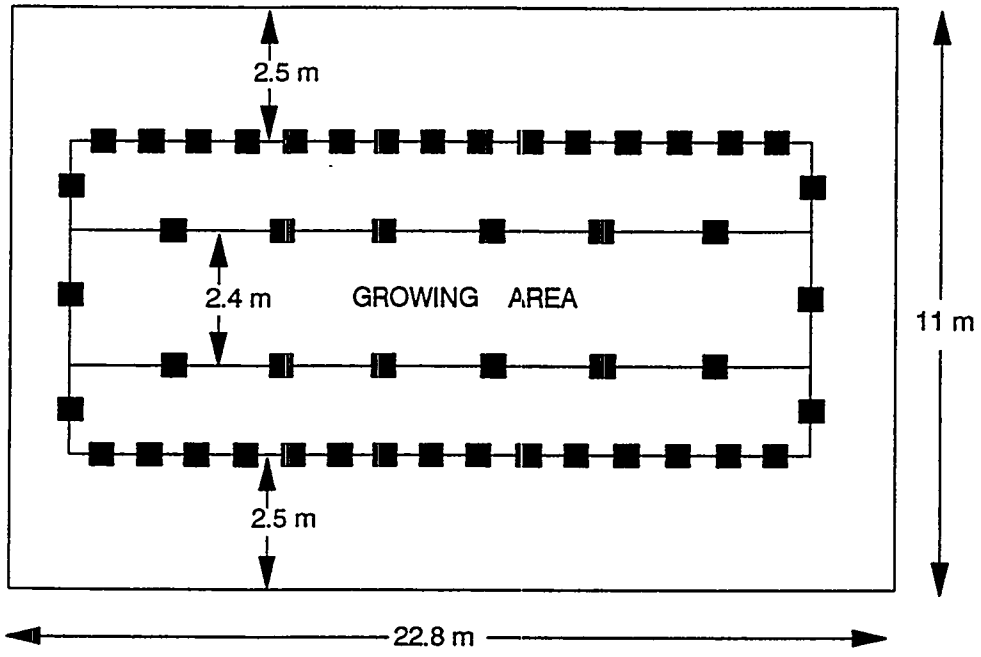

Fig. 1. Luminaire layout for a rose greenhouse at Cornell. Additional dimensions are: The bottom of the reflectors is located 1 m above the top of the canopy and the top of the canopy 1.95 m above the floor. The walkway along the left side wall is 1.45 m wide and the one along the right side wall 2 m. The distance between the luminaires in the top and bottom row is 1.22 m and the same distance in the center rows is 2.76 m. The distance between the top row and the top center row is equal to the distance between the bottom center row and the bottom row and is 1.8 m. The distance between the luminaires in the left and right columns is 2 m. The center luminaires of the left and right columns are positioned directly underneath the ridge of the greenhouse. The left most luminaire on the bottom row is positioned 2.5 m from the left side wall and also 2.5 m from the bottom side wall.

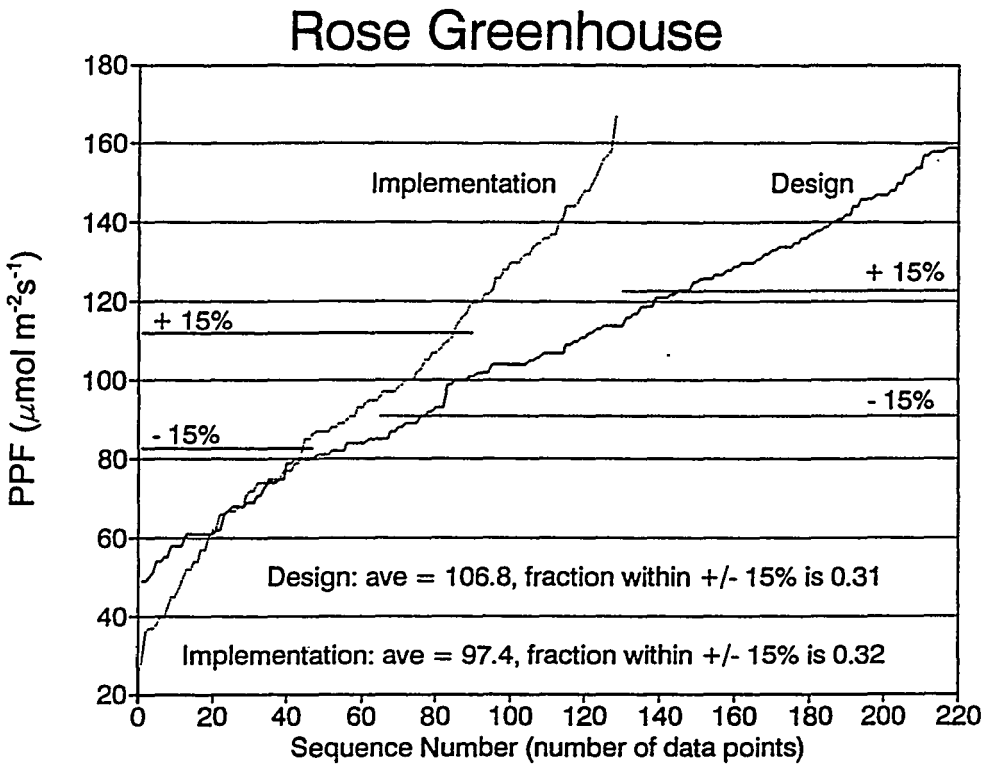

Fig. 2. Frequency graph for a rose greenhouse at Cornell.

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Albright, L.D. and A.J. Both (1994) Comparison of luminaires: efficacies and system design. Listed elsewhere in this publication.

SHORT REPORT

LIGHTING INSTALLATIONS

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Model computations that give the lay-out of a lighting installation have to be implemented in the real world. There, deviations from the ideal performance of just about every element of the installation will be felt. A list of possible sources of non-ideal behavior, based on practical experience, are the following:

Lamps: Discharge lamps are manufactured to close tolerances of, typically, $\pm 3\%$. Their light output decreases during their life, depending on operating conditions and lamp type. A typical value is 15% over 10,000 hours for HPS lamps, which is well before their "burn-out". It should be decided in the design phase what level of reduction is acceptable, and a schedule for lamp replacement should be drawn up accordingly.

Ballasts: Ballasts built to IEC standards have close tolerances of, typically, $\pm 3\%$. Their power output will gradually change during their useful life. This useful life depends largely on the highest temperatures during operation, which in turn depend on the design of the fixture.

Reflectors: A good reflector design can be reproduced to within a few percent. Sometimes, however, unfavorable conditions during production result in a significantly lower luminaire efficiency.

Mounting Position: The distance between fixtures in relation to the highest level specified (top of the crop) is often such, that adjacent light distributions only just overlap. Then, a slight tilt of a luminaire means a dark gap between the lighted areas. The mounting height is best chosen as high as possible, and careful levelling is often required.

Sagging of Lamps: The lamps often sag under their own weight in or with the socket. This always decreases lighting uniformity. Some luminaire designs provide an extra support for the lamp at its top.

Soiling: Soiling of luminaires during operation is unavoidable, though it will affect some places more than others. Regular wiping can prevent the occurrence of dark spots over the crop.

It is clear, that with all possible deviations from the ideal the homogeneity of a real lighting installation can never be as good as the one computed. The only way to make sure it is nearly as good is by measurement of the actual light distribution. Then, an occasional adjustment or replacement may often yield a satisfactory result. This measurement should really be part of the installation contract.

SHORT REPORT

OSCILLATING LAMP FIXTURE FOR GROWING AREAS

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BEAMFLICKER REPORT

The Oscillating Parabolic Mirror of "Beamflicker" was designed by Dr. Richard W. Tinus, Supervisory Plant Physiologist, USDA Forest Service, Rocky Mountain Forest and Range Experimental Station, Flagstaff, Arizona. With his idea, an economic greenhouse lighting system was developed and patented. Patent #5095414.

The Beamflicker uses a stationary 400 watt high pressure sodium arc bulb. The parabolic mirror rotates 180 degrees around the bulb to produce intermittent lighting every minute throughout the night. This one bulb can replace up to 88 incandescent bulbs in a 40 x 100 foot greenhouse over different sections of a growing area.

The lighting intensity of the Beamflicker varies greatly depending on the distance from the bulb. The light intensity varies from 1.3 μmol m^2s^{-1} 50 feet from the bulb to 52.5 μmol $m^{25}s^{-1}$ directly beneath the bulb. A year long study involving light intensity and many species will be concluded in July 1994. These research results should be published within the next year.

NASCO Machine of Flagstaff Arizona is the licensed manufacturer of the Beamflicker. For more information contact Harvey Hiatt, (602) 774-4501. FAX (602) 779-5662.

USE OF PRISMATIC FILMS TO CONTROL LIGHT DISTRIBUTION

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INTRODUCTION

Piping light for illumination purposes is a concept which has been around for a long time. In fact, it was the subject of a 1881 United States patent[1] which proposed the use of mirrors inside a tube to reflect light from wall to wall down the tube. The use of conventional mirrors for this purpose, however, has not worked because mirrors do not reflect well enough. The best conventional mirrors[2] are about ninety-five percent reflective. The rest of the light is lost through absorption. So, if a light ray traveling down a tube strikes a mirror surface ten or twenty times, and loses five percent with each "bounce," little light is left by the time it reaches the end of the tube. On the other hand, optical fibers composed of certain glasses or plastics are known to transport light much more efficiently. The light that enters is reflected back and forth within the walls of the fiber until it reaches the other end. This is possible by means of a principle known as "total internal reflection." No light escapes through the walls and very little is absorbed in the bulk of the fiber. However, while optical fibers are very efficient in transporting light, they are impractical for transporting large quantities of light. This would require large solid fibers which would be very heavy, difficult to install in many applications, and exceedingly expensive.

Lorne Whitehead, as a student at the University of British Columbia, recognized that prismatic materials could be used to create a "prism light guide," a hollow structure that can efficiently transport large quantities of light. The prism light guide was patented in 1981[3], exactly one hundred years after the first patent on "piping" light appeared! This invention is a pipe whose transparent walls are formed on the outside into precise prismatic facets. The facets are efficient total internal reflection mirrors which prevent light traveling down the guide from escaping. Very little light is absorbed by the pipe because light travels primarily in the air space within the hollow guide. And, because the guide is hollow, weight and cost factors are much more favorable than would be the case with very large solid fibers.

The early history of the development of the concept of the prism light guide has been described.[4] In 1983, Whitehead founded TIR Systems Ltd., a company in suburban Vancouver, Canada to design, develop, optimize, and manufacture prism light guides. The first guides were

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[1] W. Wheeler, U. S. Patent 247,229, *Apparatus for Lighting Dwellings or Other Structures,* September 20, 1881.

[2] For example, Silverlux™ film produced by 3M Company.

[3] L. A. Whitehead, U.S. Patent 4,260,220, *Prism Light Guide Having Surfaces which are in Octature,* April 7, 1981.

[4] *Popular Science,* May, 1988, page 76.

constructed as rectangular rigid acrylic pipes with molded-in prisms, and, as shown in Figure 1, each side of the 1/4 inch thick rigid panel was flat. While the original concept was born from the early dream of piping sunlight to the interiors of artificially lit buildings, it quickly became clear that prism light guides had applicability in a variety of diverse applications and markets.

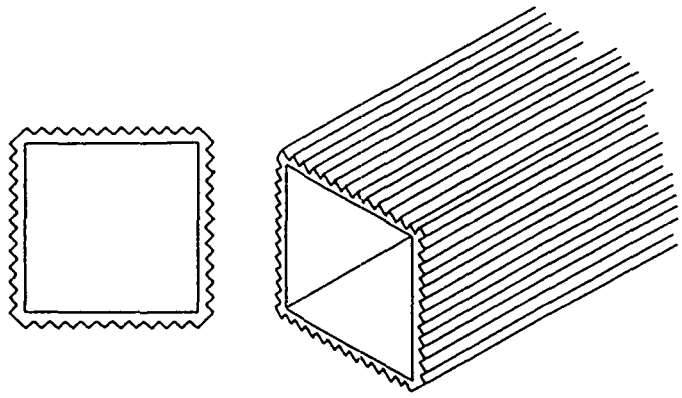

Fig. 1. Rectangular rigid hollow light guide

3M BRAND OPTICAL LIGHTING FILM

In 1983, 3M recognized that the macro-prism structure which existed in the first thick walled rigid acrylic panels could be made as a continuous thin film incorporating microscopic prisms with the same 90° geometry. The geometry of this film, known as 3M Brand Optical Lighting Film (abbreviated OLF), is shown in Figure 2.

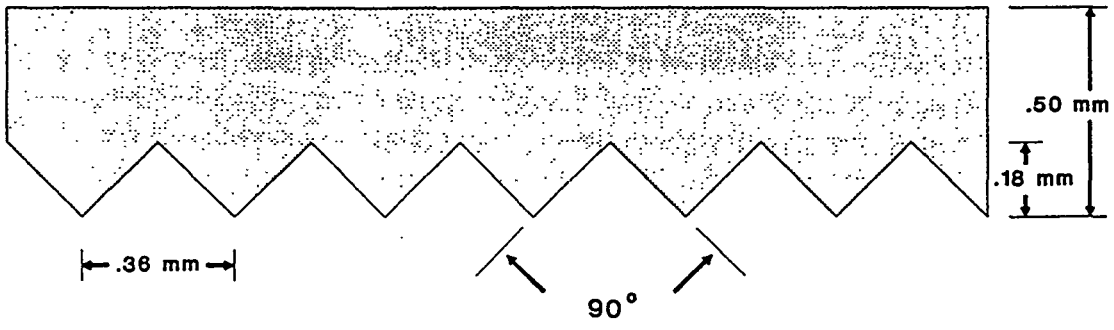

Fig. 2. 3M Brand Optical Lighting Film Cross-section

3M's goals in the development of this new film were the advantages of flexibility in cross-section shape, lower material costs, and potential for economical high volume production. The material is made from either acrylic or polycarbonate polymer resins which have been especially selected for their physical and optical properties. The acrylic film is more stable in certain adverse environments. Polycarbonate films, on the other hand, are tougher, can operate at higher temperatures, and have better handling properties. Very low light absorption in both materials is the critical feature which allows the film to transport and distribute light efficiently.

The degree to which the film's prisms shown in Figure 2 deviate from perfect prisms also affects the efficiency of the total internal reflection process, and, therefore, the effectiveness of the film in transporting and distributing light. Of course, the prisms will not be absolutely perfect, so reflectance of the film will not be 100%. Absorption and transmission will occur. Absorption, as was mentioned above, is due to bulk absorptivity of the resin used to produce the film, and is an irretrievable loss from the optical system. Transmission results from imperfections in the form of the surfaces. Examples of these imperfections include 90° corners which are not precise, surfaces which are not optically flat or which deviate from the correct angle, optical inhomogeneities in the material, etc. Transmission, while generally undesirable if not controlled, can be used to advantage if one goal of the application is light distribution. With the typical losses due to absorption and transmission, the reflectance efficiency of OLF has been calculated as approaching 99%.[5] Using OLF, circular hollow light guides, as show in Figure 3, can be produced in a variety of sizes which may be required for specific applications.

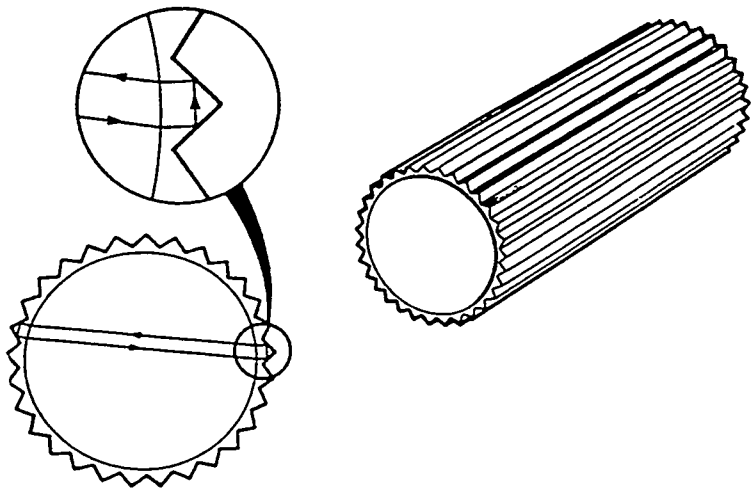

Fig. 3. Circular hollow light guide

Because of a need to protect our proprietary position, little can be said of the process which 3M uses to manufacture OLF with the precision required to produce this very high level of reflectance efficiency. Recent advances in precision micromachining, polymer processing, and certain other manufacturing technologies have made the development of OLF possible. The process is referred to within 3M as "microreplication" and has been found to have broad applicability in a number of diverse product areas.[6]

CONSTRUCTION AND OPERATION OF HOLLOW LIGHT GUIDES

OLF will act as either a nearly perfect mirror or transparent window depending upon the angle

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[5] S. G. Saxe, L. A. Whitehead, and S. Cobb, Jr., SPIE Volume 692, *Materials and Optics for Solar Energy Conversion and Advanced Lighting Technology,* p. 235, 1986.

[6] R. H. Appeldorn, *Nano-Technology Applied to Surfaces,* The Royal Society American Lecture, London, April 2, 1992.

that light strikes the material. For example, the path of a light ray in a typical hollow prism light guide is shown in Figure 4. Light enters the tube from an external source, shown as a lamp with accompanying reflector. It first strikes the smooth, unstructured side of the OLF film, is refracted according to Snell's law, and passes through the smooth side to strike one of the prism surfaces. If the ray strikes the surface at an angle greater than the critical angle, it reflects by total internal reflection, and heads for the other prism face. If it reflects again, it returns to the interior of the tube for further propagation. This light ray path is also shown in Figure 3. Note that the ray spends relatively little time in the OLF plastic bulk, especially if the film is thin, and benefits from the low absorption of propagation through air.

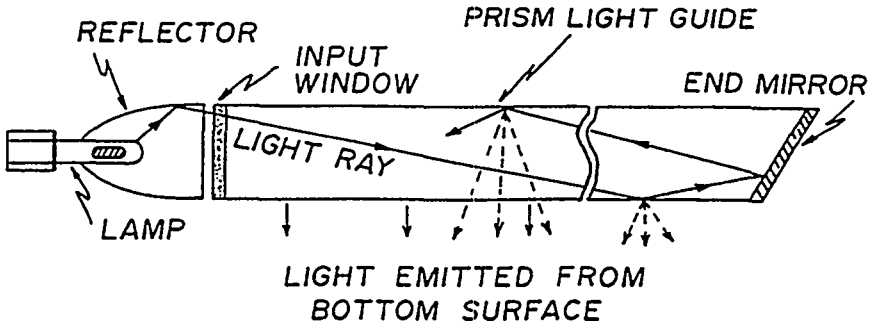

Fig. 4. Typical hollow prism light guide

Since the reflectivity of the film depends directly upon the angle at which the light rays strike the prism surface, it is obvious that the characteristics of the light source and reflector used to collimate the light are critical to the performance of a prism light guide. For the plastic materials used in OLF, light must enter the guide at an angle of 27.6° or less from the axis of the guide. This is shown in Figure 5. In other words, the cone of light from the source should form a 55.2° angle. In general, this means that very narrow spot light sources are used.

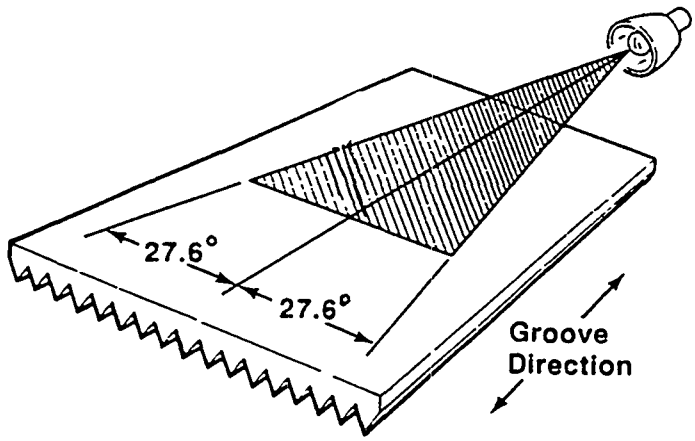

Fig. 5. Angular distribution of light rays entering hollow light guide

A "perfect" prism light guide would reflect all rays that entered within that 55.2° cone. However, as discussed above, imperfections in the film cause some of the light to be transmitted through the film and escape from the guide, making it glow and illuminating the space around

the guide. Generally, in the case of hollow light guides, one attempts to "manage" the rate at which light leaks from the tube, and create uniformity of light escaping along the entire length. One of the most efficient ways to get light out of the tube is to place an additional film (referred to as an "extractor" film) inside the tube to "interrupt" light ray propagation and create uniform light escape from the tube. This extractor film is typically a matte white vinyl material, such as 3M Scotchcal™ Series 7725-20 ElectroCut™ film. Another method is to simply cut holes in the prismatic film.

Details of the construction of hollow prism light guides, including predicted performance resulting from various light sources, tube sizes, and extractor configurations are given in previously published 3M Application Bulletins.[7 8 9] Many of the practical issues which must be addressed for the successful performance of such fixtures, such as protection from heat, dirt, UV, etc., are discussed later.

APPLICATIONS

The interesting combination of light transmission and reflection capabilities of OLF has made it possible to produce lighting products with unique properties. For example, a point light source can appear as an area source. Light can also be distributed uniformly to avoid "hot spots" which are often associated with point light sources. In addition, light can be transported from the location of the light source to a remote location where illumination is desired. Finally, OLF can be used to provide a desired directionality to light.

The performance which is achievable with OLF often translates into significant product advantages and benefits. Several examples include the following:

Unique Features

Because the angular distribution of light exiting the prism light guide is controlled, fixtures with unique capabilities are possible for some applications.

Design Freedom

The use of point sources provides the capability for variable fixture length and diameter. The lightweight construction which is possible requires less structural support. Light intensity, uniformity, and color are usually easier to control with prism light guides than with standard fluorescent fixtures.

Improved Safety

Because it is possible to deliver light efficiently to a remote location, it is often possible to locate the lamp, ballast, electrical connections, and sources of heat outside of a hazardous or sensitive area.

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[7] 3M Optical Lighting Film Application Bulletin, *General Theory,* November, 1988.

[8] 3M Optical Lighting Film Application Bulletin, *Photometrics,* September, 1989.

[9] 3M Optical Lighting Film Application Bulletin, *Photometrics Appendix,* October, 1989.

Ease of Maintenance

Lamps placed remotely may often be positioned in locations where maintenance is more convenient to perform, safer, and less expensive.

Reduced Cost

In certain situations, the use of fewer, more efficient light sources may result from the use of an OLF-containing fixture. However, in considering overall system cost, it is important to include not only the cost of the fixture, but also the potential life-cycle cost reductions for installation, operation, and maintenance.

Over our years of experience in working with OLF, we have uncovered unique and interesting lighting applications using this film which are too numerous to mention. In fact, because the apparent opportunities for the creation of new products based on the capabilities of OLF are so large and diverse, it has sometimes been difficult to assess and manage our product development priorities. We have found it easier and quicker to invent new applications for the film than to develop and commercialize these myriad opportunities. And, as will be discussed later, there are many critical variables which must be addressed in the successful development of a new lighting product. As a result, we have recently decided to confine our development efforts to products which could find utility in a market which we in 3M know -- the traffic management market. The selection of applications for this market was not accidental. It was largely based on the recognition that 3M already has good knowledge of the traffic management market through existing sales of a wide variety of retroreflective products for marking road surfaces, vehicles, and highway signs. It is a market for which we have effective distribution around the world. As a result, we have introduced several new products for use in highway applications:[10]

3M Internally Illuminated Highway Sign

This new sign product combines the property of passive retroreflectivity with that of internal illumination. OLF is used to distribute the light evenly within the sign box and thereby provide uniform luminance of the sign face. In addition, the use of OLF allows the light sources to be placed remotely at the side of the road where they may be easily maintained. The light is efficiently transported to the sign which is over the road. Advantages, therefore, include safer and more convenient maintenance allowing for the elimination of traffic diversion and delay, improved uniformity of sign luminance, improved performance under adverse weather conditions, and preferred aesthetics.

3M Lighted Guidance Tube

This product is a linear illumination system which provides positive guidance to motorists traveling along hazardous or unfamiliar roadway locations or during conditions of adverse visibility. This system utilizes small low-voltage light sources located approximately every 30 meters to illuminate a continuous polycarbonate tube mounted atop concrete barriers or steel guard rails. The effect of providing a continuous line of light is made possible by the light

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[10] D. L. Strand and K. G. Kneipp, XII International Road Federation World Meeting, Madrid, *Novel Uses of 3M Optical Lighting Film in Roadway Applications,* May, 1993.

transport properties of OLF. In addition, because of the directionality of the light which exits, it is possible to provide different colors to the light exiting the tube when viewed from either direction.

3M Pole Light

The 3M Pole Light uses OLF to transport light from a lamp located at the base of the pole to the top where it is redirected back to the ground in the desired "footprint" by a unique reflector. This product is also made possible by the efficient light transport properties of OLF, and provides advantages of easy and convenient light source maintenance and improved safety due to the location of all electrical components at the base of the pole or below grade.

In addition to these product applications being pursued directly by 3M, a number of other light fixture manufacturers purchase OLF and fabricate an array of novel fixtures which capitalize on the film's benefits. The following summary of selected applications is not intended to be a complete listing, but rather a sampling which shows the wide variety of products which have been developed based on this technology:

Thin Light Boxes

Thin boxes for backlit advertising and graphics display applications have been built by several manufacturers. The use of OLF permits uniform luminance of detailed sign graphics with a thinner box profile than would be possible using standard construction techniques. It allows for lamps to be located in positions where they may be easily maintained. Typical techniques for construction have been described.[11]

Explosion Environment/Hazardous Lighting

The light transport properties of OLF permit the construction of fixtures where the lamp, ballast, wiring, and associated electrical components may be safely located outside of hazardous or sensitive areas. All maintenance of the fixture is done in easily accessible, safe locations, and the light is delivered into the room where it is needed. This type of fixture has been used in solvent rooms and other similar environments, in food processing plants, health care MRI rooms, and over swimming pools where lamp maintenance is difficult and expensive or where elimination of electrical components is necessary.

