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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 $\mu mol\ s^{-1}$ per watt; Tibbitts pers. comm). Although the energy conversion is higher for high-pressure discharge lamps (1.67 $\mu mol\ s^{-1}$ 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.

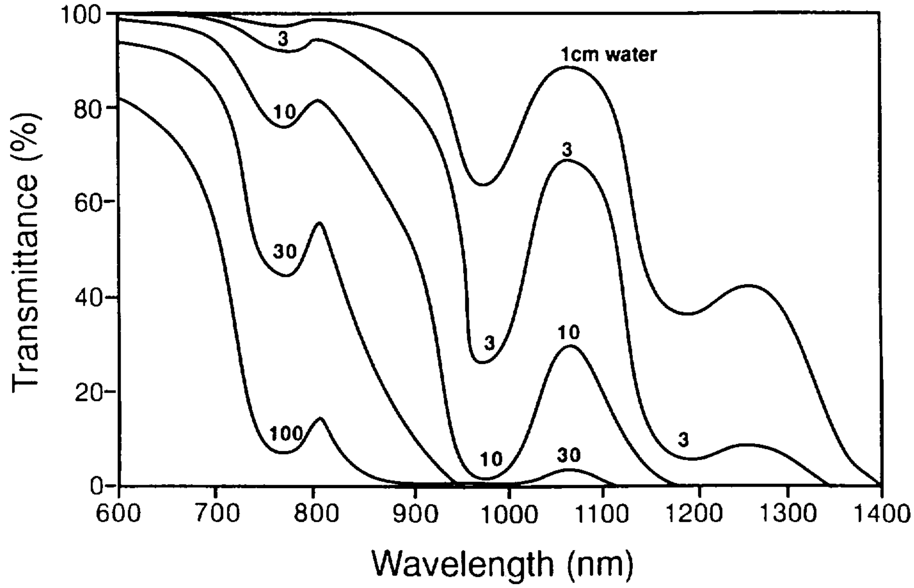

Fig. 1. Spectral transmission of liquid water of different path lengths (Curcio and Petty, 1951)

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).

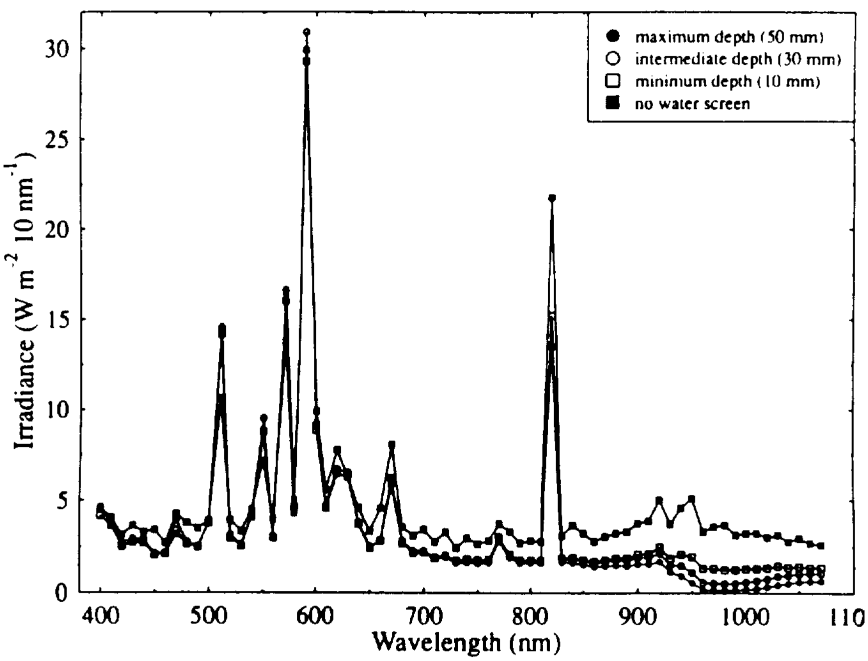

Fig. 2. Spectral energy distributions taken within a controlled environment room with a plate glass-water barrier where the water depth was either 10, 30 or 50 mm. The measurements were recorded 2 m below a lighting system comprising 4 x 1000 W Sylvania 'Metalarc' plus 4 x 1000 W Philips tungsten halogen 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 ($\mu mol\ m^{-2}s^{-1}$)		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.