Tunnel Lights

OLF fixtures for application in tunnels offer the advantage of greatly reduced number of lamps compared to fluorescent fixtures which they typically replace. Reduced and easier maintenance in these difficult-to-access locations are major benefits to the end-user or maintaining authority.

Building Highlighting

Long lines of light located atop buildings have been used to highlight the building design and create desired architectural effects. With OLF, it has been possible to design such fixtures with

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[11] 3M Optical Lighting Film Application Bulletin, *Thin Light Box,* March, 1990.

the light source located inside the building for ease of maintenance. In addition, changing colors or creating other desired visual effects is made easier than with other lighting designs. Buildings which incorporate such lighting systems may be found in several locations in North America, Europe, and Japan.

Emergency Vehicle Interior Lighting

OLF fixtures create more uniform illumination and eliminate the glare often associated with point sources. Because light sources which provide better color rendition may be used, patient care, as well as comfort, is improved.

Workstation Task Lighting

The use of OLF in fixtures located over workstation or desk areas allows the light to be directed so that undesirable glare and reflections from shiny surfaces are eliminated. This improves worker comfort and productivity.

The products which have been briefly mentioned here all capitalize on the unique light transport and distribution properties of OLF. These properties have led to a variety of benefits, including fixtures with unique designs, improved safety, reduced operation cost, and improved maintenance due to the use of longer-life lamps and the ability to locate them for ease of replacement.

IN-USE FIXTURE DESIGN AND PERFORMANCE CONSIDERATIONS

The environment in which a light fixture is to be used dictates many of the details of its design. For example, fixtures which are intended to be used in exterior locations must meet design and performance criteria which do not apply to interior fixtures. Exterior fixtures are usually constructed to different specifications using different materials than fixtures which will not be subjected to harsh exterior environments. The fact that fixtures intended for use in specific applications must each be designed and constructed to meet the unique requirements of that application has been a key factor limiting the number and types of widely different fixture designs and end-use applications which we in 3M have elected to pursue. We recognize that the effort to produce an effective fixture design, and the investment required to prove that the design functions acceptably in the intended environment, are often substantial. Some of the factors which must be considered in the design and operation of any new OLF-containing prism light guide are outlined below:

Service Access

The design freedom which often results in OLF fixtures can make maintenance of the light sources much easier and more convenient. It is important to design the fixture so that optimum advantage may be taken of this benefit by designing the proper location and type of service access for ease of lamp replacement and electrical maintenance.

Effect of Heat

OLF-containing fixtures often incorporate HID sources which provide light which is properly collimated for use in a prism light guide. However, these source also produce heat, which, if not

properly dissipated, can result in fixture overheating and ultimate destruction of certain components. Plastic components are susceptible to damage from excessive heat. For example, polycarbonate OLF will suffer film distortion at temperatures above about 265°F; acrylic OLF will be damaged at temperatures above about 190° F. It is necessary, therefore, to place hot sources in appropriate locations and to use suitable venting and cooling techniques to insure that these films and other heat sensitive components will not be damaged.

Effect of UV

Plastic resins, such as polycarbonates or acrylic materials, are often stabilized to the damaging effects of UV radiation by the use of certain additives. The polycarbonate and acrylic polymers used to produce OLF, however, do not incorporate such stabilizers. This is because stabilizing additives also absorb sufficient light in the visible portion of the spectrum such that the optical efficiency of the resulting film will be too low. As a result, because UV radiation will cause undesired resin yellowing, crazing, and cracking, it is necessary to use a filter between the light source and OLF material. While the acrylic film is less susceptible to damage from UV exposure, unstabilized polycarbonate is known to yellow when exposed to radiation of less than 337 nm.[12] An effective filter glass for use with polycarbonate is UVILEX 390 (Schott Glass).

Weatherability

While it is necessary to protect the OLF from the damaging effects of UV radiation, prism light guides which are used outdoors will be subject to the effects of sunlight. The OLF must be contained in a housing which does not allow sunlight to shine directly on the film. This may be done by using metal or stabilized plastic components for the outer housings.

Effects of Dirt and Moisture

In addition to protection from sunlight, the optical components must be protected from excessive dirt and condensing moisture, both of which will destroy the optical performance. Thus, fixtures containing OLF are often sealed to eliminate concerns from dirt and moisture. In some cases, where sealing is impractical, such as in the case of a large sign, it is necessary for the entire structure to breathe. Filters to keep out dust, insects, or other debris, are often used at the breathing ports.

Hostile Environments

While any fixture which is used outdoors is subject to the effects of sunlight, temperature extremes, and moisture, certain environments are particularly hostile and deserve separate mention. For example, products such as the 3M Lighted Guidance Tube, tunnel lights, and certain other outdoor fixtures are subjected to occasional high pressure water, detergent, or even steam cleaning. It is important that the actual operating environment be considered in fixture design and selection of components.

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[12] C. A. Pryde, ACS Polymer Preprints, Volume 25, Number 1, *Weathering of Polycarbonates - a Survey of the Variables Involved,* p. 52-53, April, 1984.

OTHER PRISMATIC MATERIALS AND THEIR APPLICATION

In addition to OLF, 3M has developed other prismatic film materials for redirecting light. An important example of such a product is a film which we call "2370" polycarbonate prismatic film. The structure of this film is similar to that of OLF shown in Figure 2, except that the prism angles are 70° instead of 90°. The way in which this film interacts with incident light is quite different. When the film is positioned so that the groove direction is perpendicular to the direction that the light is traveling within a hollow light guide, light which strikes the groove side of the film at a grazing angle (less than about 20°) will be bent 90°. The 2370 film has found use in helping to achieve uniform light extraction from our internally illuminated signs, as well as in redirecting light in a preferred direction from other hollow light guides. OLF and 2370 are often used together in order to achieve desired light control. The 2370 film is manufactured in a microreplication process similar to OLF.

Another important prismatic material is the 3M Solar Optical Products Daylighting Panel which incorporates a Fresnel lens system to collect light energy from the brightest area of the sky and redirect it vertically into the interior of a building. The bulk of available natural light varies with the time of the day as well as time of year. Conventional skylights and windows are only partially effective since they cannot constantly redirect the brightest portion of the sky into the desired areas of the building. 3M Daylighting Panels also soften direct sunlight without reducing reflective efficiency while still providing unique light collimation properties. Energy requirements for heating and cooling are substantially reduced.

In a typical installation, such as the one at the 3M Austin, Texas Center, the panels are mounted in the roof area of the building. A primary panel collects and concentrates direct solar radiation and redirects the light to a secondary panel. The secondary panel is positioned such that sunlight is directed vertically downward into the building regardless of the time of year. Due to its large collection efficiency, the system works well even on cloudy or hazy days. The construction and performance of the 3M Austin Center installation has been previously reviewed.[13]

Another application example for daylighting panels is at the Minnesota Zoo Tropics Building. The building previously utilized ordinary skylights to provide natural light for plants and animals located between 9 and 23 meters below the roof's surface. During the winter months, plants were being lost because most of the light did not transmit through the skylight due to the low sun angle. 3M installed daylighting panels on the north side of each skylight to capture the low angle sun and reflect it down into the building. This made the distribution of sunlight more uniform throughout the year, and provided light required for greater plant growth during the winter.

The ability to make the level of light delivered to the interior of a building more uniform throughout the year has been demonstrated by placing daylighting panel louvers on a greenhouse in Flagstaff, AZ. In the winter, low angle sunlight will be captured by one section of the louver and directed through the roof into the greenhouse. When the sun's altitude increases during the summer, the resultant sun's rays will reflect off a second section of the louver to reduce the transmitted sunlight. Use of these daylighting panel louvers will provide greater growing capacity for a conventional greenhouse throughout the year and reduce winter time heating and

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[13] *Architecture,* August, 1990, p. 90.

summer time cooling energy requirements.[14] Details on these daylighting installations may be obtained from 3M.[15]

Still another application of the Fresnel lens technology is in prismatic materials for solar concentrator applications. Using the 3M lens film, sunlight is focused on a strip of active solar material. This increases the efficiency of the overall collection system, reduces the amount of active cell material required, thereby eliminating the need for broad flat plates of active cells. The performance of a system which has been installed atop the parking garage at the 3M Austin Center has been described.[16]

SUMMARY

3M prismatic films are finding increasing utility in the construction of new hollow light guide fixtures which capitalize on the unique ways in which these novel materials interact with light. Often, the resulting systems provide features and end-user benefits which are difficult or impossible to achieve by alternative design or construction methods. It is apparent that the benefits may be applied to a wide variety of end-uses, and that the resulting products being developed will find utility in many diverse market areas.

With the recognition that creating hollow light guide products and systems requires a substantial resource investment, and because of an existing prominent position in the traffic management market, 3M has decided to focus its current efforts in the development, manufacture, and distribution of value-added products for this market.

However, through the sale of these prismatic films, a variety of companies have developed and are manufacturing and distributing other unrelated hollow light guide products which capitalize on the unique capabilities of these films in controlling and distributing light. There appears to be little doubt that the potential applications of this technology will grow both in numbers as well as in diversity.

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[15] Contact Paul Jaster, 3M Solar Optical Products, 3M Center, St. Paul, MN, (612) 733-1898.

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PRINCIPLES AND CHARACTERISTICS OF OPTICAL FIBERS

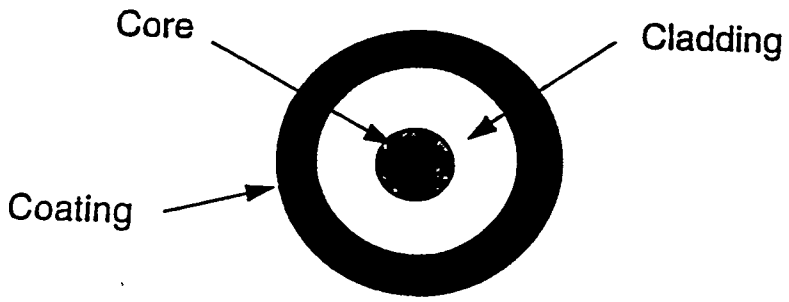
Atikem Haile-Mariam

Corning Inc., 27 W. Market St., ME-R3-O3-1, Corning, NY 14831

DEFINITIONS

Core, Cladding, Coating

- An optical fiber is made of three sections:
- The core carries the light signals
- The cladding keeps the light in the core
- The coating protects the cladding



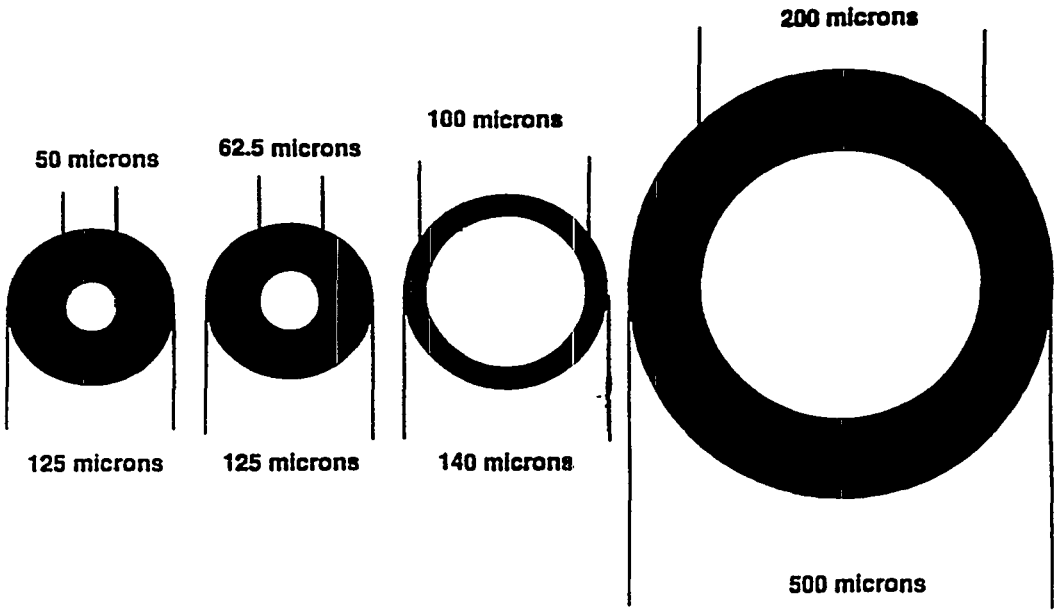
How an Optical Fiber Works

- An Optical Fiber works on the principle of Total Internal Reflection
- Light rays are reflected and guided down the length of an optical fiber.
- The acceptance angle of the fiber determines which light rays will be guided down the fiber.

CORE CHARACTERISTICS

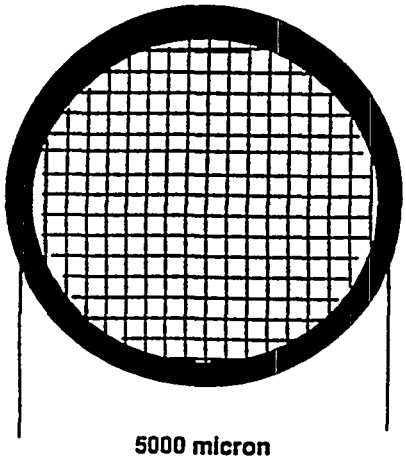
1. The diameter of the light carrying region of the fiber is the "core diameter."
2. The larger the core, the more rays of light that travel in the core.
3. The larger the core, the more optical power that can be transmitted.
4. The core has a higher index of refraction than the cladding.
5. The difference in the refractive index of the core and the cladding is known as delta.

STANDARD OPTICAL FIBER SIZES



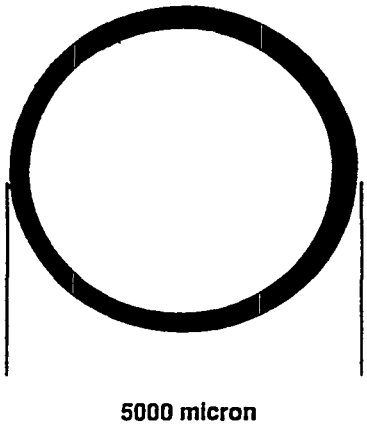
SPECIALTY ILLUMINATION FIBER

Fiber Bundle



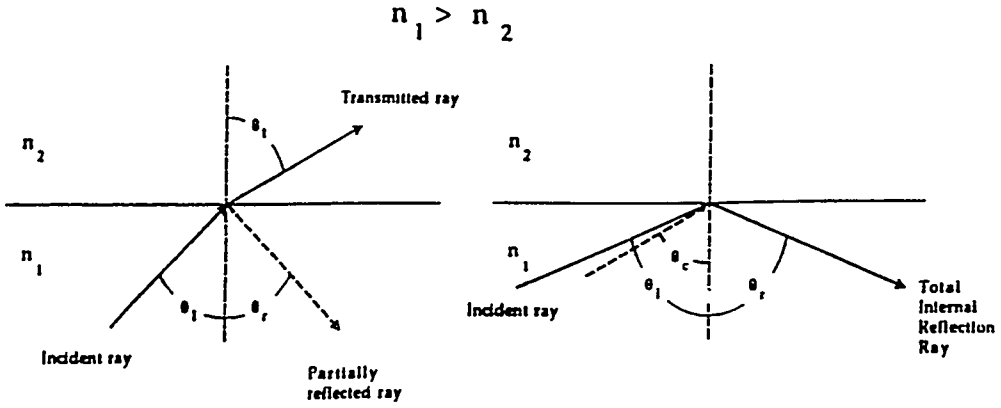
Large Core

Plastic Optical Fiber



Total Internal Reflection

Total Internal Reflection occurs when any ray traveling from a medium with a high refractive index is incident on a boundary of a lower refractive index at an angle greater than or equal to the critical angle.



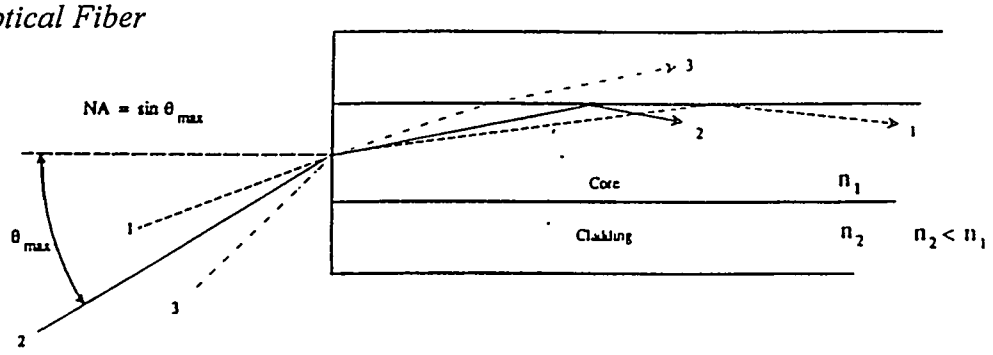
The transmitted ray is bent away from the normal **Total internal reflection: $\theta_i > \theta_c$**

(From: Michael Brininstool, 1993, Fiber Optic Design Principles Tutorial, ROV93 Conference San Diego, CA.)

Numerical Aperture (NA)

1. Measure of the acceptance angle of light that a fiber can support through total internal reflection.
2. Designed into the fiber by the difference in indices of refraction between the core and the cladding material.

Ray Tracing in Optical Fiber



Ray 1: Light is coupled into fiber since ray is within acceptance cone of fiber.

Ray 2: Light is at the maximum acceptance angle of fiber and is coupled.

Ray 3: Light is radiated out of fiber since ray is outside acceptance cone of fiber.

(From: Michael Brininstool, 1993, Fiber Optic Design PrinciplesTutorial, ROV93 Conference San Diego, CA.)

FIBER PERFORMANCE

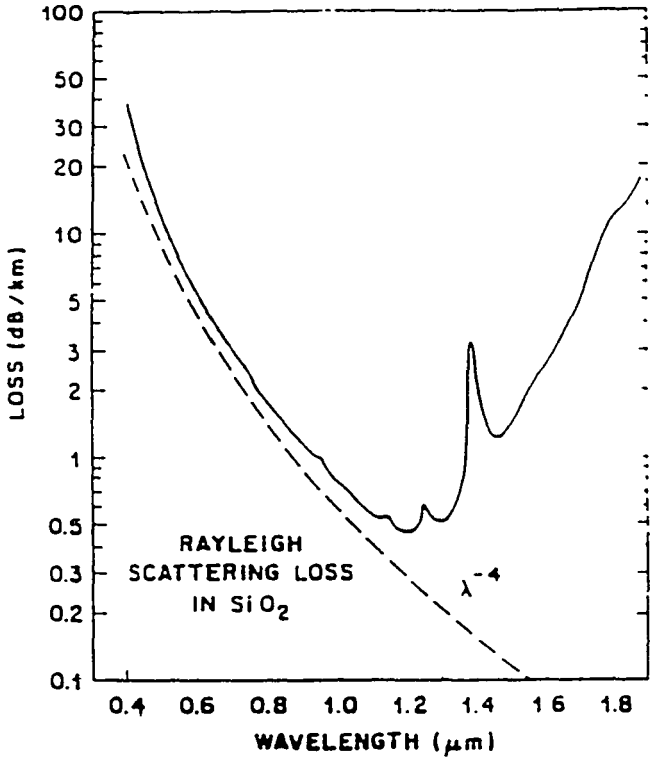
The efficiency of light transmission of optical fibers depends on fiber design and physical environment.

FIBER MATERIAL COMPOSITION

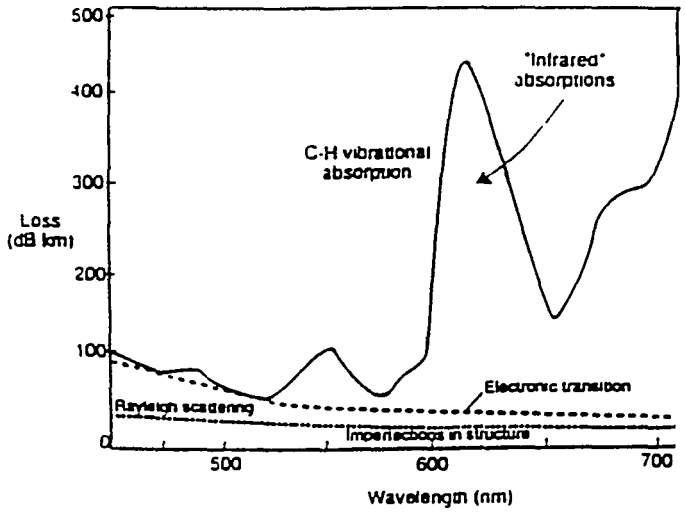
1. Corning optical fiber is an amorphous noncrystaline material made of pure fused silica and germania dopant.
2. Plastic optical fiber is generally made of a polymethyl methacrylate (PMMA).
3. Experimental fibers are made of other materials such as sapphire.
4. Coatings are usually proprietary to the manufacturer but are usually acrylate or polyimide based.
5. The primary function of coating is to protect the glass fiber from flaws.

EXAMPLES OF SPECTRAL ATTENUATION IN OPTICAL FIBER

Silica Core



PMMA Core



(From Product Information Sheet: Mitsubishi-Rayon Co. Inc.)

COMPARISON OF GLASS AND PLASTIC OPTICAL FIBER

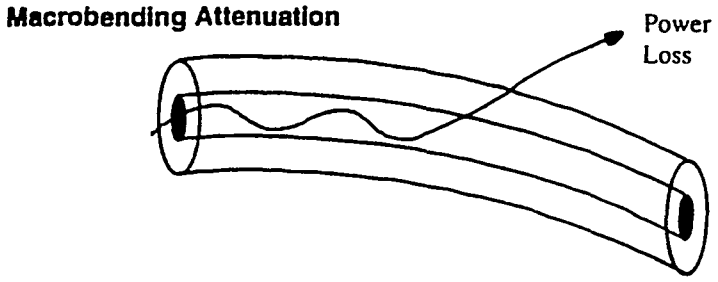
Characteristics	Glass	Plastic
Fiber core diameter, microns clad diameter	50-200 125-500	250-5000 450-6000
Attenuation at 650 nm, dB/km	4.0	150*
Maximum transmission distance for 75% power loss, meters	1,500	.53
Usable spectral range	UV,VIS,IR	VIS
Numerical aperature	.1-.4	.3-.65
Acceptance angle (cone)	35 degrees	60-75 degrees

*Current commercial limits, not theoretical limits

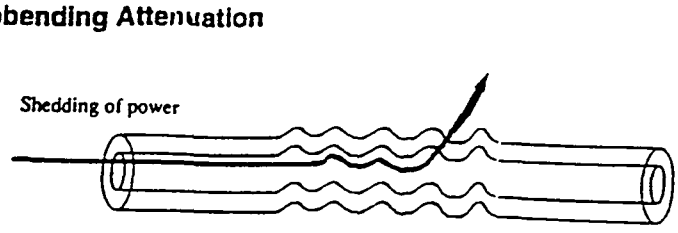
PHYSICAL ENVIRONMENT

Bend Induced Attenuation

1. Macrobending
2. Large bends in an Optical Fiber will shed rays of light. Power is lost at the bend.



1. Microbending
   - Small axial bends/bumps along the fiber axis that cause mixing or loss of power. This can be induced by fiber jacketing, cabling or environment.



Cable Design

1. Performance of fibers in cables depends on the following components:
   strength members (kevlar, steel)
   fill compounds
   tight buffer vs loose tube
2. Temperature/Humidity
   The performance of fiber/cable depends on the extent to which temperature and humidity produce microbending.

Specifications

3. Temperature (Celsius)
   Standard Glass Optical Fiber - -60 to +85 degrees
   Specialty Glass Optical Fiber - -60 to +200 degrees
   Plastic Optical Fiber -40 to 85 degrees
4. Temperature/Humidity
   Standard Glass Optical Fiber - -10 to +85 degrees and 4% to 98% RH
   Specialty Glass Optical Fiber - -10 to +85 degrees and 4% to 98% RH
   Plastic Optical Fiber - max 85% humidity for 2000 hours

TECHNICAL ISSUES THAT MERIT FURTHER INVESTIGATION

1. Cost effective diffusers and concentrators
2. Cost effective coupling techniques between light sources and fibers
3. "Multi-use' fibers

SUMMARY

1. Optical fibers works on the principle of total internal reflection.
2. Optical fibers can be used at various wavelengths including illumination applications.
3. Factors affecting the performance of fiber include material composition, geometry, and the physical environment.
4. Fiber/cabling can be optimized for the specific application and environment.
5. Manufacturing processes are available for producing glass fibers of differing refractive indices and diameters.

USE OF DIFFUSIVE OPTICAL FIBERS FOR PLANT LIGHTING

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INTRODUCTION

Lighting is one of the most critical aspects in plant production and environmental research with plants. Much research has been repeated on the effect of light intensity, spectral distribution of light and lighting cycle, but comparatively little research done on the effect of lighting direction on the growth, development and morphology of plants (Hart, 1988).

When plants are grown with lamps above, light is directed downward to the plants. Downward or overhead lighting is utilized in almost all cases. However, downward lighting does not always give the best result in terms of lighting efficiency, growth, development and morphology of plants.

Kitaya et al. (1988) developed a lighting system in which two rooting beds were arranged; one above and the other under fluorescent lamps. Lettuce plants grew normally in the lower bed and suspended upside-down under the upper bed. The lettuce plants suspended upside-down were given the light in upward direction (upward lighting). No significant difference in growth, development and morphology was found between the lettuce plants grown by the downward and upward lighting. Combining upward and downward lighting, improved spacing efficiency and reduced electricity cost per plant compared with conventional, downward lighting. From the above example, when designing a lighting system for plants with lamps more lighting direction should be considered.

In the present study, a sideward lighting system was developed using diffusive optical fiber belts. More higher quality tissue-cultured transplants could be produced in reduced space with sideward lighting system than with a downward lighting system. An application of the sideward lighting system using diffusive optical fiber belts is described and advantages and disadvantages are discussed.

'Normal' and 'Diffusive' Optical Fibers and Diffusive Optical Fiber 'Belts'

Normal optical fibers. A 'normal' optical fiber is a filament-shaped photon (light) guide, made of dielectric material, such as glass or plastic. The fibers usually consists of a single discrete optically transparent transmission element consisting of a cylindrical core with cladding on the outside (Figure 1a; Weik, 1989). The refractive index of the core has to be higher than the cladding for photons to remain within and propagate in the fiber. 'Normal' optical fibers are used to transmit photons as signals or energy carrier for a long distance with minimum attenuation

and disturbance.

Diffusive optical fibers. On the other hand, a 'diffusive' optical fiber is used as a thin line light source. For this purpose, the cladding of a 'normal' optical fiber is chemically eroded (scratched) to some degree so photons come out through the cladding gradually along the fiber (Figure 1b). Photons are sent through either or both ends (cross section of the core) of the fiber. The diffusive optical fiber used in the present experiment is made of acrylic and the refractive indices of the core and cladding are, respectively, 1.496 and 1.402. Thus, the fibers are considered to be an apparent light source and the lamp a true light source.

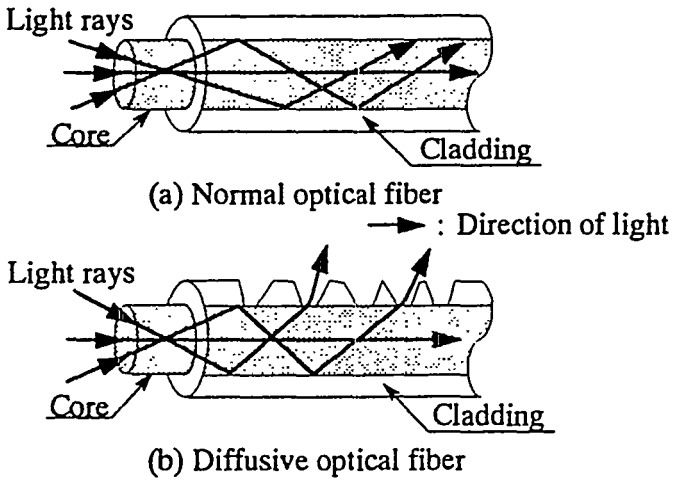

Fig. 1 Schematic diagram showing light transmission pathways in 'normal' and 'diffusive' optical fibers.

Diffusive Optical Fiber Belts

A diffusive optical fiber belt used in the present experiment is basically a flat belt (90 mm wide and 1.3 mm thick) composed of ninety diffusive optical fibers (each 1 mm in diameter) attached and fixed with a white (and opaque) reflective film on one side, with both ends of all the fibers bunched tightly together to make a circular cross-section (Kozai, 1991). When the light emitted from lamps is sent through both ends of the belt, this array of optical fibers functions as an area (surface) light source. The diffusive optical fiber belt is physically flexible.

SIDEWARD LIGHTING

Sideward Lighting System Using Fluorescent Lamps

A sideward lighting system using fluorescent lamps was developed. Quality tissue-cultured (micropropagated) transplants were produced with reduced shoot length and enhanced leaf and root growth in limited space at lower costs (Hayashi et al., 1992; Hayashi et al., 1994: Kitaya et

al., 1994). Figure 2 shows schematic diagrams of the sideward lighting system using fluorescent lamps and a conventional, downward lighting system using fluorescent lamps.

When both systems supplied with the same amount of electricity for lighting, dry weight, fresh weight, leaf area and stem diameter of potato (Solanum tuberosum L., cv. Benimaru) plantlets in vitro in the sideward lighting treatment were 80% greater than those in the downward lighting treatment. On the other hand, the shoot length of the plantlets in the sideward lighting treatment was only one half of the downward lighting treatment (Hayashi et al., 1992; Kozai and Ito, 1993). Tissue-cultured transplants tend to have elongated, thin stems with small leaves and few roots, which are undesirable characteristics of transplants. Higher quality potato transplants were produced in the sideward lighting treatment than in the downward lighting treatment.

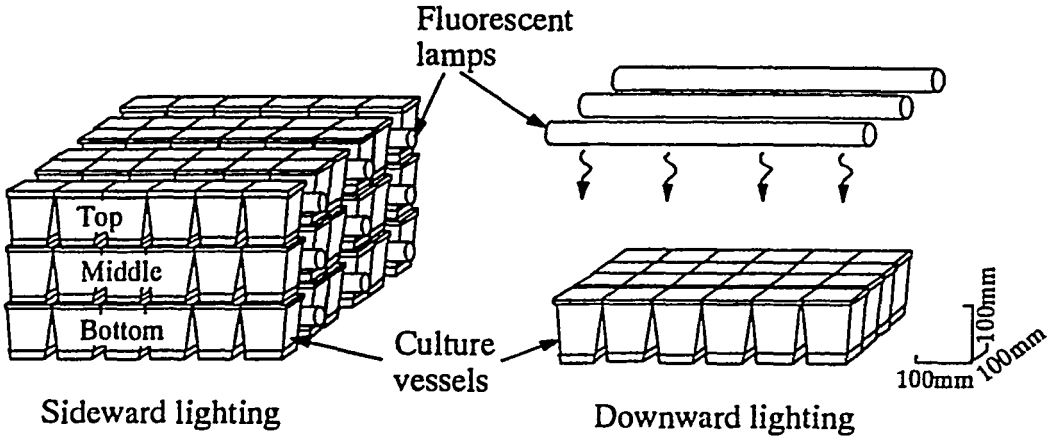

Fig. 2 Schematic diagram of the sideward lighting system using fluorescent lamps and the conventional, downward (overhead) lighting system using fluorescent lamps (Hayashi et al., 1992).

Sideward Lighting System Using Diffusive Optical Fiber Belts

A prototype of a sideward lighting system using diffusive optical fiber belts was developed for lighting plant tissue culture vessels (Figures 3 and 4). The main assembly of the system consists of two metal halide lamps, each with a reflector and a thermal filter and a pair of diffusive optical fiber belts (90 mm wide, 1.3 mm thick and 2.3 m long each). In this system, a 'true' light source is the metal halide lamps, but an 'apparent' light source is the belt. With this system, the space for the 'apparent' light source (between the rows of culture vessels) can be greatly reduced compared with the sideward lighting system, using fluorescent lamps.

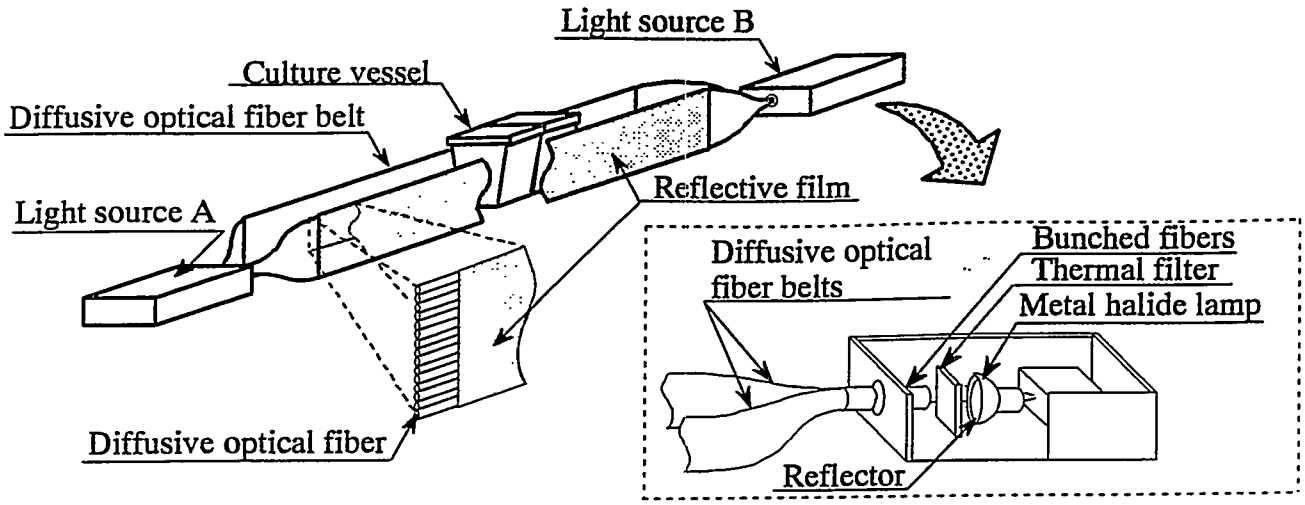

Fig. 3 Schematic diagram of the sideward lighting system using a pair of diffusive optical fiber belts for plant tissue culture (Kozai et al., 1992).

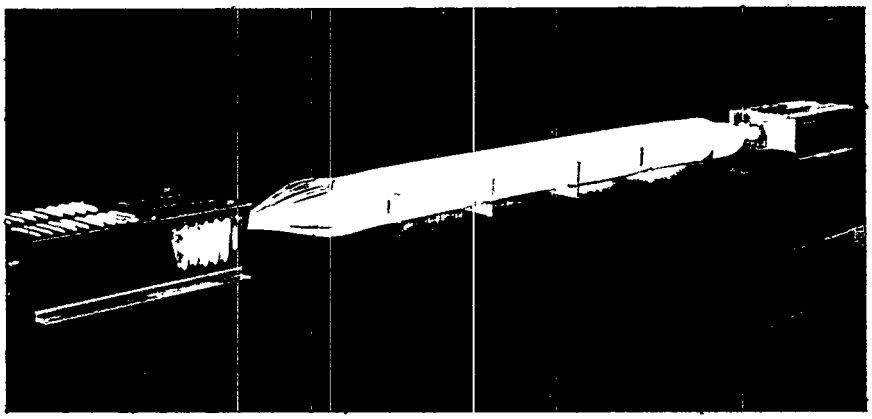

Fig. 4 Photograph of the sideward lighting system using a pair of diffusive optical fiber belts for plant tissue culture.

Light emitted from the lamps and transmitted through the thermal filters is focused, using the reflector, at the ends of the bunched optical fibers. The transmitted light passes into the bunched optical fibers and is released from the entire inner surface of the belts. The outer surface with the white reflective film is faced out. A pair of diffusive optical belts, 8 cm apart, are placed vertically in parallel on the culture shelf. Plant tissue culture vessels are placed in the space between the belts and plantlets in vitro receive light through the side walls.

Thermal radiation emitted by the lamp is removed by thermal filter before it enters the bunched optical fibers, and only photosynthetically active radiation (wavelength: 400 - 700 nm) passes into the belts. 'Actual' spectral distribution of light entering the belts is determined by the spectral distribution of light emitted from the lamp and the spectral transmissivity of thermal

filter. The light emitted from the belts and transmitted through one of sidewalls of the vessel, but not received by the plantlets in vitro passes through the opposite side wall of the vessel. Thus, increase in air temperature in the culture vessel due to the radiation from the light source was less than 0.5 °C (Kino, 1993).

In application of this system, the lamps are placed outside the culture room, so not only thermal radiation, but also convective heat produced from the lamps can be removed outside the culture room, which results in a significant reduction in the cooling load of the culture room.

Figure 5 shows longitudinal PPF (photosynthetic photon flux) distributed along the diffusive optical fiber belts as measured on the vertical surface, at the center of the plant tissue culture vessels (75 mm x 75 mm x 98 mm each), when either lamp A or lamp B or both were turned on. The PPF was more or less evenly distributed along the belts when both lamps A and B were turned on. The longitudinal PPF distribution along the belts is mainly determined by the degree of erotion along the fibers.

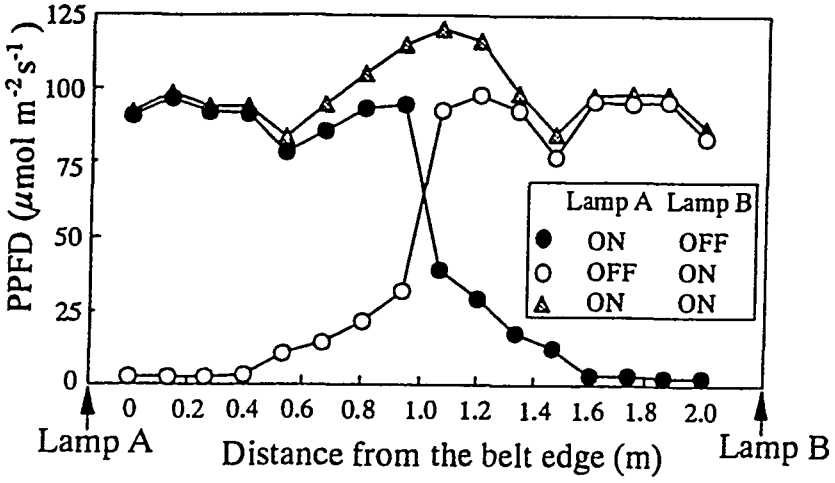

Fig. 5 Longitudinal PPF (photosynthetic photon flux) distribution along the diffusive optical fiber belts measured on the vertical surfaces at the central points of the plant tissue culture vessels shown in Figure 3.

Growth of potato (Solanum tuberosum L., cv. Benimaru) plantlets in vitro was compared using sideward and downward lighting systems. Leafy single node cuttings were used as explants without sugar in the medium. CO_2 was available in the plant space through gas permeable filters in the culture vessel. Plantlets cultured in vitro for 28 days had significantly reduced shoot length and increased stem diameter in the sideward lighting treatment than in the downward lighting treatment. There were no significant differences in dry weight, leaf area, number of unfolded leaves and net photosynthetic rate per plantlet between the two treatments (Kozai et al., 1992). Reduced shoot length and increased stem diameter are preferred characteristics of tissue-cultured plantlets for acclimatization and transplanting to ex vitro conditions.

PLANT GROWTH CHAMBER WITH DIFFUSIVE OPTICAL FIBERS

A prototype of a plant growth chamber with diffusive optical fibers was developed for plant tissue culture and transplant production (Figures 6, 7 and 8). Eight 150 W metal halide lamps were installed in the lamp house and thermally isolated from the culture room to reduce the cooling load of the culture room.

The culture room consisted of 12 (= 4 × 3) compartments , which are 20 cm wide, 30 cm high and 450 cm deep each. Thus, each compartment contained 36 (= 2 × 3 × 6) Magenta GA7 culture vessels (75 mm × 75 mm × 95 mm), totaling 432 (= 36 × 12) Magenta GA7 culture vessels in the culture room. Vertical PPF measured at the center of empty compartments averaged approximately 60 μmol $m^{-2}s^{-1}$. This PPF value was too low for plant tissue culture and transplant production when applied on the horizontal surface. However, a PPF of 60 μmol $m^{-2}s^{-1}$ at the vertical surface was high enough for plant tissue culture in the present experiment.

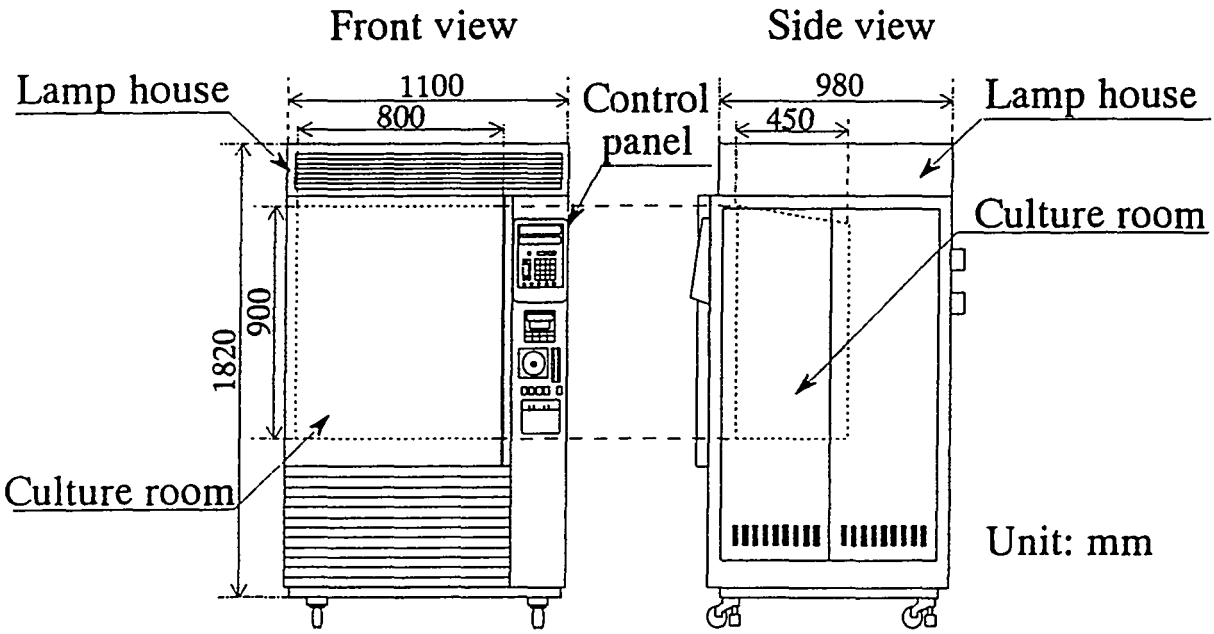

Fig. 6 Front and side views of a plant growth chamber with diffusive optical fibers developed for plant tissue culture and transplant production.

Using the plant growth chamber, quality potato (Solanum tuberosum L. cv. Benimaru) plantlets were successfully cultured in vitro (Kino, 1993; Kozai et al., unpublished). Further details are under study using the plant growth chamber

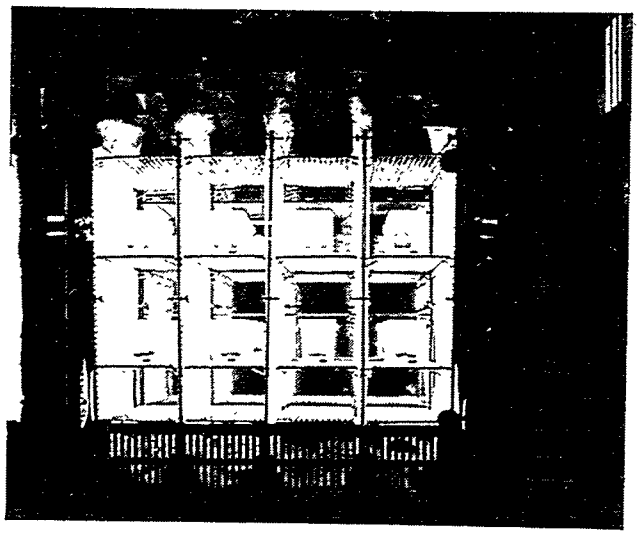

Fig. 7 Photograph of a plant growth chamber using diffusive optical fibers with the front door open, developed for plant tissue culture and transplant production.

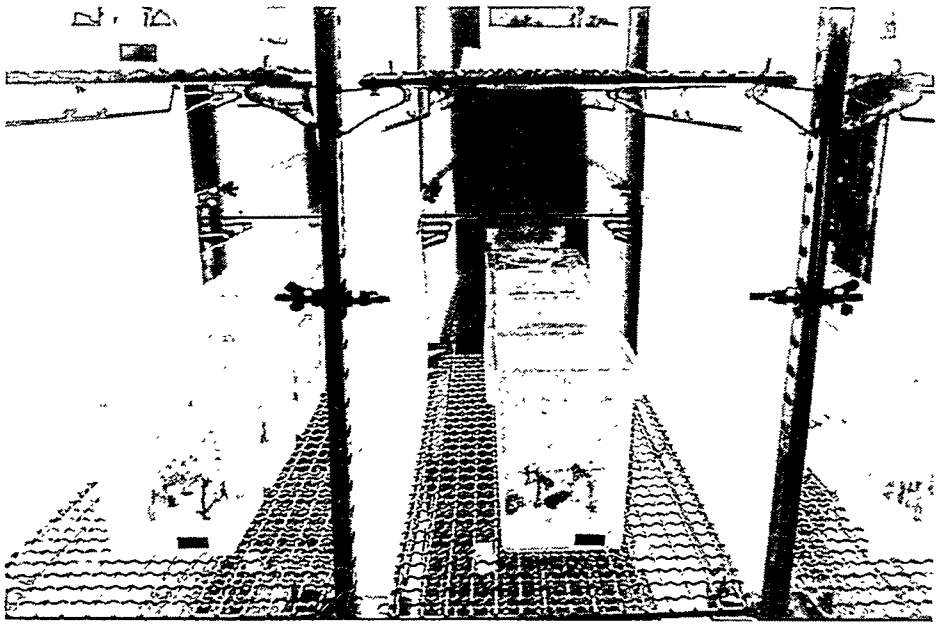

Fig. 8 Inside view of a plant growth chamber using diffusive optical fibers developed for plant tissue culture and transplant production.

ADVANTAGES AND DISADVANTAGES

Advantages of Sideward Lighting

Advantages of the sideward lighting system over the downward lighting system for plant tissue culture and transplant production include: 1) enhanced space utilization by vertically stacking culture vessels without a significant reduction in the amount of light energy received by the

plantlets, 2) increased ratio of light energy received by the plantlets to the light energy released from the light source, since culture vessels or plantlets are placed next to the light source, 3) increased leaf area exposure to light, especially lower leaves of plants. Since the light is applied from the sides, the lower leaves remain photosynthetically active (Kitaya et al., 1994), and 4) sides of vessels are often more transparent to light than lids.

Advantages of Diffusive Optical Fiber Belts

Advantages of the sideward lighting system given above are further enhanced when diffusive optical fiber belts are used instead of fluorescent lamps. Additional advantages of the sideward lighting system with diffusive optical fiber belts for plant tissue culture and transplant production include: 1) reduced culture room cooling load since only photosynthetically active radiation is released in the culture room, and 2) an optical filter or an optimal light source such as light emitting diodes (LED) could be easily used with a thermal filter to obtain an improved light spectral distribution. The diffusive optical fiber belts could be used, as an area light source for downward or upward lighting systems as well as sideward lighting system. This light distribution system (diffusive optical fibers) could be used as an effective lighting system for algae culture in a tank, mushroom culture, supplementary lighting in the greenhouse, etc.

Disadvantages and Their Possible Solutions

In the present sideward lighting system, using diffusive optical fibers, the ratio of PAR (photosynthetically active radiation) energy emitted by the lamp to the PAR energy entering into the cross section of bunched optical fibers was low (approximately 0.2). This is mainly because the metal halide lamp is not a point light source and the light energy emitted by the lamp could not be effectively focused to the cross section of bunched fibers. Using a lamp reflector. This ratio should be higher than 0.8.

However, using a microwave-powered lamp (Fusion Systems Inc., MD U.S.A.; Dolan et. al., 1992; Krizek et. al., 1993) a point light source (9.5 mm in diameter for 500 W lamp and 30 mm in diameter for 3.4 kW lamp), this problem would be largely solved (Kozai and Kitaya, 1993).

Methods of designing the lighting system using the diffusive optical fibers have not been adequately developed. There are many possible geometrical layouts of lamps, reflectors, thermal filters and the fibers. There are many design problems to be solved for further development.

CONCLUSIONS

A plant growth chamber with a sideward lighting system was developed using diffusive optical fiber belts as an 'apparent' light source. High quality tissue-cultured transplants with reduced shoot length and increased stem diameter could be produced with this growth chamber. Advantages of this lighting system include: 1) enhanced space utilization, 2) increased ratio of light energy received by the plants to the light energy released from the light source, 3) increased leaf area exposure to light, 4) reduced cooling load, and 5) reduced air and leaf temperature rise. A disadvantage of this lighting system is the low ratio of light energy emitted from the lamp to the light energy entering the diffusive optical fiber belts.

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LIGHTING APPLICATIONS

FILTERS & HEAT DISSIPATION

SPECTRAL FILTERING FOR PLANT PRODUCTION

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RADIATION AND PLANTS

In the scheme of living things, plants play the vital role of *producers* in the food chain that is crucial to all life. Animals and microbes, on the other hand, are generally *consumers* and/or *decomposers* of the foodstuffs produced by plants. Animals and humans utilize light from a portion of the electromagnetic spectrum radiated by the sun for 'vision' to enable transfer of information that relates shape and color of objects and perceives position and motion. For plants, however, light is not only a medium for information transfer; it is also a medium for energy transfer that enables the crucial processes of **photosynthesis** and **photomorphogenesis**. From light, plants may not be able to 'see' objects and to guide motion, yet they can perceive intensity, direction and spectral composition of radiation, can keep track of time and can adjust their biological processes to optimize their capacity for survival within the environment in which they are placed. Consequently, it can be surmised that plants have their own form of 'vision' related to the medium of light.

Both plants and animals have one general commonality in their perception of light. They both are sensitive primarily to the 400 to 700 nm wavelength portion of the electromagnetic spectrum. This is referred to as the visible spectrum for animals and as the photosynthetically active radiation (PAR) spectrum for plants. Within this portion of the spectrum, animals perceive colors. Relatively recently it has been learned that within this same spectral range plants also demonstrate varying responses at different wavelengths, somewhat analogous to the definition of various colors at specific wavelengths. Although invisible to the human eye, portions of the electromagnetic spectrum on either side of the visible range are relatively inactive photosynthetically but have been found to influence important biological functions. These portions include the ultraviolet (UV≈280-400 nm) and the far-red (FR≈700-800 nm).

The basic photoreceptor of plants for photosynthesis is chlorophyll. It serves to capture radiant energy which combined with carbon dioxide and water produces oxygen and assimulated carbon, used for the synthesis of cell wall polysaccarides, proteins, membrane lipids and other cellular constituents. The energy and carbon building blocks of photosynthesis sustain growth of plants. On the other hand, however, there are other photoreceptors, or pigments, that function as signal transducers to provide information that controls many physiological and morphological responses of *how* a plant grows. Known photomorphogenic receptors include **phytochrome** (the red/far-red sensor in the narrow bands of 655-665 nm and 725-735 nm ranges, respectively) and **"cryptochrome"** (the hypothetical UV-B sensor in the 280-320 nm range). Since the USDA team of W. L. Butler, S. B. Hendricks, H. A. Borthwick, H. A. Siegleman and K. Norris in Beltsville, MD detected by spectroscopy, extracted and identified phytochrome as a protein in

the 1950's, many other investigators have found evidence of its control functions in plants. Considerably less, however, is known about the yet non-isolated cryptochrome.

The information-transferring roles of photoreceptors in plants at specific spectral ranges quite naturally stimulated plant scientists and engineers to consider physically manipulating light to achieve desired physiological and morphological characteristics. One way to manipulate light is to filter it through materials that selectively transmit portions of the sun's spectrum in and near the PAR range.

NATURALLY FILTERED RADIATION

Radiation from the sun is naturally filtered in numerous ways before it reaches plants at the earth's surface. Approximately 30% of the sun's radiation actually never penetrates the earth's atmosphere but is reflected back into space by clouds and other particles. This is primarily the ultraviolet part of the spectrum. About 20% evaporates water to form clouds. Slightly less than 50% is converted into heat and reradiated into outer space as infrared radiation. Only about 0.02% of the sun's energy is actually utilized by plants.

Another interesting fact is that numerous determinations of daylight spectral distributions have consistently indicated that the red to far-red ratio (R/FR ratio) is remarkably constant. Whenever the solar angle is greater than 10°, the R/FR ratio averages 1.15 ± 0.02. Although clouds and weather conditions reduce the intensity (quantity) of radiation as much as tenfold, they virtually have no effect on R/FR. This remarkable constancy of R/FR in daylight affords a standard value against which natural radiation, modified by spectral filtering techniques, can be compared. Virtually no natural terrestrial situations permit the R/FR ratio to go higher than the 1.15 daylight value.

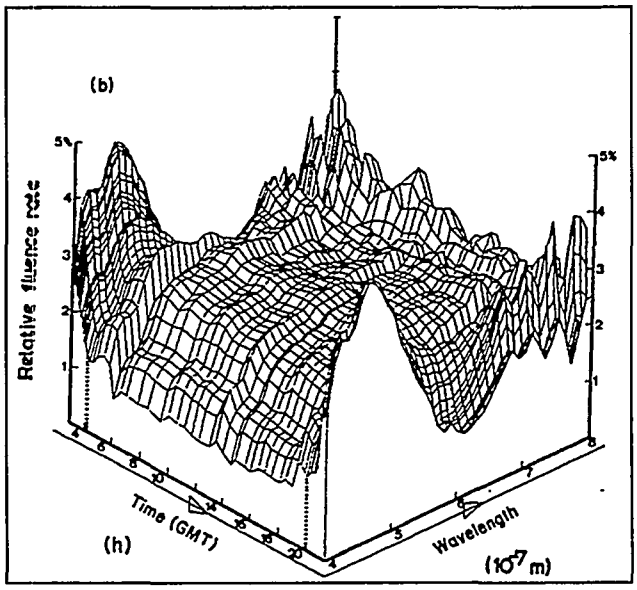

Figure 1. Light quality surface for unshaded daylight at Sutton Bonington, UK on 7 July 1981 (Hughes et al, 1984).

Diurnal fluctuations predictably occur in daylight spectral distributions across the 400-800 nm range at fixed, short time intervals during the day (Hughes et al, 1984). Two primary fluctuations were observed as the solar angle diminishes toward dawn and dusk when the proportion of direct versus diffuse radiation declines, Figure 1. First, and more markedly, there is a pronounced relative peak in the blue (B≈400-500nm) region. Secondly, since direct beams traverse a longer path through the atmosphere at this time of day, atmospheric absorption and scattering is increased. Thus shorter wavelengths are depleted and a small, yet measurable, drop occurs in the R:FR ratio. This striking rise in the B

level at dusk could suggest that a photoreceptor in this range acts to detect the end of daylight.

In the canopies of plants, vegetation absorbs R and is relatively transparent to FR. Densities and orientations of crop canopies, presence of competing plants and residues on the ground and heliotrophic movement of leaves can all contribute to far-red reflection patterns which may induce crop plants with fewer branches and longer internodes (Kasperbauer, 1987). Consequently, there can be major reductions in the R/FR ratio within plant canopies. Total irradiance may be reduced by a factor of 100 below the canopy compared to direct sunlight throughout the spectrum with the exception of the far-red (Smith, 1986). Therefore, canopy shade is a natural filter that can greatly alter the R/FR spectral composition and, subsequently, the photoreceptor response of shaded plants.

Since more than half of the plant life on the earth is underwater, it is worthy of note that light scattering and absorption by water itself and by dissolved molecules or suspended particles can alter light quality underwater. For example, at depths of one to five meters, water may have strong absorption bands at 730 nm (FR) and in the near IR. Thus, with increasing depths, radiation is effectively 'compressed' into a narrower band of wavelengths toward the lower end of the PAR, often peaking near 500 nm. Large increases in R:FR can occur with depth underwater. Shading vegetation, however, can greatly reverse this trend within a water column.

Diurnal fluctuation at dawn and dusk, densities, heliotrophic movements and orientations of plant canopies and underwater attenuation are the primary natural modifiers of light quality. Since surprisingly large amounts of light may penetrate some soils to depths of seed germination and seedling growth, it may be worth noting that the predominant impact of soil on light quality is a substantial attenuation of B and a decrease in R/FR.

FILTERING OF RADIATION

Sheltered plant environments such as controlled environment chambers and greenhouses filter radiation by virtue of the lamps which they utilize and the materials from which they are constructed.

Spectral distributions of lamps generally provide poor duplication of solar radiation. Traditional combination use of fluorescent plus incandescent lamps in controlled environments typically provide no more than one-third the photosynthetic photon flux (PPF) levels of full sunlight. Various high-intensity discharge (HID) lamps can increase PPF levels in controlled environments. Barrier materials such as glass, Plexiglas (acrylic) and water are usually placed between the lamps and the growing area to provide ventilation of the lamp space for removal of heat. Bubenheim et al. (1988) observed that spectral compositions (in the 400 to 800 nm range) produced by any of several lamp types tested were not significantly changed by filtering through any of these barrier materials. The dry-tempered, 4 mm glass and the 5 mm Plexiglass single sheet filters reduced PPF 7%. Two layers of glass separated by a 50-mm air space reduced PPF by 14%. Both materials filtered longwave radiation more than shortwave. Plexiglas, which is opaque to ultraviolet radiation, reduced shortwave radiation more than glass and removed the 360 to 370 nm peak from a metal halide (MH) lamp. A 20 to 50 mm-layer of water above both materials reduced longwave radiation for all lamps. Water was by far the most effective filter for longwave radiation, reducing it to less than 10% of total incoming radiation. Unless other

pigments are involved, neither glass nor Plexiglas should influence photomorphogenesis because they do not appreciably alter light quality in the phytochrome action spectrum.

Greenhouse Construction and Shading Materials

McMahon et al (1990) investigated the spectral filtering properties of several greenhouse construction and shading materials used to reduce solar radiation reaching plants. Construction materials tested included single-layer glass, channelled, double-walled polycarbonate (untinted and tinted Lexan by General Electric Co.), channelled, double-walled acrylic (Exolite by Cyro), double-layered and inflated clear polyethylene films (Monsanto 602, 703 and Cloud-9 and 6-mil Fog-bloc by FVG-America, Inc.) and double-layered and inflated yellow polyethylene film (6-mil Fog-bloc by FVG-America, Inc.). All materials were new and clean. Radiation measurements were made with a LI-COR LI-1800 spectroradiometer equipped with a LI-1800-10 remote cosine sensor. Readings were made on cloudless, sunny days in the Spring at solar noon when the sun was near its zenith. Table 1 summarizes the percentage transmission of sunlight through different materials for photosynthetic photons (400-700) and photomorphogenic photons both blue (B) photons (400-500nm) and R/FR ratio (660/730). The listing of narrow-band R/FR ratios should be qualified as limited in ability to correlate consistently with all plant growth parameters and is shown for comparative purposes only (Rajapakse et al, 1992). At present, because of weaknesses of any phytochrome light quality designator (narrow-band R/FR, broad-band R/FR, or phytochrome photoequilibrium (ϕ)) to correlate consistently with observed plant responses, the presentation of complete spectral data over a frequency range is probably the most useful format. PPF transmission ranged from 95% through Exolite to 44% through tinted Lexan. Percentage transmission of B light were generally 3-10% lower than that of PPF light for all construction materials except glass where they were equal. The narrow-band R/FR ratio ranged from 0.95 for yellow Fog-bloc film to 1.03 for glass as normalized to 1.00 for unfiltered sunlight.

Shading materials (McMahon et al, 1990) tested included liquid compounds and solid screening products. The liquid compounds included white latex paint and Kool Ray green (Continenal Products Co., Euclid, OH). They were uniformly sprayed one time until close to runoff onto a piece of clean glass tilted to approximate the angle of a greenhouse roof. The screening products included the following: black, woven fabric (55% shade Chicopee, Inc.); black, knitted fabric (50% shade V-J Weathershade); vinyl coated polyester fabric with aluminized pigment (80% shade Enduro Silver by Handlee Enterprises); green vinyl coated polyester fabric (60 % shade Enduro Green by Handlee Enterprises); green, woven saran fabric (63% shade Chicopee Lumite) and Cravo LS-7 green polyester fabric (Cravo Ltd.). Table 2 summarizes photosynthetic and photomorphogenic light for the shading materials. Transmission properties varied appreciably for these shading materials. PPF reductions, however, were within 5% of manufacturer's specifications for all materials. Percentage transmission of full sun PPF ranged from 21% for Cravo LS-7 to 49% for V-J Weathershade. Unlike the construction materials, some shading materials transmitted a higher percentage of B light than PPF. For example, Cravo LS-7 transmitted 6% more B light than PPF as a percent of full sun. On the other hand, Kool Ray green compound transmitted only 7% of the B compared to 35% of the PPF, or 28% less B than PPF. The remaining shading materials transmitted from 0 to 3% less B than PAR. The

photomorphogenic R/FR ratio normalized to full sunlight (1.00) ranged from 0.94 to 1.06 for all shading materials except for 0.18 for Cravo LS-7 polyester fabric and 0.55 for Kool Ray compound.

TABLE 1. Spectral transmission properties of selected greenhouse coverings.

Material	Photosynthetic Light	Photomorphogenic Light	
	Photosynthetic Photon Flux (PPF) (400-700 nm) ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Blue Light (400-500 nm) ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Red/Far-red (660/730 nm)* Ratio
	% of full sun		Normalized to full sun
Sunlight	100	100	1
Glass	93	93	1.03
Monsanto 602	88	83	0.99
Monsanto 703	67	63	0.96
Monsanto Cloud-9	52	48	0.96
Fog-bloc 6 mil	68	64	1.02
Fog-bloc 6 mil, yellow	63	53	0.95
Exolite	95	92	0.98
Lexan	78	75	0.96
Lexan, tinted	44	38	0.96

Non-unity values for R/FR ratios of the construction and shading materials indicate alterations of light quality which could potentially modify growth of plants exposed to light transmitted through the materials. Some plant "stretching" may be attributed to reduced light under artificial shading, analogous to natural filtering in plant canopies. Altered light quality, however, will

TABLE 2. Spectral transmission properties of selected nursery and greenhouse shading materials.

Material	Photosynthetic Light	Photomorphogenic Light	
	Photosynthetic Photon Flux (PPF) (400-700 nm) ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Blue Light (400-500 nm) ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Red/ Far-red (660/730 nm)* Ratio
	% of full sun		Normalized to full sun
Sunlight	100	100	1
Kool Ray	35	7	0.55
Paint	41	39	1.01
Chicopee	45	44	1
V-J Weathershade	49	49	1.01
Enduro Silver	21	18	0.94
Enduro Green	42	40	1.06
Chicopee Lumite	35	34	0.96
Cravo LS-7	21	27	0.18

*Any current phytochrome light quality designator (narrow-band R/FR, broad-band R/FR, or phytochrome photoequilibrium (ϕ)) fails to correlate consistently with observed plant responses. The presentation of complete spectral data over a frequency range is probably the most useful format, if available.

also probably elongate internodes and cause greater plant heights. Phytochrome modifications in growth patterns might be particularly expected under Cravo LS-7 and Kool Ray shading materials. Moreover, the B light filtering characteristics of materials like yellow Fog-bloc polyethylene construction film and Cravo LS-7 green fabric and Kool Ray compound shading materials could potentially alter both photosynthetic and photomorphogenic activity in plants.

A further observation by McMahon et al (1990) was that the construction and shading materialscould be grouped as *non-selective* and *selective* filters over the radiation spectrum. The neutrally colored (black, white and silver) shading materials characteristically transmitted all wavelengths uniformly (non-selectively) as illustrated by the percent spectral transmission plot in Figure 2 for V-J Weathershade knitted black shade fabric over 400 to 850 nm. In contrast, the construction materials and the green shading materials were variable (selective) filters as illustrated in Figure 3 for percent spectral transmission with Kool Ray shading compound.

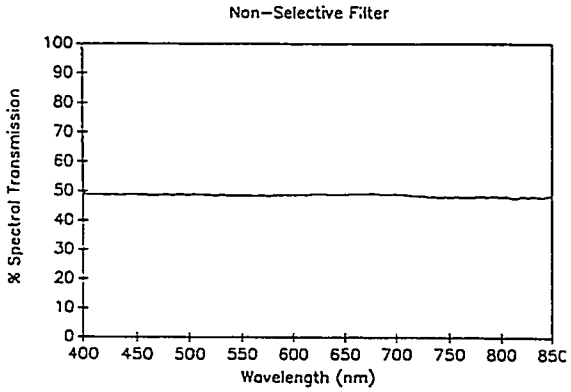

Figure 2. Example of a non-selective filter using spectral transmission values for V-J Weathershade 50% knitted black shade cloth. (McMahon et al, 1990)

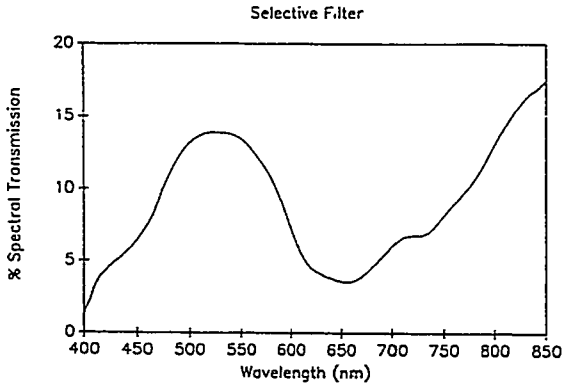

Figure 3. Example of a selective filter using spectral transmission values for Kool Ray green shading compound. (McMahon et al, 1990)

Channelled Plastic Fluid-Roof Filters

Channelled, double-walled acrylic and polycarbonate plastic greenhouse glazings have provided the opportunity to use water or liquid dyes as filtering materials contained in the hollow channels of the glazing. These filters have been variously called liquid optical filters (LOF), optical liquid filters (OLF), liquid radiation filters (LRF) and liquid spectral filters (LSF). They can both filter out infrared rays (heat) while transmitting PPF and can with colored liquids selectively transmit various parts of the electromagnetic spectrum to influence plant development.

In the 1970's, French scientists investigated and patented both double-layered acrylic and glass structures with fluid flowing within an enclosure between glazing layers (Chiapale et al, 1977; Chiapale et al, 1978). They used water and copper chloride ($CuCl_2$) in a closed loop flow as well as water over infrared absorbing glass as a lower layer. Their primary interests were modelling energy balances. They experienced reductions in earliness and yield with tomatoes, probably because of limited biological considerations for depressed CO_2 levels in atightly closed

environment. In the early 1980's, American, French, Canadian and Israeliscientists conducted further studies utilizing channelled plastic sheets (Benschop et al, 1980; van Bavel et al, 1981; Chiapale, 1981; Weichman, 1981; Sadler, 1983; Sadler and van Bavel, 1984; Tross et al, 1984). Benschop et al (1980) confirmed the earlier observations of Chiapale et al (1977) that circulating aqueous $CuCl_2$ absorbed infrared radiation. Simulation models of energy flow in the plastic fluid-roof greenhouses by van Bavel et al (1981), in collaboration with Chiapale et al (1983), predicted 20-40% reductions in heating requirements and virtual elimination of the need for forced ventilation. In experiments at College Station, TX, predictions of the model were confirmed. A later dynamic simulation model by Sadler and Van Bavel (1984) predicted various temperatures in the plastic fluid-roof greenhouse within 2-3 °C and net radiations within 20-30 W m^{-2}. Tross et al (1984) confirmed close approximations of his model of an optical liquid filter (OLF) channelled polycarbonate fluid-roof greenhouse with a triangular, prism-shaped structure. A patent for specific copper chloride solutions intended for fluid-roof applications was issued in 1988 (Navon and Gan, 1988). For a number of years, scientists (Kopel et al, 1991; Levi et al, 1991; Zeroni et al, 1991) have been investigating plant culture in a full-scale (330 m^2), channelled polycarbonate LRF greenhouse in the Negev Desert in Israel. They were able to reduce temperatures sufficiently within the greenhouse to practice daylong CO_2 fertilization except for a few midday hours in mid-summer when ventilation was necessary. In addition to circulating aqueous $CuSO_4$, the Negev project has claimed, yet not disclosed for proprietary reasons, a less noxious fluid dye. Pollock et al (1992) established temperature profiles over the length of a 9.8-m long by 8-mm thick channelled polycarbonate panel for various steady-state combinations of flow rate and inlet temperature of circulating $CuSO_4 \cdot 5H_2O$ aqueous solutions. The primary factor for efficient cooling of a fluid-roof panel was adequate fluid flow rate.

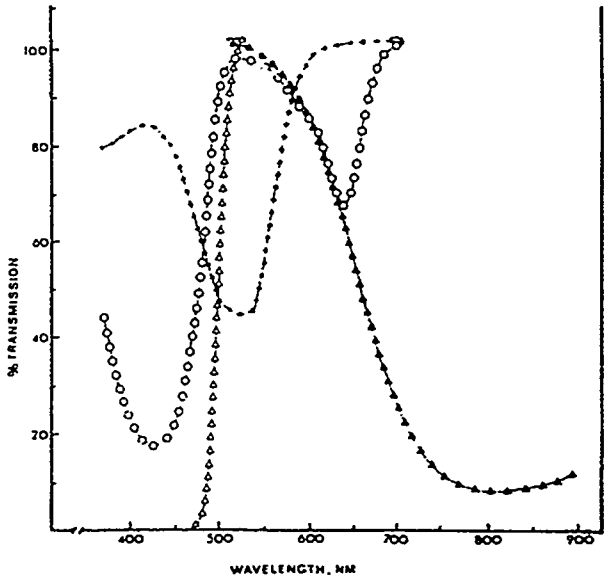

Figure 4. Light transmission of water with different dyes in the range 350 to 900 nm wavelength, pure water; ▲, blue; ○, green; △, yellow; *, red. (Mortensen et al., 1987)

Selective filtering of light primarily to influence photomorphogentic responses of plants was demonstrated in Norway in both solar-exposed growth chambers and a production greenhouse using green (#1358), red (#1409 Tetrazine) and yellow (#14123 Red 2G) dyes (all from D. F. Anstead Ltd.) and 2.5% $CuSO_4$ in channelled acrylic sheets (Mortensen et al, 1987; Mortensen and Stromme, 1987). Neutral shading was used so that the PPF levels were similar at all light qualities. The light transmission properties of these aqueous filters are shown in Figure 4. (Ciba-Geigy # 178) that filtered out much R but not FR and 16% w/v $CuSO_4 \cdot 5H_2O$ which filtered more FR than R light. Neutral shading was used to get constant PPF levels (about 40-45% PPF reduction) with each filter. Figure 5 summarized the light transmission properties of the liquid filters tested at Clemson. Table 3 compares the broad band (R=600-700 nm; FR=700-800 nm) R/FR ratios for the liquid spectral filters used by the Norwegian and Clemson investigators and lists the narrow band (R=655-665 nm; FR=725-735 nm) R/FR ratios for the Clemson filters.

Plant Responses to Spectral Filters

Mortensen and Stromme (1987) observed that the blue $CuSO_4$ filter (high R/FR ratio) reduced dry weight in chrysanthemum (*Chrysanthemum x morifolium* Ramat.), tomato (*Lycopersicon esculentum* Mill.) and lettuce (*Lactuca sativa* L.) compared to natural sunlight and green, yellow and red filters. Plant heights for chrysanthemum and tomato were reduced by the $CuSO_4$ filter and increased by the green and yellow filters compared to natural light. In all species except poinsetta (*Euphorbia pulcherrima* Willd.), leaf area was significantly reduced by $CuSO_4$. Green and yellow filters increased leaf area in tomato compared to natural light. Lateral bud breaks were stimulated by the $CuSO_4$ filter in chrysanthemum and tomato, but inhibited by green and yellow filters in tomato. $CuSO_4$ filters led to dark green leaves while green and yellow filters caused light green leaves in chrysanthemum, tomato and lettuce. Light quality was similar in three experiments at decreasing PPF levels over the period from July to October.

McMahon et al, (1991) observed that two species of chrysanthemum (*Dendranthema x grandiflorum* (Ramat.) 'Spears' and 'Yellow Mandalay') grown under $CuSO_4$ filters had reduced heights, reduced internode lengths and increased chlorophyll content compared to controls grown under water- and/or air-filled channelled panels. Reduced B light with the red dye decreased chlorophyll content of pinched plants. Pinched plants under $CuSO_4$ filters and long days developed fewer nodes than controls because of the formation of abnormal capitula. Controls and unpinched plants from the other light treatments developed more nodes before forming similar abnormal capitula. Stem diameters and leaf areas did not differ among light treatments.

TABLE 3. Broad and narrow band R/FR ratios for various liquid spectral filters used by Norwegian and Clemson investigators.

		R/FR Ratio*	
Country	Filter	Broad band**	Narrow band***
Norway	Water	1.00	--
	$CuSO_4$(2.5%)	4.10	--
	Red	0.99	--
	Green	0.82	--
	Yellow	1.00	--
Clemson	Water	1.05	1.16
	Air	1.05	1.16
	$CuSO_4$(16%)	7.20	3.30
	Red	1.03	1.16
	Blue	0.70	0.99

* Any current phytochrome light quality designator (narrow-band R/FR, broad-band R/FR, or phytochrome photoequilibrium (ϕ)) fails to correlate consistently with observed plant responses. The presentation of complete spectral data over a frequency range is probably the most useful format, if available.

* R = 600-700 nm; FR = 700-800 nm

** R = 655-665 nm; FR = 725-735 nm

(Data from Mortensen and Stromme, 1987 and from McMahon et al, 1991)

Further studies of the influence of liquid spectral filters on regulation of chrysanthemum by Rajapakse and Kelly (1992) utilized 4, 8 and 16 % (w/v) $CuSO_4 \cdot 5H_2O$ filters in channelled polycarbonate panels. These filters reduced PPF from natural irradiance inside a greenhouse (average ≈950 μmol m^{-2} s^{-1}) by 26, 36 and 47 %, respectively. Control treatments were shaded with plastic shade cloth to insure equal PPF with the $CuSO_4$ filters. Following a 4-week experimental period, average plant heights were approximately 40% shorter and average internode lengths were 34% shorter than those of control plants. Reductions in plant heights and internode lengths were observable within one week after initiation of the experiments. Total leaf area was reduced by 32% and leaf size by 24% under the $CuSO_4$ filters. Specific leaf weight (leaf fresh weight/leaf area), however, was greater under $CuSO_4$ filters than under the control treatment, indicating thicker leaves. Other observations under $CuSO_4$ filters were that fresh and dry leaf weights decreased by 30% and fresh and dry stem weights decreased by 60%, resulting in increased relative dry matter accumulation into leaves and reduced accumulation in the stems.

A similar study by Rajapakse and Kelly (1991) sought to determine the involvement of gibberellins in regulation of plant height under $CuSO_4$ filters. Using 6% $CuSO_4$ filters which reduced average PPF by about 34%, they evaluated the response of chrysanthemum to GA_3 and daminozide. Weekly applications of GA_3 increased plant height under both the $CuSO_4$ and control filters, but by about 20% greater under the $CuSO_4$ than under the control filter. Daminozide, a GA inhibitor, reduced plant height under both filters, but more under the control filter. Under both filters, plant height reduction caused by daminozide was prevented by GA_3 application. It appears that GA_3 may be partially involved in plant height reduction under $CuSO_4$ filters.

Rajapakse and Kelly (1993) also observed with the same species of chrysanthemum that, after 28 days, cumulative transpirational water loss of plants under $CuSO_4$ filters was approximately 37% less than of control plants under water-filled panels. Expressed as transpiration rates per leaf area, however , plants under both filters responded similarly, suggesting that the reduced cumulative water loss was a result of smaller plant sizes under $CuSO_4$ filters. Plants grown under $CuSO_4$ filters had slightly lower (10%) stomatal density than control plants. The size of individual stomata were not altered by the $CuSO_4$ filter, yet total number of stomata and total stomatal pore area per plant was about 50% less in plants grown under $CuSO_4$ filters because of less leaf area. Results such as these suggest that altering light quality might reduce water use and fertilizer demands in addition to controlling growth of plants in greenhouse production.

In similar studies using the same liquid spectral filters with miniature roses (*Rosa x hybrida* 'Meirutral'), McMahon and Kelly (1990) noted that plants were significantly shorter (25 to 35%) and had higher leaf chlorophyll (20 to 25%) when grown under the $CuSO_4$ filters (high R/FR ratio). Light quality treatments, however, did not affect the number of flower buds or the number of buds showing color. Differences in plants grown under filters deficient in B light or low in R/FR ratio were not observable, indicating that these light quality alterations were less influential in morphology of 'Meirutral' pot roses. Modifications of plant morphologies for both roses and chrysanthemum, as well as unpublished results with exacum, geranium and poinsetta were observed by McMahon and Kelly (1990) to be comparable to morphologies of compact, attractive, dark green plants being widely achieved commercially by the application of chemical growth regulators such as butanedioic acid mono (2,2-dimethylhydrazide), daminozide, B-Nine, Alar and uniconazole. The use of daminozide on edible crops has already been prohibited, and its use on other greenhouse crops is being continually scrutinized. Manipulation of light quality

to control plant morphology could be an attractive, natural alternative to chemical grouth regulators.

Rajapakse and Kelly (1994) also investigated the influence of spectral filters on the postharvest quality of potted miniature roses (*Rosa x hybrida* 'Meijikatar'). Again they observed that $CuSO_4$-filtered light significantly reduced plant height and internode length and increased the number of lateral shoots. Some seasonal variability was observed, however. $CuSO_4$ filters slightly accelerated flowering in early spring but slightly delayed flowering in late spring and summer. Total numbers of flowers were unaffected but the sizes of flowers were increased by $CuSO_4$ filters. Leaf sucrose and starch concentrations were reduced by 40% and 65%, respectively, while leaf glucose and fructose concentrations were unaffected by $CuSO_4$ filters. Plants grown under $CuSO_4$ filters had slightly more yellow leaves than control plants after shipping at 4 or 16°C. This response is probably a result of reduced carbohydrate status.

Rajapakse et al (1993) also investigated the responses of chrysanthemums (*Dendranthema x grandiflorum* (Ramat.) 'Spears and 'Bright Golden Anne') to end-of-day (EOD) R and FR exposures. At the end of 9-h light exposure inside a greenhouse, plants grown under $CuSO_4$ filters were exposed to either a R- or FR-light treatment of 15 minutes before being placed in a 15-h dark period. The R-light treatment was obtained inside a specially designed treatment box with 2.1 W m^{-2} in the 600-700 nm range obtained from six 40-W cool white fluorescent bulbs filtered through a Roscolux No. 19 acetate filter (Rosco, Port Chester, NY). Similarly, the FR treatment was obtained with 12.0 W m^{-2} in the 700-800 nm range obtained from two internal reflector incandescent bulbs filtered through a polyacrylic sheet of cast acrylic No. 2711 dark red filter (Rohm and Haas, Bristol, PA). EOD light treatments were given for 21 consecutive days. Non-EOD-treated plants remained in the growth chambers and were covered with black cloth during the 15-h dark periods. As observed in other experiments, light through $CuSO_4$ filters significantly reduced plant height, internode length and stem dry weight. Exposure to EOD-FR reversed the reduction of plant height, internode length and stem dry weight by $CuSO_4$ filters to a level comparable with plants receiving no EOD treatment. EOD-R treatment reduced plant height and stem dry weight of 'Bright Golden Anne' plants grown under the control filter, but had no effect under the $CuSO_4$ filter. EOD-FR treatment did not significantly alter plant height and stem dry weight under the control filters. In 'Spears' plants, EOD-R reduced stem dry weight under control filters but did not reduce stem or internode elongation. These results suggest that phytochrome may be involved in controlling plant response under the $CuSO_4$ filter. There is evidence, however, to suggest that an additional mechanism may be influencing stem and internode elongation.

Additional, non-liquid spectral filter experiments at Clemson have investigated EOD-R and -FR treatments of watermelon (*Citrullus lanatus* (Thunb.) Matsum & Naki cv.Sugar Baby) and tomato (*Lycopersicon esculentum* Mill. cv. Mountain Pride). Decoteau and Friend (1991) used the same R- and FR-treatment chambers with acetate and acrylic filters described earlier to treat 2-week old (two true leaf stage) watermelons. After four days of EOD-FR treatment, petiole lengths were longer and the angle between petioles more acute than in plants treated with EOD-R or non-EOD treated (control) plants. The EOD-FR promotion of internode length, petiole angle and petiole elongation was reversible by immediately following the FR with R light, implicating phytochrome involvement in growth regulation of watermelon. Plants treated 21 days with EOD light and subsequently grown 14 days without EOD treatment exhibited no residual EOD light effects on internode elongation as compared to plants receiving no EOD light treatments. Two-week pretreatments of tomatoes with EOD-R light before placement in a

greenhouse under ambient light conditions increased the number of flowers before the first harvest but had no effect on subsequent fruit production as compared with plants receiving similar FR-light treatments or no EOD treatments (Decoteau and Friend, 1991). In a second experiment with tomatoes when cool white fluorescent lights (high in R) were used to supplement natural light in an unshaded greenhouse for one hour before the end of the natural photoperiod, Decoteau and Friend found reduced plant height and total leaf length but no subsequent influence on fruit production when transplanted into the field. The supplemental R light (as provided by the fluorescent bulbs) probably affected plant growth by nullifying the EOD reduction in R/FR associated with the end of the daylight. These EOD treatments of plants suggest that light manipulation in the greenhouse may not need to be performed throughout the entire daylight period, but rather may be performed only for short intervals at the end of the daylight period.

SUMMARY

Research to date suggests that spectral filtering can be an effective alternative to chemical growth regulators for altering plant development. If properly implemented, it can be non-chemical and environmentally friendly. The aqueous $CuSO_4$ and $CuCl_2$ solutions in channelled plastic panels have been shown to be effective filters, but they can be highly toxic if the solutions contact plants. Some studies suggest that spectral filtration limited to short EOD intervals can also alter plant development.

Future research should be directed toward confirmation of the influence of spectral filters and exposure times on a broader range of plant species and cultivars. Efforts should also be made to identify non-noxious alternatives to aqueous copper solutions and/or to incorporate these chemicals permanently into plastic films and panels that can be used in greenhouse construction. It would also be informative to study the impacts of spectral filters on insect and microbal populations in plant growth facilities. The economic impacts of spectral filtering techniques should be assessed for each delivery methodology.

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PRINCIPLES OF LIGHT ENERGY MANAGEMENT

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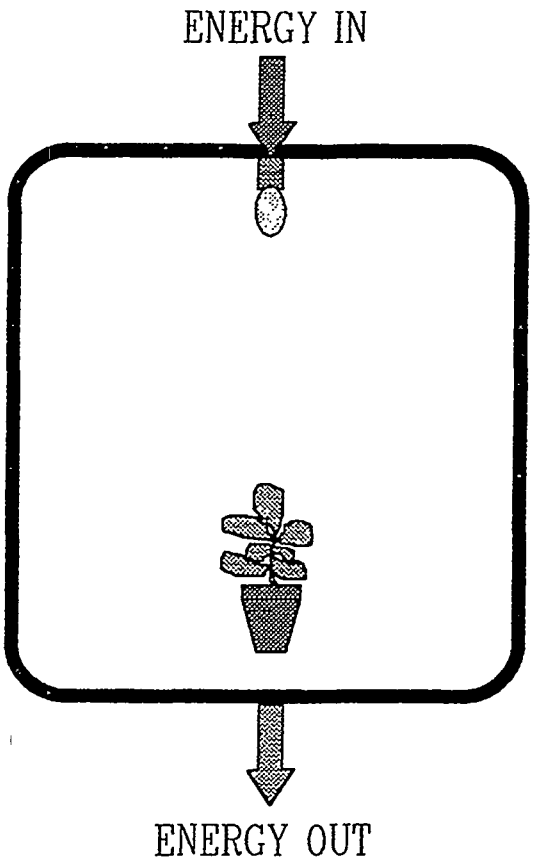
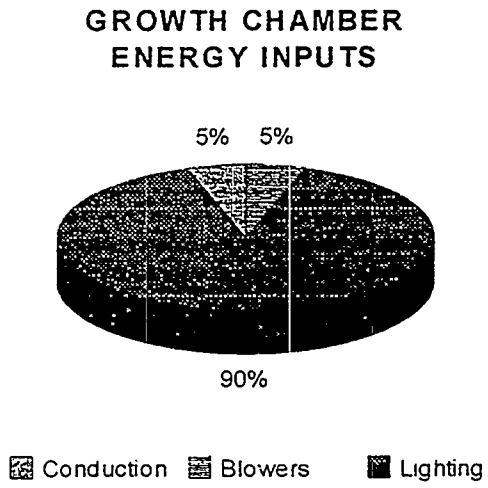
This paper presents a review of several methods of minimizing the effects of the excess energy associated with lighting systems for plant growth.



BASIC GROWTH CHAMBER

In these considerations the growth chamber is defined as an enclosure in which temperature, humidity and light can be maintained at one or more desired levels, an envelope in which the energy that goes in must come out. Some of the effects of the lighting energy on chamber and light source performance are identified and illustrated. Six methods of dealing with the lighting energy are reviewed.

Of all of the energy relations within a growth chamber those which are related to the lighting are dominant. The energy associated with wall transmission and chamber operating equipment are not considered. Experimental requirements such as fresh air and internal equipment are not considered. Only the energy associated with providing and removing the energy for lighting is considered.

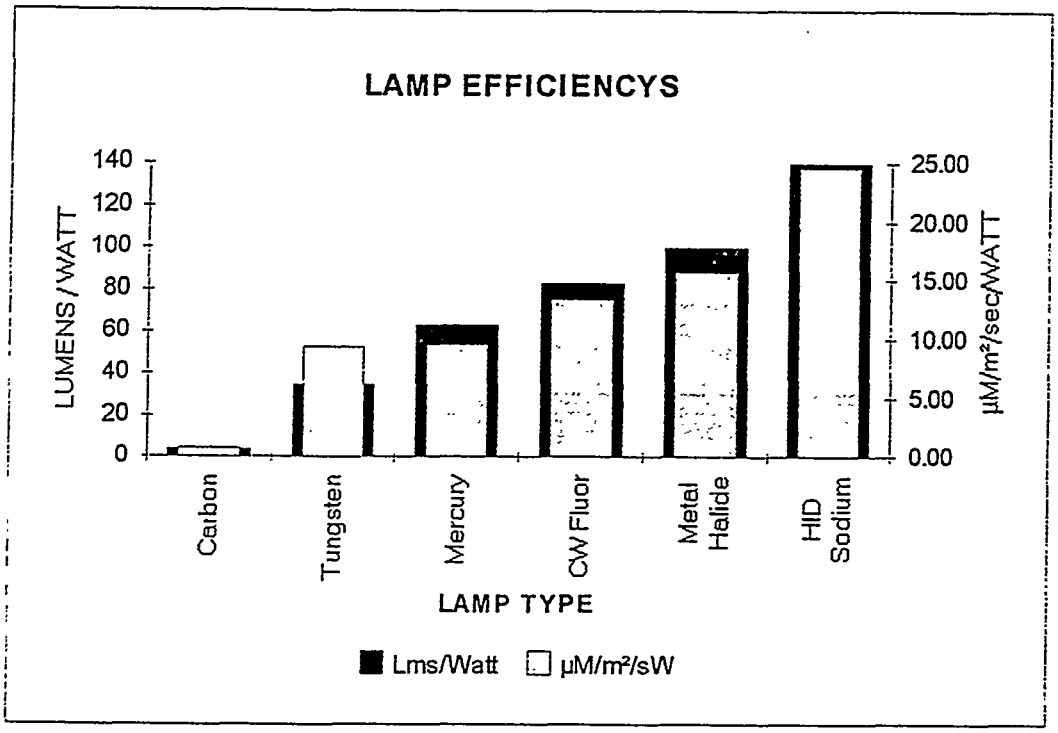


To provide radiation at any chosen level two separate factors must be considered. They are the means chosen to provide the radiation and the means chosen to remove the unwanted energy associated with that radiation. The energy associated with the delivery of the desired conditions must be balanced with the removal of the excess energy involved.

In all growth chambers energy gains and losses occur at varying levels at all times. It is desirable to maintain the closest possible desired conditions with the minimum of control and energy. The less energy required to maintain the controlled environment the more easily it is controlled. The more easily it is controlled the more evenly it will perform. The more evenly it performs the less control cycle is imposed on the mean conditions. The less control cycle the less maintenance it will require. The less maintenance it requires the longer it will meet its specifications.

Several controllable variables are available for obtaining the required radiation which if optimized can substantially lower the total energy required to obtain the necessary radiation and operate the chamber.

All lamps are not created equal. All lamps convert a portion of the energy they consume into radiation between the 400 and 700 nanometer wavelengths. This radiation varies between 10 and 40% of the total energy applied. Radiation between these wavelengths is measured in foot-candles for purposes of vision and in moles of quanta per meter^2 per second for plant growth. The following chart shows the relationship between a number of commercially available light sources.



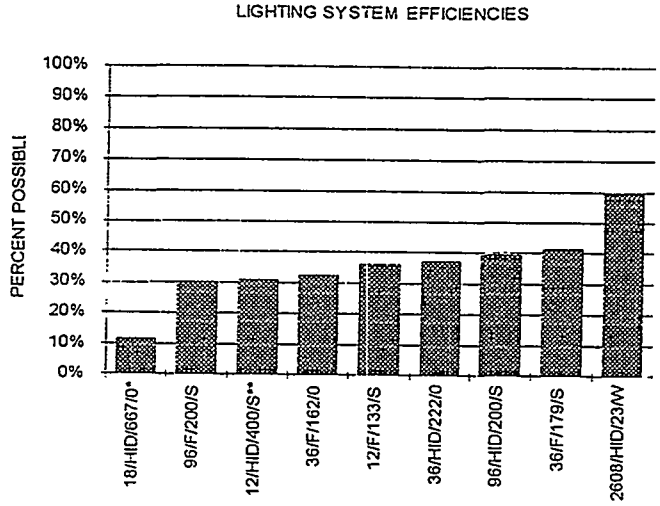
By choice of lamp type it is possible to reduce the input energy significantly for the same radiation. This choice must be consistent with the light quality that is necessary for the research objectives.

Also consistent with the objective of minimizing the energy required to provide the necessary radiation for plant growth, is the consideration of the system used to deliver the radiation from the source to the plants. Measurements of growth chambers with different light delivery systems show efficiencies varying from 30% to 60%. This efficiency is the ratio of the radiation measured at the growing surface to the manufacturer's rating of the radiation emanating from a standard lamp.

Selecting the most efficient light delivery system can reduce the required energy input by as much as 50%.

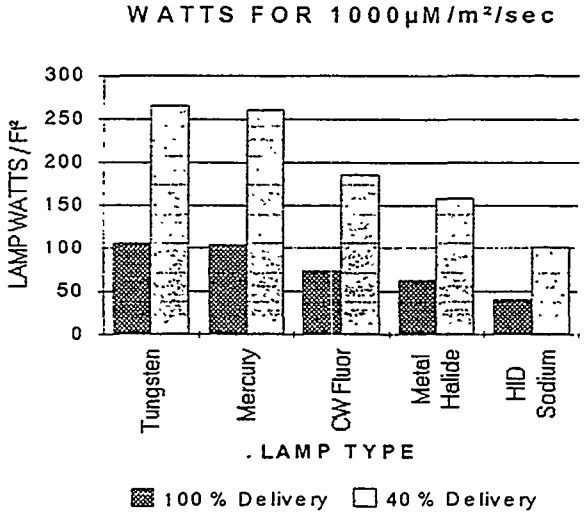
Combining the information in the two previous charts the input energy required to deliver an equal amount of radiation to a growing surface may be calculated for two different delivery

systems. The systems selected are the ideal, or 100% of the source radiation and 40%, the high end of the range of most currently available growth chambers.



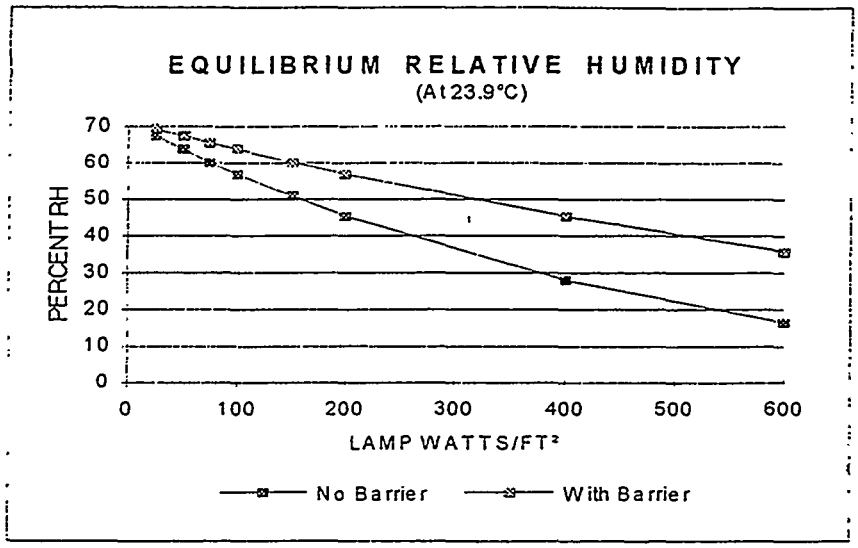
The indicated **Chamber Code** for the nine different growth chambers and rooms is as follows: Area (ft^2)/Light Type (Fluorescent or HID)/ Watts Ft^{-2}/Barrier Type. The Barrier Type is 0 (none); S (single); W (water)

* > 1500 μmol $m^{-2}s^{-1}$ **> 700 μmol $m^{-2}s^{-1}$.



Before choosing which method to use to remove the unwanted heat of lighting the effects of two interactions should be understood. First the effect on the system's equilibrium relative humidity which is dependent on the amount of energy that must be removed by the primary environmental control system and second the effect on the light output of the source which is dependent on the rate heat transfer from the lamps and their resulting operating temperature.

The equilibrium relative humidity of the system, is defined as that maximum relative humidity that would be maintained indefinitely in the system without the addition of moisture. This is established by the coldest part of the system which is in contact with the system air and becomes the controlling dew point. This temperature in turn is dependent on the amount of heat removal that is necessary by the primary environmental control system. The less lamp heat to be removed the less depression of the equilibrium dew point.

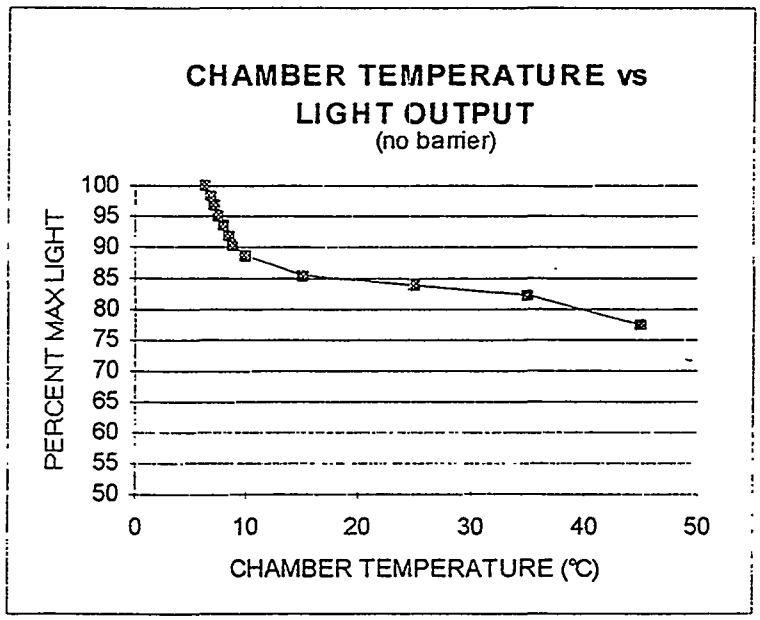


While the natural dew point, or minimum coil temperature, is primarily dependent on the amount of heat to be removed, it can be influenced by the rate at which chamber air is circulated over the cooling surfaces. In general practice commercial growth chambers have air moving at volumes per square foot between 30 and 60 cubic feet per minute. The preceding chart is based on an air flow of 50 cubic feet per minute. A simple, single layer barrier is considered providing a generic heat load reduction of 50%. The calculations for this chart assume chamber temperature of 23.9 C, a constant temperature cooling surface and a 5.5 C change in air temperature across the cooling coil. Loads not considered but capable of influencing dew point depression include heat gain from ambient, heat loads from equipment, fresh air heat and moisture loads and the temperature cycle of the cooling surfaces associated with control systems.
The range of lamp loads is taken from chambers built and operated over a period of years. The PhytoFarm in DeKalb, Illinois operated for 12 years with a light load of 23 watts/ft², the walk-in chambers designed in 1961 for the Cornell University Bio Climatic Laboratory

project provided 200 watts/ft² and newer chambers reaching for ever higher light intensities have exceeded 600 watts/ft².

As can be seen from the chart the effect on humidifying requirements increases rapidly as the lamp wattage increases in response to the need for higher light intensities.

Another consideration of the energy management in a growth chamber relates to the temperature effect of the lamp environment on the lamp's output. The following chart illustrates this effect on closely spaced 1500 milliamp fluorescent lamps.

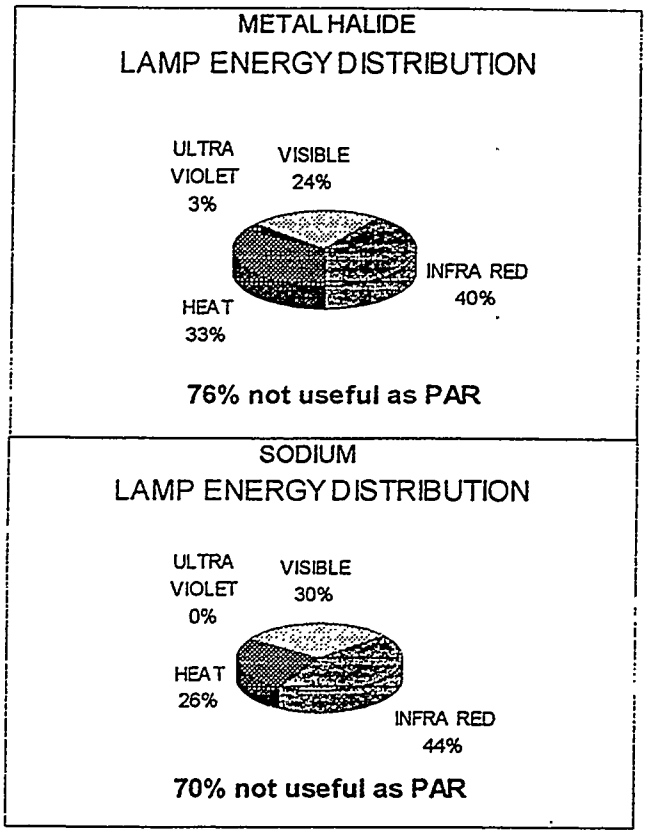


For this chart a 36 ft² growth chamber was operated with full lights. The initial temperature was 45 C. The temperature was reduced in steps while the light intensity was recorded. At lamp environment temperatures greater than 15 C the lamps are operating at 15 to 23% less than their optimum capability. The optimum lamp environment is seldom the temperature required for the experiment. This temperature light relationship in growth chambers was recognized and described in the early work on plant growth chamber development at Cornell University in 1958. More detailed information is available in US Patent Numbers No's. 3,393,728, Davis, N, 1968 and 3,604,500, Davis, N, 1971.

To reduce unnecessary humidification, maximize the light source efficiency and minimize the energy required for lighting and chamber operation it is important to manage the energy balances within a growth chamber.

After minimizing the input energy by selecting the most efficient light source and the most efficient delivery system appropriate for the application, the issue of minimizing the heating effect of the light energy on the growth chamber conditions may be addressed. In general 70% of the energy supplied to the lamps does not produce any Photosynthetically Active Radiation but impacts on heat removal requirements, dew point depression and lamp performance.

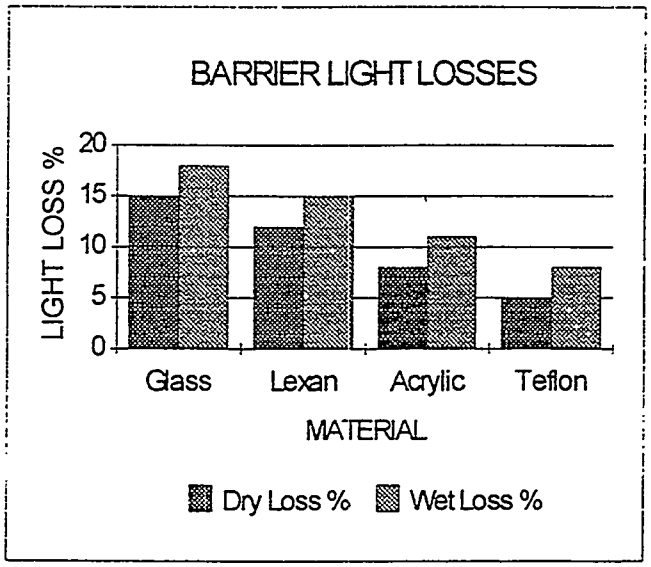
Using High Intensity Discharge, Metal Halide and Sodium lamps rated for 400 watts the energy available for removal can be illustrated.



With two of the most common light sources for supplying high light intensities in plant growth chambers all but 24 to 30% of the lamps wattage could be removed with out loss of light. Some of this light will be lost in barriers. Heat recovery, at best, has only 70% of the lamps wattage that can be recovered. Most secondary cooling systems can prevent up to 75% of this energy from entering the growing area. Temperature controlled, water filtered systems can prevent up to 90% from entering the growing area.
The methods for removal of this heat fall into two classifications. It may be absorbed into the primary environmental control system or it may be separated, to varying degrees, from the

primary system and removed by a secondary removal system. This secondary system may employ direct expansion refrigeration, cool water or air as a heat rejection medium.

Secondary heat removal systems use some form of light transmitting barrier to isolate the lamp environment from the growing environment. The choice of barrier material from a thermal separation concern is less important than the effect on light loss and spectral altering that may occur with some materials. The following chart illustrates the light loss of several materials suitable for use in growth chambers. When used in conjunction with a film of water the increase in heat recovery exceeds the loss in light.

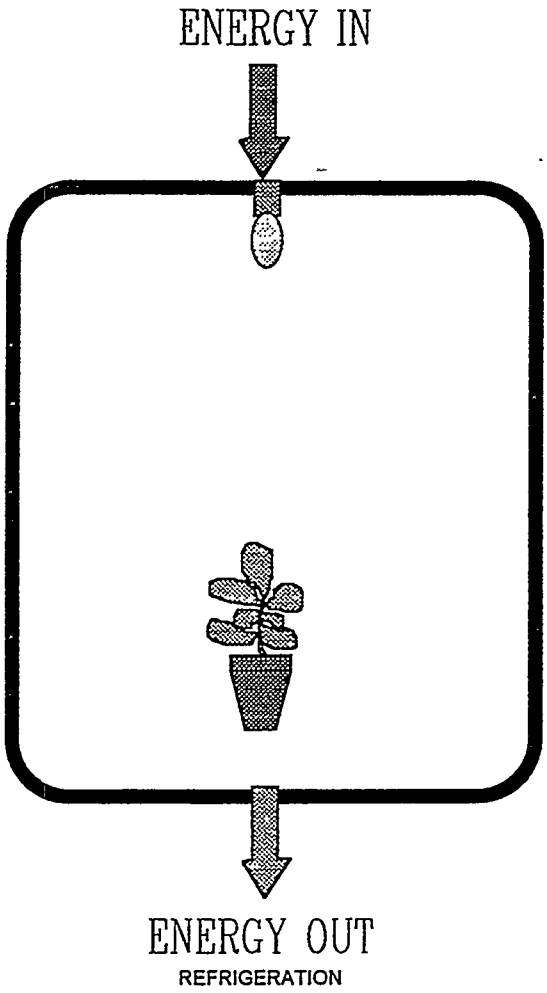


The following pages describe several methods for separating and collecting the unwanted heat in preparation for its removal by the secondary system.

NOTE:

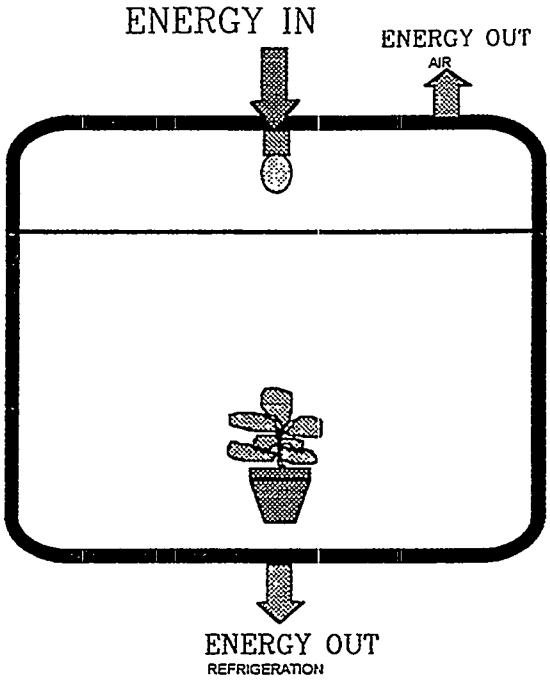
This paper is intended as a check list when considering light associated heat management in controlled environments. Before applying any of the described methods a careful analysis or consultation with an experienced source should be completed.

DIRECT ABSORPTION INTO THE PRIMARY COOLING SYSTEM



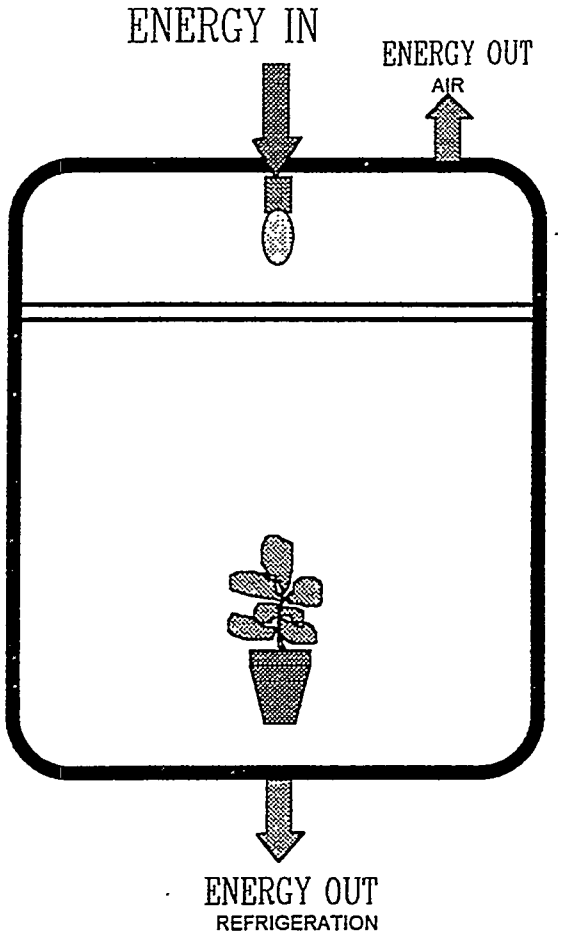
This system represents the base from which all energy management programs derive. The primary heat removal system is defined as that system which provides control of the environment in which the plants are located. In this case it must provide control of the growing environment while removing the full input energy of the lighting system. Even with the best choice of light sources and light delivery systems this system requires the most energy removal and the most humidificaton of all of the systems considered. It also represents the most temperature dependent lighting system in chambers which have variable lighted temperatures. This is the least complex, least flexible and the least efficient of the approaches considered for providing a controlled environment for plant growth.

ABSORPTION INTO A SECONDARY COOLING SYSTEM



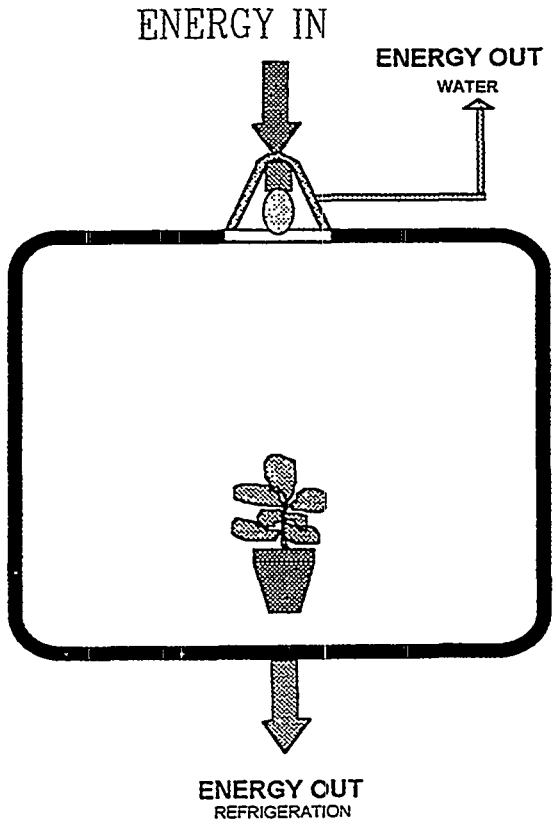
In systems utilizing a secondary cooling system for growth chamber heat removal some form of isolation of the lamps from the growing area is required. The earliest and still the most widely used is a single transparent membrane separating the lamp area from the growing area. This membrane is most frequently an acrylic plastic, obtainable as either Ultra Violet transmitting or Ultra Violet absorbing. It is described by its manufacturer as 'optically pure' and has the same transmission losses, 8%, in all thicknesses up to 1 full inch. It's losses are surface phenomena of 4% per surface. The early uses of this type of system employed a flow of outside air through the lamp area to remove the heat generated by the lamps. These systems, while reducing the cooling load on the growing area, were plagued with maintenance problems. Even good filters could not keep dust and bugs from littering the top surface of the membrane. They also suffered from a lack of temperature control as the seasons changed. An improved system was developed and described in the Cornell work. A closed system with recirculating air and separate cooling coils provided a temperature controlled, dust free method of removing the heat from the lamp area Light intensity and chamber temperature were more independent variables. As much as 50% of the lamp energy can be removed from the growing area. With the critical temperature for fluorescent lamps being higher than the cooling water available from most cooling towers it is possible to remove this heat without the requirement for more refrigeration. More detailed information on this method is available in US. Patent Number 3,393,728, Davis, N, 1968.

IMPROVED ABSORPTION INTO A SECONDARY COOLING SYSTEM



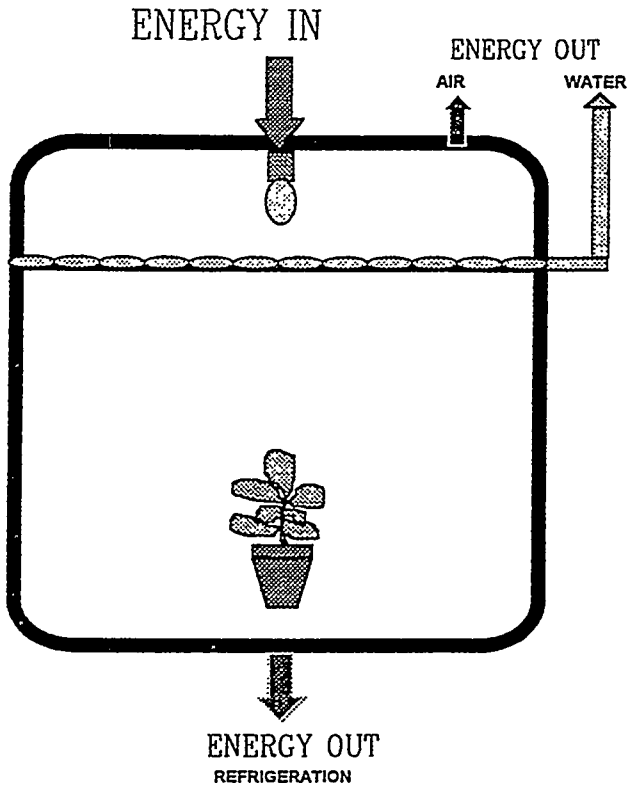
As growth chamber temperature requirements became lower and relative humidity requirements became higher the need for better isolation between the lamps and the growing area became more important. At low temperatures, where refrigeration efficiencies are declining, any lessening of the heat load is important. When the lights were off at high relative humidities and high temperatures it was possible to get condensation on the underside of a single barrier while at low chamber temperatures and high ambient humidities it was possible to get condensation on the top surface of the barrier. A double barrier reduces this tendency. By assuring a highly reflective housing for the lamp area surface reflection losses are minimized. This system is applicable for chambers requiring extreme conditions. More detailed information is available in US. Patent No. 3,447,595, Davis, N, 1969.

ABSORPTION INTO A WATER JACKETED REFLECTOR



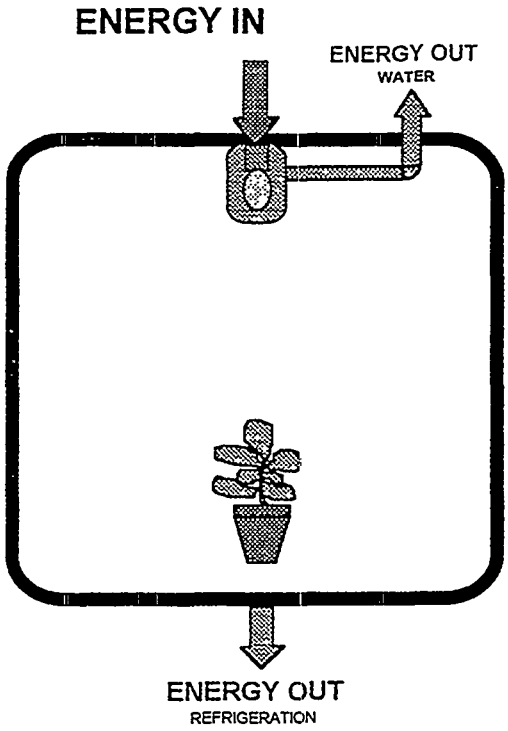
It is possible to remove a portion of the heat associated with lamps by enclosing them in a water cooled reflector. In this system a special porcelain is selected which will provide good reflection of radiation between 400 and 700 nanometers and transmit infrared radiation. This material is bonded with a good thermal joint to a backing that can be cooled by flowing water. The whole assembly is well insulated to maximize the amount of heat that can be collected by the water and minimize the heat load on the environment. The fixture can be operated with or without a barrier. Water temperatures can be extracted up to 220 F, depending on the flow rate and entering temperature of the input water. As much as 50% of the lamp wattage can be collected in the water depending on flow and input temperature. These fixtures have been made to accommodate two 400 watt HID lamps, one Metal Halide and one Sodium, in order to provide a blended light output. Water at cooling tower temperatures can be utilized, but careful filtering must be provided to prevent obstruction to the small diameter water passages in the cooling element. A closed water system for the fixtures is desirable. Fixtures of this type have been used for greenhouses, converting coolers and on growth chambers. More detailed information is available in US. Patent 3,869,605, Davis, N, 1975.

ABSORPTION INTO A PLANAR, FILTERING, SECONDARY COOLING SYSTEM



A flooded barrier adds the reduction of infrared radiation to the separation of the lamp heat from the primary growing area. An advantage of this system lies in the ability to control the water temperature and bring the barrier to the chamber temperature thus completely eliminating any thermal exchange between the two areas. This enables the highest relative humidities. It also requires special consideration to achieve equilibrium dew points more than a few degrees less than air temperature. The flooded barrier is a combination system requiring both a water cooling method and an air cooling method Both water and air systems require stringent filtering to prevent contamination of the barrier and loss of light. While the system offers some performance advantages, it requires particular consideration of the support of the barrier, the leak sealing of the barrier to the chamber and any chemical interactions between the cooling water and any system components. It is not recommended where chamber temperatures go below freezing. Flooded barriers are most applicable for smaller areas where structural support and maintenance can be are readily accomplished. Light transmission is a function of the barrier material, the depth of the water, any induced turbulence on the water surface and the clarity of the water.

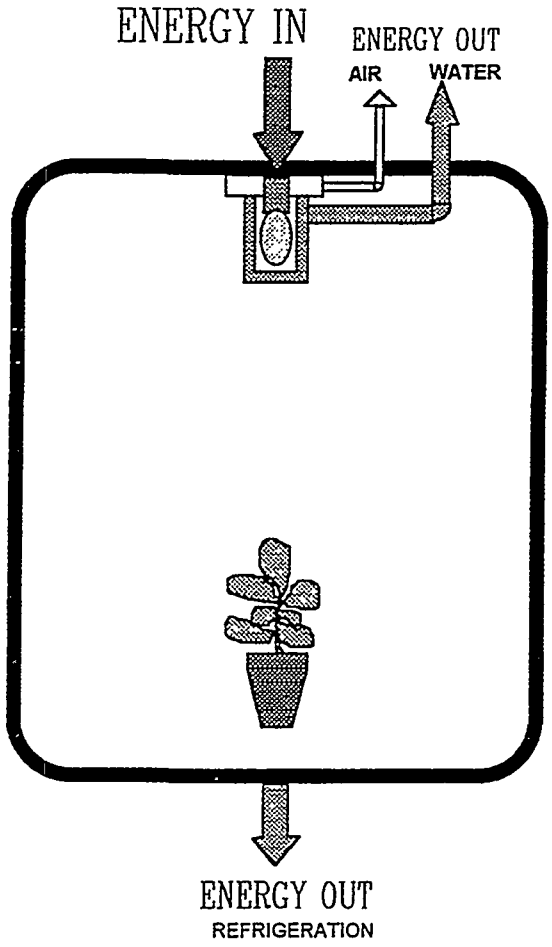
ABSORPTION INTO INDIVIDUAL, FILTERING, SECONDARY COOLING SYSTEMS



A water jacketed lamp provides the heat collection advantages of the flooded barrier without some of the disadvantages. Using a closed water circuit and no secondary air the jacketed lamp reduces maintenance of the water and the barrier. Heat collection is consistently greater than 50% of the lamp wattage. The lamp water is presently restricted to temperatures between 37 C, the upper limit for algae growth, and 60 C, the lower limit for PVC pipe softening. Metal ions in the water will deposit on the lamp surface and require occasional cleaning. De-ionized water is recommended for contact with the lamp surfaces. Stainless steel heat exchangers and pumps are required. Heat can be collected at temperatures up to 55 C.

Lamps operating submerged in water have greater heat transfer than when operated in air. Lamps operating under these cooler conditions do not develop their full wattage or light output. Wattage and light output are reduced by 10 to 20%. With appropriate ballasts the wattage and light output can be returned to standard. Operations at reduced levels result in operating lives approaching 50,000 hours. Both Metal Halide and Sodium H.I.D. lamps can be operated in these fixtures. 1000 watt Metal Halide lamps require special construction. These fixtures can be operated in large areas without sacrifice of their heat control and recovery capabilities. More information is available in US Patent No. 4,1996,544, Davis, N.B. et al, 1980.

ABSORPTION INTO COMBINED SECONDARY COOLING SYSTEMS



A combination of air and water cooling of individual lamps represents the best of both systems. The lamps running in air will develop full wattage with no additional circuitry. The water jacket, separated from the lamp, can be operated with controls set to match chamber temperature when desired and eliminate any heat transfer between the lamps and the growing area. With the lamps insulated from the water algaecides can be used to allow water temperatures lower than the algae growth upper limit. The need for de ionized water is reduced or eliminated. With widely spaced fixtures the effect on dew point is minimized. This arrangement is suitable for large area illumination. The fixtures can be suspended from the structure internally or they can be dropped through holes in a solid ceiling. All connections can be made outside of the chamber. Maintenance and lamp replacement are minimized. More detailed information is available in US. Patent No's 3,624,380, Davis, N, 1971 and 3,777,199, Davis, N, 1973

HEAT DISSIPATION IN CONTROLLED ENVIRONMENT ENCLOSURES THROUGH THE APPLICATION OF WATER SCREENS

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INTRODUCTION

Full simulation of the short-wave characteristics of daylight, including simulation of the complex changes in diurnal and seasonal energy fluxes and spectral energy distributions (SEDs) has always been a major goal in the design and operation of modern controlled environment chambers. Very few existing facilities, however, have the sophistication in their installed lighting systems which is required to achieve such conditions. Nonetheless, the adoption of high intensity discharge (HID) lamps, including the use of xenon-arc lamps, has allowed advances at least in regard to attaining photosynthetic and total short-wave energy fluxes which can simulate and even exceed maximum daylight values (Bugbee and Salisbury, 1988; Warrington and Norton, 1991). These systems also provide SEDs, especially with regard to xenon-arc lamps, which are closer simulations of daylight than attainable from fluorescent tube systems (Hartmann and Kaufmann, 1990; Seckmeyer and Payer, 1990).

Nonetheless, no single lamp type is currently available which provides an SED identical to daylight and controlled environment biologists have, for many years, sought combinations of lamps which provide such conditions. The primary deficiency of many fluorescent and HID lamps is their low output in the red and near-infrared regions of the spectrum. For example, while daylight has a red:far-red (660:730 nm) ratio of 1.20, the R:FR ratio with metal halide lamps is 4.59. The corresponding calculated phytochrome photoequilibria values are daylight 0.54 and metal halide 0.63.

The main solution to resolving these imbalances is to provide supplementation from various forms of incandescent lighting. In the early application of artificial lighting to controlled environment research, carbon arc lamps were supplemented with 30 percent incandescent lamps to achieve satisfactory plant growth (Parker and Borthwick, 1949). This amount of supplementation was adopted when cool white fluorescent tubes were introduced (Dunn and Went, 1959) - apparently without systematic assessment of the actual amount of supplementation which was either necessary or desirable (Downs and Hellmers, 1975).

The evaluation of HID lamps in the mid to late 1960s, for their suitability in plant growth and development research, identified the desirability of incorporating incandescent lamps in controlled environment chambers in order to achieve satisfactory plant growth of many plant species (Warrington and Mitchell, 1976; Warrington, Mitchell and Halligan, 1976). In particular, stem elongation was responsive to changes in the R:FR ratio (and to the phytochrome photoequilibrium) in many species and supplementation of 50% of the total installed wattage was recommended where metal halide lamps were employed (Warrington, 1978; Warrington et al., 1978). Subsequent studies, primarily motivated because of dissatisfaction with the growth form of some species - especially tree stem growth, illustrated that higher amounts of

supplementation were desirable. These amounts were as high as three-times the metal halide wattage or 75% of the total installed wattage. The consequent R:FR ratio was 1.15 (i.e., the same as daylight) and the calculated phytochrome photoequilibrium value was 0.575 (cf. daylight 0.54). It was not surprising, therefore, that the resultant plant growth was more acceptable and the plant form more consistent with that of field-grown material (Morgan et al., 1983; Warrington et al., 1988). Nonetheless, other species are obviously much less responsive (Tibbitts et al., 1983).

Compromises must be reached between those amounts of incandescent lamp supplementation considered ideal for normal plant growth and development and those deemed to be affordable, especially considering the low operating efficiency (photosynthetic photon flux output per energy input) of incandescent lamps. Nonetheless, both HID and incandescent lamps have very high outputs of near-infrared radiation, irrespective of installed wattage ratios, and this energy must be dissipated if high plant temperatures and excessive air-conditioning loads are to be avoided.

HEAT DISSIPATION

A major concern in controlled environment lighting is the dissipation of the considerable quantity of input energy which is converted to heat by the lamps and their control equipment. For incandescent lamps, only a small proportion of the input electrical energy is converted into light energy (photosynthetic efficacy: 0.44 μmol s^{-1} per watt; Tibbitts pers. comm). Although the energy conversion is higher for high-pressure discharge lamps (1.67 μmol s^{-1} per watt), these lamps have additional heat generated by ballasts which are essential components of the control circuits. Ballasts typically consume additional power equivalent to 8 - 18% lamp wattage, depending on lamp size. Larger wattage lamps generally have higher photosynthetic efficacy and proportionally lower power consumption by the lamp ballasts. Consequently, in addition to input energy converted to radiant energy, there are also considerable amounts of heat generated that must be dispersed through both conduction and convection.

One advantage of heat which is either conducted or convected is that it can be dispersed using simple air-conditioning systems and such methods are widely used in controlled environment enclosures. In many configurations, lamp ballasts are housed in ventilated cabinets external to the main controlled environment enclosure. In other systems, such as the walk-in rooms at the National Climate Laboratory, ballasts are located within the lighting enclosure to allow ease of access and fault diagnosis. This, however, results in the need to ensure that the entire lamp enclosure is very well ventilated.

SPECTRAL TRANSMISSION CHARACTERISTICS OF WATER

The spectral transmission characteristics of both plate glass and water are well documented (e.g. Curcio and Petty, 1951). Water provides a very effective filter for controlled environment applications as it has almost neutral absorption over the visible and near infra-red wavebands (400 - 800 nm) but strong absorption in the longer wavelengths, especially from 960 to 1050 nm and also above 1100 nm (Figure 1). It should be noted that strong absorption occurs with water films as shallow as 30 mm depth.

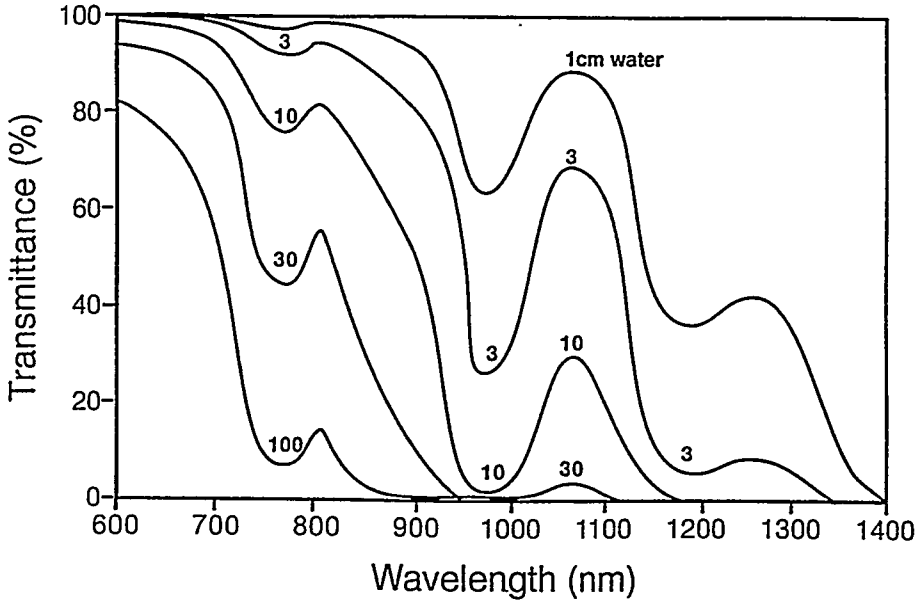

Fig. 1. Spectral transmission of liquid water of different path lengths (Curcio and Petty, 1951)

These absorption characteristics can be clearly identified using scans of the spectral energy distributions from a high-pressure discharge lamp-based controlled environment lighting system where the depth of the water thermal barrier was varied between 0 and 50 mm (Figure 2).

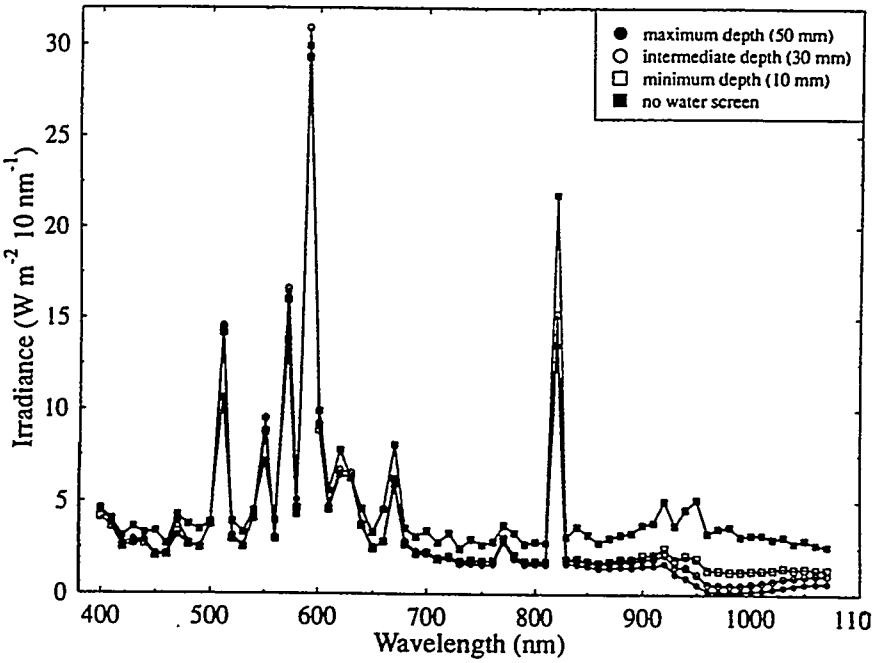

Fig. 2. Spectral energy distributions taken within a controlled environment room with a plate glass-water barrier where the water depth was either 10, 30 or 50 mm. The measurements were recorded 2 m below a lighting system comprising 4 x 1000 W Sylvania `Metalarc' plus 4 x 1000 W Philips tungsten halogen lamps. The values used to estimate the spectral energy distribution in the absence of a water screen were obtained by measuring the output of one metal halide plus one tungsten halogen lamp mounted in an open space at the same height above the spectroradiometer as in the CE room tests (values presented are measured values x 4).

These data are further summarized in Table 1. The minor effects on both the photosynthetically-active and formative wavebands are clearly evident. Previously, Tibbitts et al. (1983) had shown very close agreement between measurements taken with a pyranometer which was either glass covered (280 - 2800 nm) or polyethylene covered (350 - 50,000 nm) which also confirms the very small amounts of radiation at longer wavelengths in these chambers where water thermal barriers are used (Table 2).

Similar, more detailed, data are presented in Bubenheim et al., 1988 (see Table 3). In those studies, increasing the depth of the water was also found to reduce the transmission of both short- and long-wave radiation but no marked reduction in transmission occurred when water depth was increased from 40 to 60 mm. None of the filter materials used (water, glass and plexiglas) were found to change the spectral energy distributions of any lamp type in the 400 - 800 nm waveband. This is surprising as some reduction in transmission over the 700 - 800 nm waveband would have been expected (Figure 1). Water was clearly more effective in reducing the short-wave radiation component (55% of no filter value) than either a single (91%) or a double glass (87%) filter, largely because the upper limit of radiation transmission for glass is 4000 nm (Holleander, 1956) whereas for water it is 1400 nm (Curcio and Petty, 1951).

TABLE 1. Characteristics of radiation measured in a controlled environment room with a plate glass-water thermal barrier where the water depth was either 10, 30 or 50 mm. The measurements were recorded 2 m below a lighting system comprising 4 x 1000W Sylvania `Metalarc' plus 4 x 1000W Philips tungsten halogen lamps.

Water depth (mm)	PPF (μmol $m^{-2}s^{-1}$) (400-700 nm)		PI (Wm^{-2}) (400-700 nm)	Short-wave (Wm^{-2}) (400-1100 nm)	Blue: red	Red: far-red	Phytochrome photo-equilibrium
10	642[1]	663[2]	137[1]	254[3]	0.43[4]	1.48[5]	0.62[6]
30	665	659	142	217	0.45	1.49	0.62
50	656	659	140	198	0.44	1.61	0.62

[1]Determined using an Optronics Model 740A spectroradiometer
[2]Determined using an LI-190S quantum sensor
[3]Determined using an LI-200SA pyranometer sensor (note limited waveband)
[4]Ratio of 410 - 500 : 610 - 700 nm (value without thermal barrier : 0.45)
[5]Ratio of 660 : 730 nm (value without thermal barrier : 1.69)
[6]Value without thermal barrier : 0.60

Radiation filtered by a plate glass-water thermal barrier, therefore, has a higher proportion of photosynthetic irradiance in the total short-wave component than unfiltered radiation. In daylight, this ratio has been variously determined to be between 0.47 and 0.49 (e.g. Stanhill and Fuchs, 1977). Bubenheim et al. (1988) found, with metal halide lamps, that the PI:short-wave ratio was 0.37 where no filter was used and 0.67 with a water filter (Table 3). Similarly, the ratio changed from 0.49 to 0.71 with high-pressure sodium lamps. Data from Tibbitts et al. (1988), examining the same two lamps, determined PI:short-wave ratios under the water filter to be 0.76 and 0.84, respectively. Hence, in addition to limiting the upper wavelength limit to approx. 1400 nm, the use of the water barrier also leads to a marked shift in the PI:short-wave ratio with resultant values being somewhat different to daylight. The significance of these differences in ratio values to plant development is largely unexplored.

TABLE 2. Influence of a plate glass - water thermal barrier on radiation characteristics from a range of HID lamp types (from Tibbitts et al., 1988).

	PPF (μmol $m^{-2}s^{-1}$)		PI (Wm^{-2})	Irradiance (Wm^{-2})		Phytochrome photo-equilibrium
	(400-700 nm)		(400-700 nm)	(280-2800 nm)	(350-50,000 nm)	
Sodium	708[1]	704[2]	137[3]	164[4]	175[5]	0.69
Sodium & metal halide	702	698	143	182	186	0.66
Metal halide	712	708	152	200	209	0.63
Metal halide & tungsten halogen	711	705	149	217	228	0.61

[1]Determined using an LI-190S quantum sensor
[2]Determined using an Optronics Model 740A spectroradiometer
[3]Determined using a LI-190SE radiometric sensor
[4]Determined using a Swissteco pyranometer with a quartz glass dome
[5]Determined using a Swissteco pyranometer with a polyethylene dome
All measurements recorded 2 m below a plate glass - water thermal barrier

In agreement with the data of Tibbitts et al. (1983), Bugbee et al. (1988) generally found only small differences between total and shortwave radiation fluxes where water barriers were used. However, in the absence of barriers, or where water is not included in the filter, the amount of long-wave radiation reaching the planting surface can be considerable (Table 3). A high proportion of this long-wave component originates from the operating temperature of each lamp

reflector although all surfaces within a lamp loft contribute because according to the Stefan-Boltzman law.

TABLE 3. Influence of filter combinations on the radiation environment of a plant growth room lit with a single 1000 W metal halide lamp (after Bubenheim et al., 1988)

	PPF (μmol $m^{-2}s^{-1}$) (400-700 nm)	PI (Wm^{-2}) (400-700 nm)	Irradiance (Wm^{-2}) (300-100,000 nm)	(285-2800 nm)	(2800-100,000 nm)	PI: Short-wave	PI: Total
No filter	400	87	398	235	163	0.37	0.22
One layer glass	400	87	328	213	115	0.41	0.27
Two layers glass	400	87	312	205	107	0.42	0.28
20 mm water	400	87	156	130	26	0.67	0.56
40 mm water	400	87	136	129	7	0.67	0.64

LIGHTING SYSTEM ENERGY FLUXES

The energy input to a controlled environment lighting system is dissipated in a number of ways, including:

- transfer of short-wave radiation to the plant growth area
- evaporation of water from the water screen
- transfer of sensible heat from the components of the lamp loft to the air venting the loft
- transfer of sensible heat to and absorption of short-wave radiation by the water screen
- heat storage in the lamp loft
- heat conduction from the lamp loft
- heat conduction through the water screen between the lamp loft and the plant growth area.

The magnitude of each of these terms is, in turn, dependent on the amount of installed lighting and the types of lamps in use, the nature of materials used in the construction of the rooms, the temperature of the air used to ventilate the lamp loft, and so on. Nonetheless, physical measurements can be made of most of these components to estimate the individual contributions to the energy balance of the lighting system.

In the National Climate Laboratory rooms, with the standard 8 kW lighting system, approximately 2.1 kW are removed via the lamp loft air ventilation system, 2.1 kW in the water flow, and 1.2 kW via evaporation from the water screen (Figure 3). The lag of 2 - 3 hours in achieving these heat fluxes is primarily due to heat storage within the various components of the lamp loft.

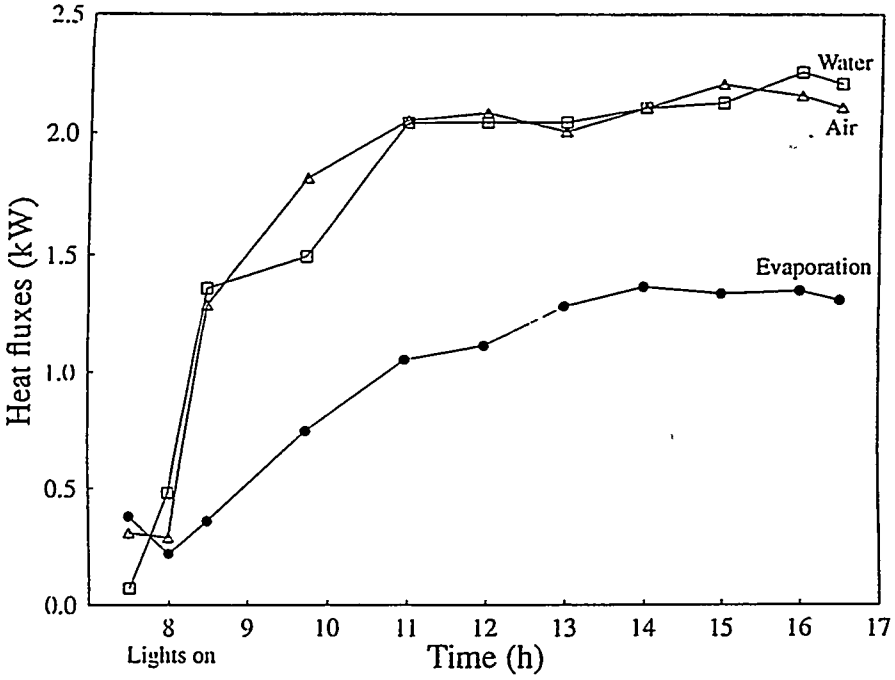

Fig. 3. Heat fluxes (kW) measured in the lamp loft of a controlled environment room with a lighting system comprising 4 x 1000W Sylvania `Metalarc' and 4 x 1000W Philips tungsten halogen lighting. Lights were switched on at 0800 h. The depth of the water on the thermal barrier was 46 mm and the flow rate was 9.7 $L.h^{-1}$ (other details of the lighting system design are provided in Warrington et al. 1978).

OPERATIONAL ADVANTAGES OF WATER SCREENS

The operation of a plate glass-water thermal barrier has a number of disadvantages, including the initial installation costs and those associated with maintenance. In contrast, however, the advantages are considerable.

Firstly, the reduced thermal load results in the temperatures of plant parts, especially leaves, and soil being very close to air temperature. While, for example, leaf temperature will be determined by other factors including vapour pressure deficit and air speed, measurements under plate glass water thermal barriers show that leaf temperatures are within 0.5°C of air temperature under photosynthetic photon fluxes of 700 - 800 $\mu mol\ m^{-2}s^{-1}$ (Tibbitts et al., 1983). Consequently, true plant growth and development rates can be ascribed to actual air

temperatures rather than to an apparent temperature influenced by the thermal loading in the chamber.

Secondly, the reduced thermal loading results in reduced refrigeration demand. The obvious consequence is a lower operating cost for air conditioning. However, a less obvious advantage is that the reduced refrigeration demand makes humidification and dehumidification much easier to achieve, leading to increased versatility and application of the controlled environment unit.

DESIGN AND MAINTENANCE CONSIDERATIONS FOR WATER SCREENS

There are several key elements which must be considered in the design and operation of water screens used in controlled environment chambers.

- Temperature control. Control of the inlet water temperature is essential if condensation is to be avoided on the plant growth chamber side of the plate glass screen. The temperature of the water must always be higher than the dew-point temperature of the air in the plant growth area (Figure 4). In practical terms, this means water set point temperature slightly above growing area temperature (usually 2 - 4°C).

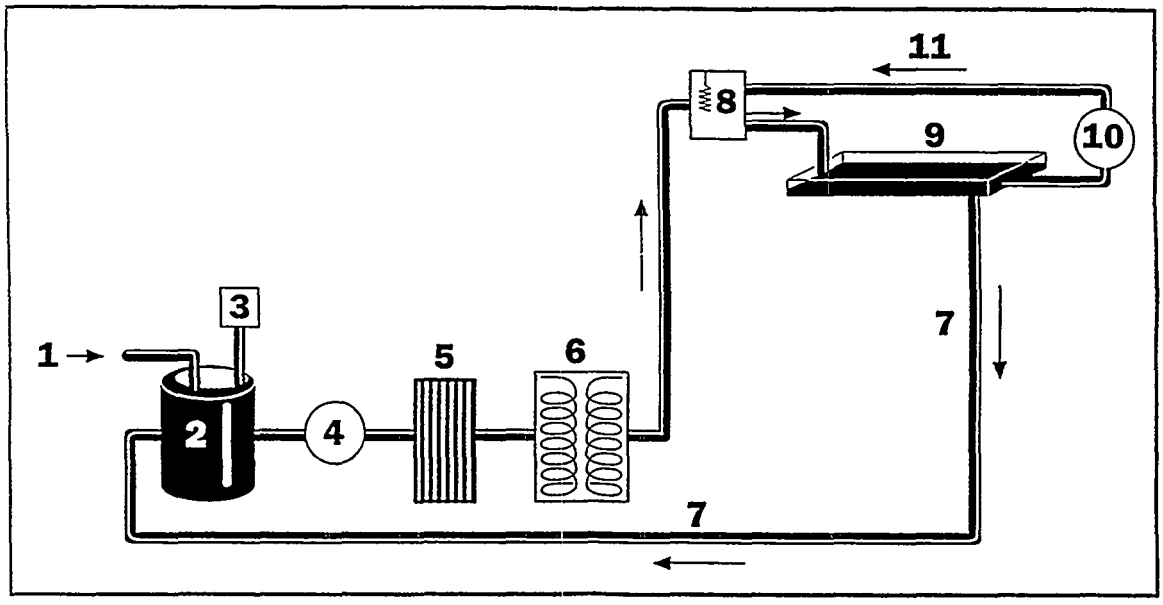

Fig. 4. Schematic diagram of the equipment layout and pipe circuits required for maintaining the temperature-controlled water supply to the plate glass-water thermal barriers used in the National Climate Laboratory (1. Inlet water supply; 2. Supply tank; 3. Injection system for algae control; 4. Circulation pump; 5. Filter; 6. Heat exchanger; 7. Main circulation system; 8. Header tank with heating element; 9. CE room plate glass-water thermal barrier; 10. Circulation pump; 11. Secondary circulation system.)

- Water depth and flow rates. There is no "optimum" operating depth for the water since within sensible operating limits there is little significant impact of water depth on either photosynthetic photon flux or on physiological indices such as R:FR ratio or phytochrome photoequilibrium. We have found 30 - 40 mm to be satisfactory as it provides adequate depth to allow for the fall in slope across the glass (which is needed to achieve water flow across the screen) with minimum rippling of the water surface. It is necessary to avoid ruffling of the water's surface as such conditions can result in considerable back-scatter of radiation and a loss of PPF across the plant growth area (this loss can be as great as 15%; R. Kerslake, pers. comm.) Provision of a simple weir can greatly assist in achieving the desired depth and uniformity of water over the plate glass screen.

  Flow rates must be adequate to ensure effective water movement across the thermal barrier and the avoidance of high water temperatures at any point on the screen. We use a flow rate of 10 L per minute across the 2.60 x 1.62 m screen with a resultant water temperature differential (outlet - inlet) typically of 4 - 5°C.

- Safety. The volume and, therefore, weight of water on the thermal barrier of a walk-in CE room can be considerable - in our case 200 - 250 L or 0.25 tonne. Internal support of the plate glass screen is, therefore, essential. The glass screen itself is 8 mm thick and it is preferable that it be heat-toughened. Nonetheless, the high intensity point sources of the high-pressure discharge lamps can result in extreme temperature gradients which, in the absence of a water film, can break the glass. Consequently, provision of continuous depth monitoring of the water film (using for example, a conductivity-based floatless switch), which can be programmed to switch off the lighting system in the event of a failure in water supply, is desirable.

- Water quality. Supply and maintenance of clean, clear water is essential if maximum light transmission through to the plant growth chamber is to be achieved. Inlet water should be filtered, conditioned as needed to remove mineral contamination (e.g., of iron and calcium), and treated for control of algae. The technologies and chemicals used for the operation and maintenance of swimming pools can be directly applied to CE water screens. The plate glass screen must also be regularly cleaned and accumulated solid matter (dead algae, dirt) removed as needed with a vacuum line.

CONCLUSIONS

The use of plate glass-water thermal barriers in controlled environment facilities effectively reduces the thermal load within the plant growth chamber. This allows high PPFs to be provided for plant growth and development studies, adequate simulation of daily light integrals, and simulation of peak PPFs. Further, substantial amounts of incandescent lamp supplementation can be used to achieve simulation of daylight R:FR ratios which are needed to ensure adequate stem development in some species.

While the focus in this paper has been on the use of entire thermal barriers which separate the lighting enclosure from the plant growth chamber, the same principles apply to the use of water jackets for cooling individual lamps (such as can occur with xenon-arc lamps). In this instance, the barrier separating the lamps from the plant chamber can be much simpler (e.g.,

plexiglas) as the main function of the barrier is to separate the air ventilation of the lamp enclosure from the air system within the plant growth chamber.

The main advantage of water as a thermal barrier is the negligible absorption of radiation in the photosynthetically-active and near infra-red wavebands. Consequently, plate glass-water barriers typically allow transmission of approximately 90% of radiation in these regions. While ventilated double and triple glazing systems appear to be attractive alternative to water barriers from an operating standpoint, their significant absorption in the biologically-important wavebands (7 - 12%) with each glass layer and longer-wave cut-offs (typically 2500 - 4000 nm) makes them a much less attractive alternative.
The data presented here demonstrate clearly that measurement of PPF alone is not an adequate representation of the radiation environment being used in a controlled environment study. The amounts and proportions of long-wave and short-wave radiation in a plant growth chamber are dependent on lamp type, lamp combination, presence of a thermal barrier, the type of thermal barrier between the lamps and the plant growing area and the overall construction and design of the chamber. It is important, therefore, in reporting results of controlled environment studies, to adequately describe both the details of the lighting system used and the characteristics of the radiation produced by that system, so results of different studies can be adequately evaluated and compared.

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SHORT REPORT

HEAT DISSIPATION IN WATER-COOLED REFLECTORS

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The energy balance of a high pressure sodium lamp with and without a reflector is given in Fig. 1. The energy balance of a lamp varies with the thermal and optical characteristics of the reflector. The photosynthetic radiation efficiency of lamps, defined as input power divided by photosynthetically active radiation (PAR, 400-700 nm) emitted from the lamp ranges between 0.17 and 0.26. The rest of the energy input is wasted as longwave (3000 nm and over) and non-PAR shortwave radiation (from 700 nm to 3000 nm), convective, and conductive heat from the lamp, reflector, and ballast, and simply for increasing the cooling load.

Furthermore, some portion of the PAR is uselessly absorbed by the inner walls, shelves, vessels, etc. and some portion of the PAR received by the plantlets is converted into sensible and latent heat. More than 98% of the energy input is probably converted into heat, with only less than 2% of the energy input being converted into chemical energy as carbohydrates by photosynthesis. Therefore, it is essential to reduce the generation of heat in the culture room in order to reduce the cooling load.

Through use of a water-cooled reflector, schematically shown in Fig. 1, the generation of convective and conductive heat and longwave radiation from the reflector can be reduced, without reduction of PAR.

With the water temperatures at the inlet being 13° C and the water flow rate being 3.2 g/s, 50% of the energy input was removed by the water, resulting in a water temperature at the outlet of 25°C. The temperature distribution of the lamps with different reflectors is given in Table 1.

The warmed water coming out of the reflector can be used as a low-temperature heat source and for washing, because the water will not be polluted in the closed-water distribution system. Details of this study are provided in Kozai (1991).

TABLE 1. Temperatures of lamp, reflector and surroundings.

	Lamp type				
	A	B	C	D	E
Lamp bulb	160	177	175	205	180
Inner surface of reflector	-	46.6	58.0	92.3	30.4
Outer surface of reflector	-	-	57.0	78.8	24.6
Ballast	62.6	62.6	62.6	62.6	62.6
Room air	25.1	25.0	25.1	25.0	25.0
Floor	24.7	25.5	25.2	25.2	25.2
Wall	25.7	25.0	25.2	25.0	24.7
Ceiling	25.1	25.0	24.7	24.7	24.7

For lamp types, see legend to Fig.2

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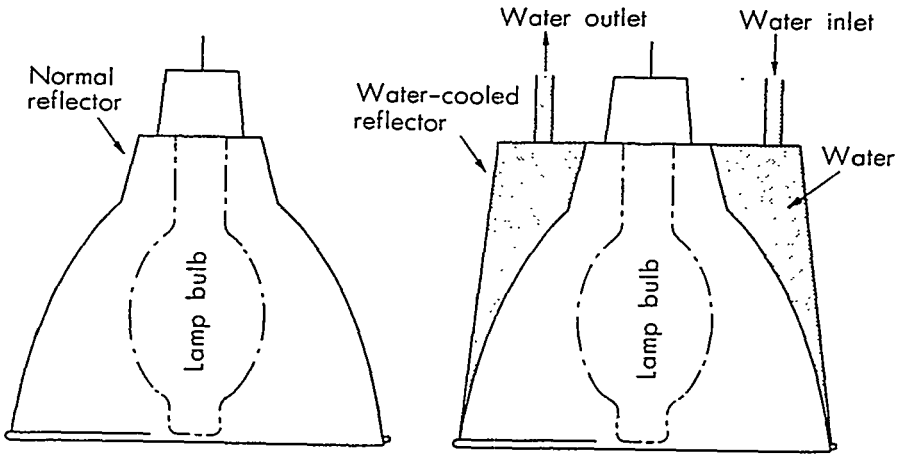

Fig. 1. Schematic diagram of a lamp bulb with normal and water-cooled reflectors.

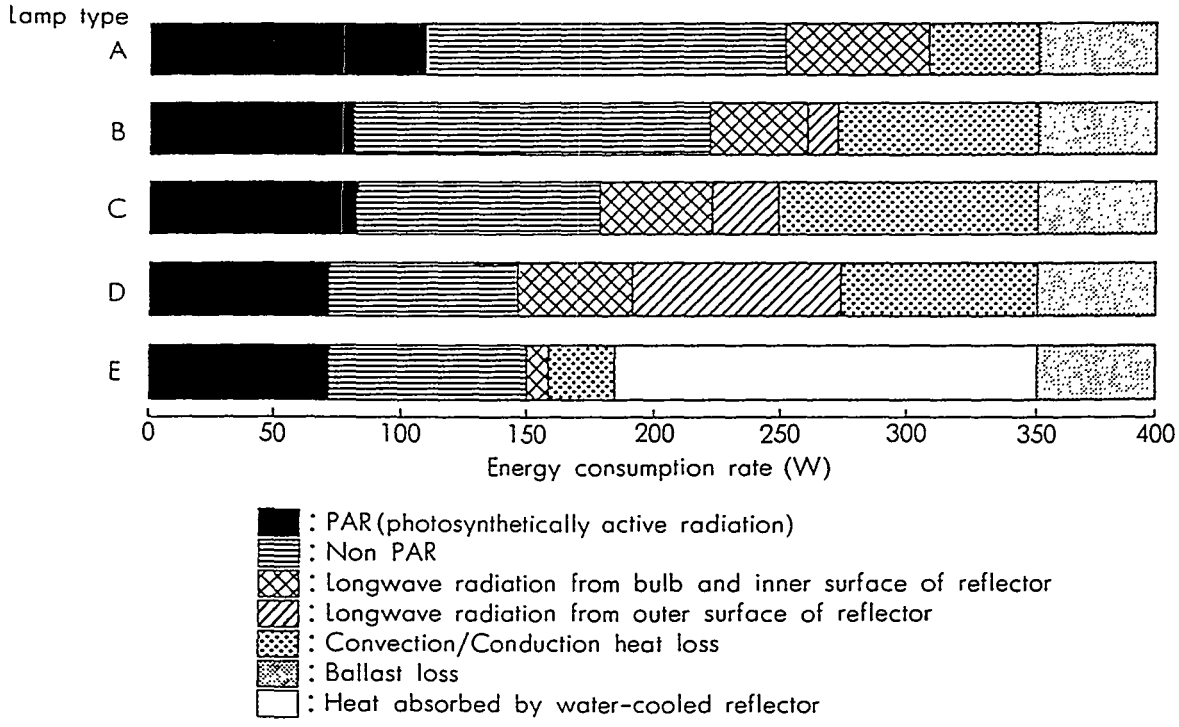

Fig. 2. Energy distribution of a high pressure sodium lamp bulb with or without a reflector Lamp type: A lamp without reflector; B lamp with polished aluminum reflector; C lamp with white-colored aluminum reflector; D lamp with white-colored enameled iron reflector; E lamp with water-cooled white-colored enameled iron reflector.

SHORT REPORT

UV FILTERS FOR LIGHTING OF PLANTS

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INTRODUCTION

Plants as result of biological evolution exhibit a complex system of pigments and photoreceptors and respond very sensitively to changes of the spectral irradiation. Lighting for ecological plant research, therefore, requires an engineering which provides a spectral irradiance close to natural conditions. (Kofferlein et al. 1994) Terrestrial global radiation is characterized by a cut-off between 280 and 320 nm by several orders of magnitude due to the filtering effect of stratospheric ozone (Bener 1972). A reduction of the ozone layer will cause a shift of the UV absorption edge to shorter wavelengths thereby increasing the integral UV irradiation (Fig. 1).

The wavelength dependent interaction of biological systems with radiation is commonly described by appropriate action spectra (Caldwell et al. 1986). Particularly effective plant responses are obtained for UV radiation. Excess shortwave UV-B radiation will induce genetic defects and plant damage. As an example the action spectrum of DNA damage is plotted in Figure 1. Due to the strong wavelength dependence of this action spectrum, a shift of the UV absorption edge of the radiation spectrum towards shorter wavelengths will effect a significant increase of DNA damage. A 13% decrease of the ozone column from 320 DU to 280 DU, for instance, will result in a 36% increase of DNA damaging irradiation.

Besides the ecological discussion of the deleterious effects of the excess UV radiation there is increasing interest in horticultural applications of this spectral region. Several metabolic pathways leading to valuable secondary plant products like colors, odors, taste, or resulting in mechanical strength and vitality are triggered by UV radiation. Thus, in ecologically as well as in economically oriented experiments the exact generation and knowledge of the spectral irradiance, particularly near the UV absorption edge, is essential.

The ideal filter 'material' to control the UV absorption edge would be ozone itself. However, due to problems in controlling the toxic and chemically aggressive, instable gas, only rather 'small ozone filters' have been realized so far (Tevini et al. 1989). In artificial plant lighting conventional solid filter materials such as glass sheets and plastic foils (celluloseacetate or cellulosetriacetate) which can be easily handled have been used to absorb the UV-C and the excess shortwave UV-B radiation of the lamp emissions.

The artificial generation of spectral UV irradiances for plant research requires more than appropriate combinations of lamp systems. Reliable filter systems are also necessary to cut the UV irradiance within defined spectral ranges.

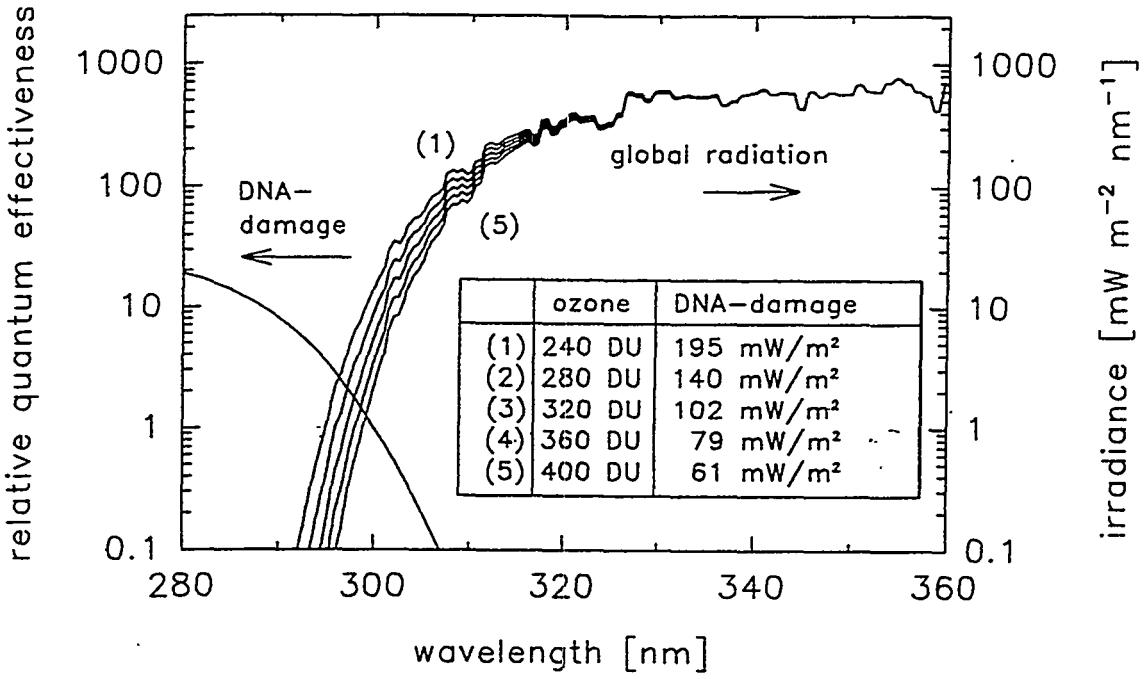

Fig. 1. Spectra of terrestrial global radiation (sun elevation 60°) for different values of the stratospheric ozone column. The spectra were calculated using a radiation transfer model based on Green (1983). The DNA action spectrum (Caldwell et al. 1986), normalized to 1 at 300 nm, is also plotted. The insert gives the resulting integral radiation dose of these spectra weighted for DNA damage.

Lighting set-up at the GSF Phytotron

The phytotron uses a combination of quartz halogen lamps (Osram, Halostar), metal halide lamps (Osram HQI D), blue light lamps (Philips TL18), and UV-B lamps (Philips TL12) in order to obtain a good match to the solar spectrum (Seckmeyer and Payer 1993, Payer et al. 1993). Four walk-in-chambers and a smaller solar simulator are in operation, furthermore two new solar simulators are under construction. Different glass filter systems applied to artificial lighting and monitored by appropriate spectroradiometric instruments are used at the GSF phytotron at Munich.

The standard UV filtering in these chambers is performed by layers of borosilicate glass (Tempax, and Pyran,) which exhibits a steep absorption edge near 300 nm. The respective UV monitoring and spectral measurements have to be performed with high precision and accuracy. This spectral measurement can only be achieved by a double monochromator providing the required wavelength resolution with a maximum of straylight rejection and with dynamics of about 6 decades.

The spectral irradiances at plant level were measured in the chambers by a double monochromator system (Bentham, U.K.) as described by Seckmeyer (1989). The results of

these measurements are compared to a model of global radiation (60° sun elevation and 320 DU based on Green 1983) as shown in Figure 2. The spectral distribution of UV irradiation demonstrates the close approximation to natural global radiation. The integral irradiance (Table 1) within the solar simulator reaches values comparable to those referring to a sun elevation of 60°. Within the large walk-in-chambers approximately 60% of this irradiance data are achieved.

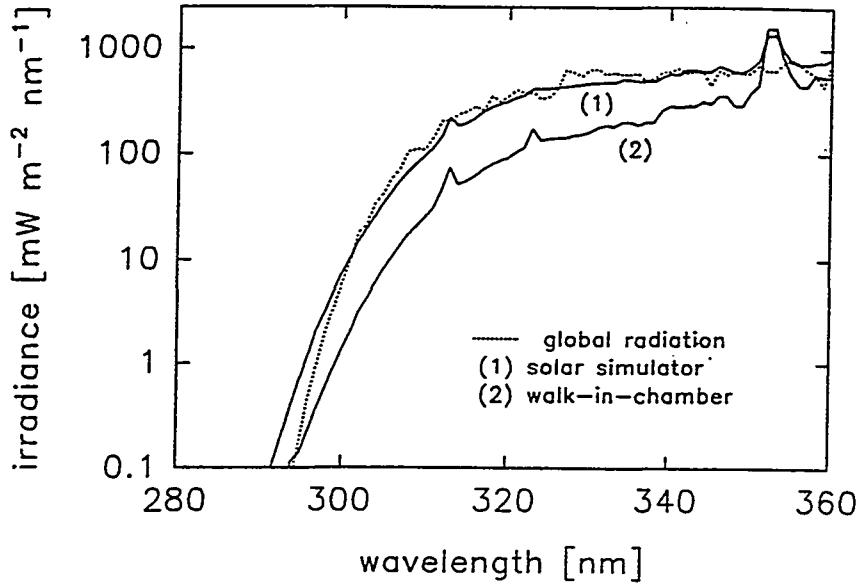

Fig. 2. UV spectra of the small solar simulators and the walk-in-chambers of the GSF phytotron (Seckmeyer and Payer 1993, Payer et al. 1993), compared to a model of global radiation (60° sun elevation, 320 DU) based on Green 1983. The superposed spectra of different lamps are filtered by borosilicate glass.

TABLE 1 Integral parameters of walk-in-chambers, solar simulators and model of global radiation calculated according to Green (1983).

		Solar Simulator	Walk-in Chamber	Global Radiation (60°, 320 DU)	Unit
UV-C	(200 - 280 nm)	$< 10^{-7}$	$< 10^{-7}$	$< 10^{-7}$	W/m^2
UV-B	(280 - 320 nm)	2.4	0.67	2.8	W/m^2
UV-A	(320 - 400 nm)	53.5	36.6	53.3	W/m^2
VIS	(400 - 800 nm)	571	343	532	W/m^2
IR	(800nm - 2500nm)	410	290	292	W/m^2
Total irradiance		1038	670	880	W/m^2
PAR	(400 - 700 nm)	2100	1260	1940	μmol/m^{2}s
Erythemal dose		3	0.9	3.4	MED/h
Illuminance		126	72	107	klx

Closed chambers are particularly suited for reproducible dose response studies under simultaneous variation of other environmental parameters. Interactive effects as well as action spectra will be obtained under these controlled conditions. In order to perform experiments on possible biological consequences of the predicted depletion of the stratospheric ozone column, the UV absorption edge has to be varied. UV absorption edges can be varied to some degree by use of cut-off filters, for instance WG-filters (Schott Glaswerke, Mainz, FRG). However, to cover an experimental area of several squaremeters with this type of filter would not be an economical approach. The variation of UV absorption edges is also limited by the restricted graduation of filters with different cut-off wavelengths.

Commercial borosilicate and other glasses are used at the GSF research center in order to simulate different UV spectra corresponding to those resulting from a proposed depletion of the natural ozone layer. Glass sheets from different production batches and of different thickness are carefully selected to shift the UV absorption edge over a wide spectral range (Fig. 3). For a quantitative comparison with natural UV irradiation the spectra have been weighted by appropriate action spectra (Table 2). These calculations provide insight into the biological effectiveness of changing UV spectra. As seen from Figure 3 glass can only approximate the sharp absorption edge of ozone. The differences between natural and experimental effects have to be considered in the evaluation of such experiments.

Ageing of filter materials

Inside the UV compartment of the lamphouse a harsh, almost 'extraterrestrial' radiation environment is encountered. Materials are exposed to high levels of UV-B radiation (approximately 30 Wm-2) and even UV-C radiation (about 0.1 Wm-2). Filters are, therefore, subject to enhanced ageing processes. The effect of such ageing is demonstrated in Figure 4, showing the results of UV-B monitoring by a Robertson-Berger-meter (Solar Light, USA) obtained during a long-term experiment in the walk-in-chambers of the GSF phytotron. The continuous decrease of erythemal weighted UV-B irradiation at the plant level amounted to approximately 25% after 250 hours of UV-B lamp operation.

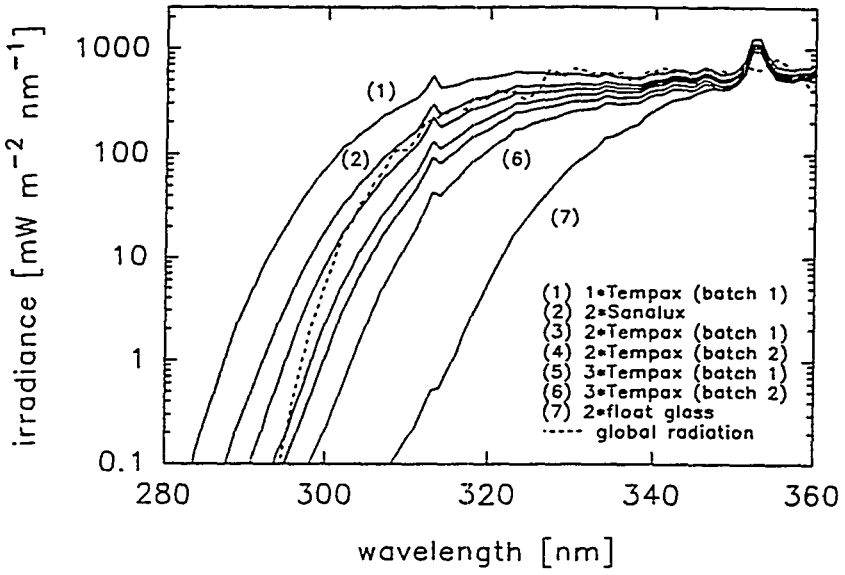

Fig. 3. Spectra of the solar simulator for different filter combinations of 5 mm Tempax®, 4 mm Sanalux®, 4 mm float glass.The dotted line represents the model of global radiation based on Green 1983 (sun elevation 60°, 320 DU).

TABLE 2 Integral values for weighted spectra with different filter combinations as plotted in Figure 3 (action spectra according to Caldwell et al. 1986).

Spectrum	UV-B (W/m^2)	DNA-damage (mW/m^2)	Plant damage (mW/m^2)
(1)	5.1	751	1000
(2)	3.5	248	427
(3)	2.4	123	246
(4)	1.6	45	103
(5)	1.2	27	64
(6)	0.6	10	20
(7)	0.02	1.4	0.3
Global radiation	2.8	102	264

The corresponding changes of the spectral transmittance of borosilicate glass during a period of 100h UV irradiation are plotted in Figure 5(a). The absorption edge was red shifted during this period by about 3 nm and the slope is somewhat flatter. The detailed analysis (Figure 5(b)) revealed the transmittance decrease to be exponential with rates depending on the wavelength. A fast 'decay' of UV-B transmittance was obtained, particularly in the first few hours. A slower decrease in the UV-A range and nearly no change in the region of visible light was observed. These wavelength dependent transmittance changes are supposed to be caused by photochemical reactions within the glass and seem to be correlated to a contamination of the glass by metal ions, most probably iron ions. The iron content of the investigated glasses differed from batch to batch within a range of a few hundred mg/kg.

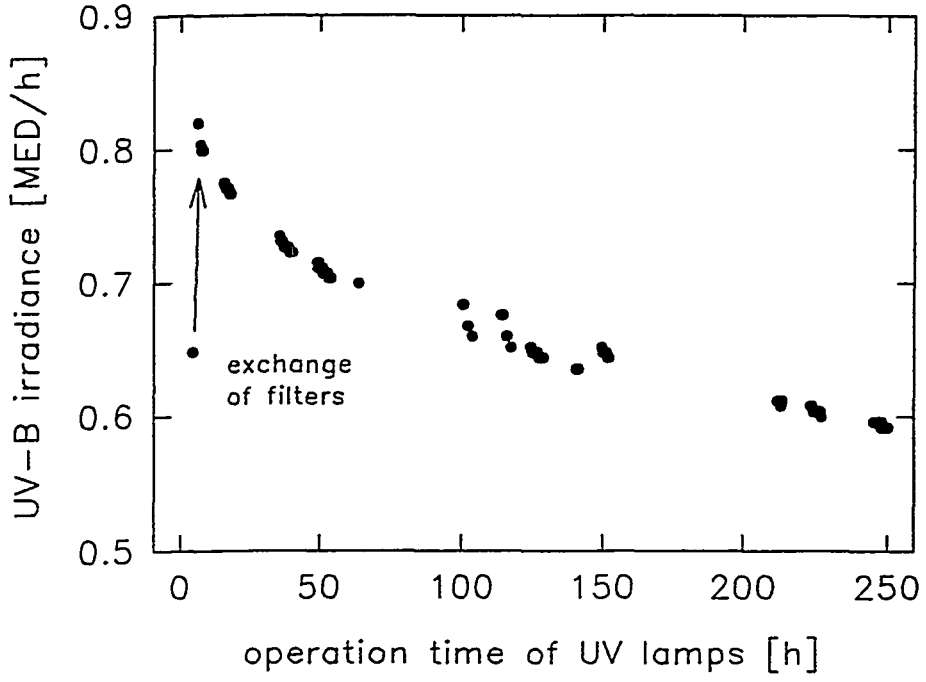

Fig. 4. Decrease of UV-B during 250h of filter ageing, measured with a Robertson-Berger-meter (erythemal weighting of the irradiance).

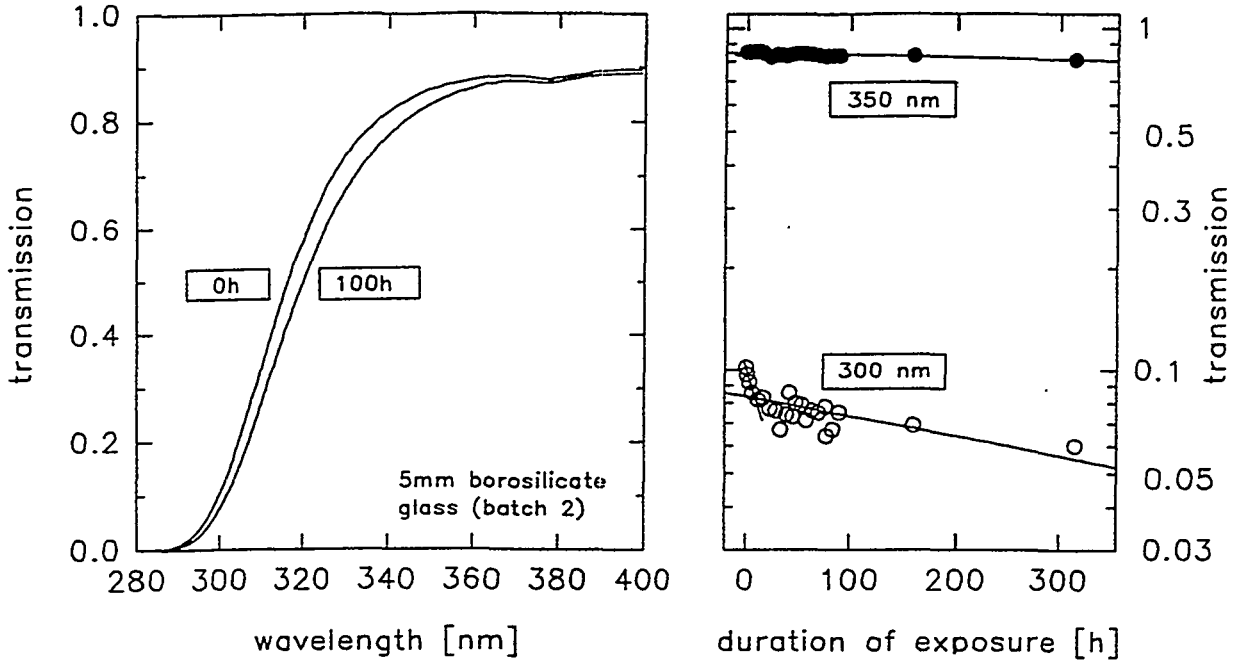

Fig. 5. Behaviour of borosilicate glass filters (batch 2 of Figure 3) during ageing with UV-B radiation of approximately 32 Wm-2.
(a): Change of spectral transmission
(b): Decrease of transmission vs. exposure time

The described degradation of borosilicate filters imposes problems and limitations particularly for investigations using artificial irradiation in the UV-B range. Plastic materials are even less resistant to the extreme radiation in the phytotron lamp house and deteriorate more rapidly than glasses. At present there is no other choice than the periodical exchange of the whole filter set.

CONCLUSIONS

Different filter glasses are available which provide absorption properties suitable for gradual changes of the spectral UV-B illumination of artificial lighting. Using a distinct set of lamps and filter glasses an acceptable simulation of the UV-B part of natural global radiation can be achieved. The ageing of these and other filter materials under the extreme UV radiation in the lamphouse of a solar simulator is presently unavoidable. This instability can be dealt with only by a precise spectral monitoring and by replacing the filters accordingly. For this reason attempts would be useful to develop real ozone filters which can replace glass filters. In any case chamber experiments require a careful selection of the filter material used and must be accompanied by a continuous UV-B monitoring.

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GUIDELINES

GUIDELINES FOR LIGHTING OF PLANTS IN CONTROLLED ENVIRONMENTS

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The organizing committee outlined draft guidelines for plants to provide a focus for the discussions at the workshop. These were distributed to the participants before the meeting. It was recognized that there was insufficient data to support many of the particular quantities presented. The guidelines served as a basis for discussion amongst the workshop attendees and led to a number of recommendations that were recorded by the session chairpersons. The organizing committee indicated they would incorporate the recommendations and suggestions into a revised set of guidelines for additional discussion. Interested participants were then asked to indicate their willingness to review this revised set of guidelines to lead toward the future development of guidelines for lighting in controlled environments. It was understood that these guidelines will not be standards and will require upgrading and modifications as lamps and equipment become available and as new insights are obtained on plants response to light.

Revised draft guidelines are included as Tables 1 and 2 that have been developed by the organizing committee following the suggestions obtained at the workshop. Table 1 are the guidelines for growth chambers and Table 2 for greenhouses. These have been distributed to the participants that indicated a willingness to review proposals that were developed. It is hoped that these proposals will lead to the development of guidelines that will have general acceptance by plant scientists.

TABLE 1 GUIDELINES FOR LIGHTING IN GROWTH CHAMBERS

The purpose of these guidelines is to help writers of specifications, engineers, and architects, who have to make recommendations for the installation of lighting in growth chambers. It is not the intent of these guidelines to mandate the lighting a researcher may need for specific projects, but rather guidelines that indicate reasonable lighting that can grow acceptable crops any time of the year.

PHOTOSYNTHETICALLY ACTIVE RADIATION (PAR)

A daily average irradiance of 26 mol m^{-2} day^{-1} will effectively grow most species of higher plants. This equates to an instantaneous irradiance of 300 μmol m^{-2} s^{-1} for 24 hours or 600 μmol m^{-2} s^{-1} for 12 hours. For comparison in the continental United States, the average annual daily irradiance is about 26 mol m^{-2} for Madison, WI and Washington, DC. In the summer the maximum daily irradiance is 62 mol m^{-2} at Phoenix, AZ and in the winter the minimum irradiance is 8 mol m^{-2} at Madison, WI (see Table 1). The maximum solar irradiance around midday of 2000 μmol m^{-2} s^{-1} is transient and is not necessary for normal plant growth since the plants response is based on the average daily irradiance.

UNIFORMITY

Less than $\pm$ 10% variation on a horizontal plane over the growing area at the plant canopy height. The variation should be based on measurements taken in the center of each square meter of the plant growing area.

SPECTRAL

280-320 nm (Ultraviolet-B)	Unspecified, but in general the effects of UV-B are deleterious to plant growth and development. However, some plants, such as members of the Solonaceae, may require a small quantity ($\approx$3 W m^{-2}) to avoid abnormal development.
320-400 nm (Ultraviolet-A)	Unspecified, but may have an additive effect with the requirement for blue.
400-500 nm (Blue)	An absolute quantity for elongation control is required for most higher plants ($\geq$ 30 μmol m^{-2} s^{-1}).
500-600 nm (Green)	Not necessary for photosynthesis, but contributes to photosynthesis and is a significant component of most radiation sources.
600-700 nm (Red)	Optimize output for maximal photosynthesis. Monochromatic red will cause abnormal development in some species.
700-750 nm (Far-red)	Enhancement flowering, stem elongation, etc. of certain species (as a function of the red/far-red ratio) with the quantity centered around 725 nm equal to or greater than the guantity centered around 660 nm.

TOTAL IRRADIANCE (Over the range of 280-50,000 nm)

A ratio of total irradiance to PAR of 0.50 or less W m^{-2} per μmol m^{-2} s^{-1} (2.3 W m^{-2} per W m^{-2} PAR) is desirable to reduce thermal heating of plants and soil. The solar radiation ratio is less than 0.50 W m^{-s} per μmol m^{-2} s^{-1} PAR. A ratio below 0.50 cannot be obtained with most lamps without a barrier and adequate ventilation or a luminaire specifically designed to dissipate infra-red radiation. For example, the ratios for metal halide lamps without a barrier, with an acrylic barrier, and with an acrylic barrier with 5 cm of water was shown to be 0.60, 0.53, and 0.24 W m^{-2} per μmol m^{-2} s^{-1} PAR, respectively. Low temperature sources such as low pressure sodium lamps and light emitting diodes (LEDs) without barriers have been shown to have ratios of 0.41 and 0.28, respectively.

TABLE 2. GUIDELINES FOR INSTALLATION OF SUPPLEMENTAL LIGHTING IN GREENHOUSES

The purpose of these guidelines is to help writers of specifications, engineers, and architects, who have to make recommendations for the installation of supplemental lighting in greenhouses. It is not the intent of these guidelines to mandate the lighting a researcher may need for specific projects, but rather guidelines that indicate reasonable lighting that can grow acceptable crops any time of the year.

PHOTOSYNTHETICALLY ACTIVE RADIATION (PAR)

A daily average irradiance of 26 mol m^{-2} day^{-1} from sunlight plus added supplementation will effectively grow most species of higher plants. Lamp lighting should be used to supplement sunlight and provide 26 mol m^{-2} day^{-1}. Installations of lighting providing greater than 200 µmol m^{-2} s^{-1} generally add too much heat to the greenhouse environment and the extra luminaries add too much shade. Lighting can be provided during the sunlight hours or during the night period depending upon the plant's photoperiod requirements, and/or depending upon the most cost-effective time to activate the lamps. Shading systems should be utilized under high sunlight conditions to reduce the average irradiance to 26 moles day^{-1}.

UNIFORMITY

Less than ± 15% variation on a horizontal plane over the growing area at the plant growing canopy height. The variation should be based on measurements taken in the center of each square meter of the total lighted area. Installation of a uniform lighting system in the greenhouse is difficult. It is seldom possible to obtain this uniformity on the outside edges of the growing area, particularly against the walls of the greenhouse.

SPECTRAL

There are no special spectral requirements for the supplemental lighting for photosynthesis in greenhouses. Sunlight should supply the balance of wavelengths required by plants. Most glazings remove some portion of the ultraviolet radiation from sunlight and thus certain plant species, including most *Solonaceous* species, may have some abnormal development (oedema) as a consequence. However daylength extensions should use lamps high in red and far-red.

TOTAL IRRADIANCE (Over the range of 280-50,000 nm)

Recommend that supplemental lighting produce no more than 0.6 Wm^{-2} of total irradiation for each µmol m^{-2} s^{-1} of PPF.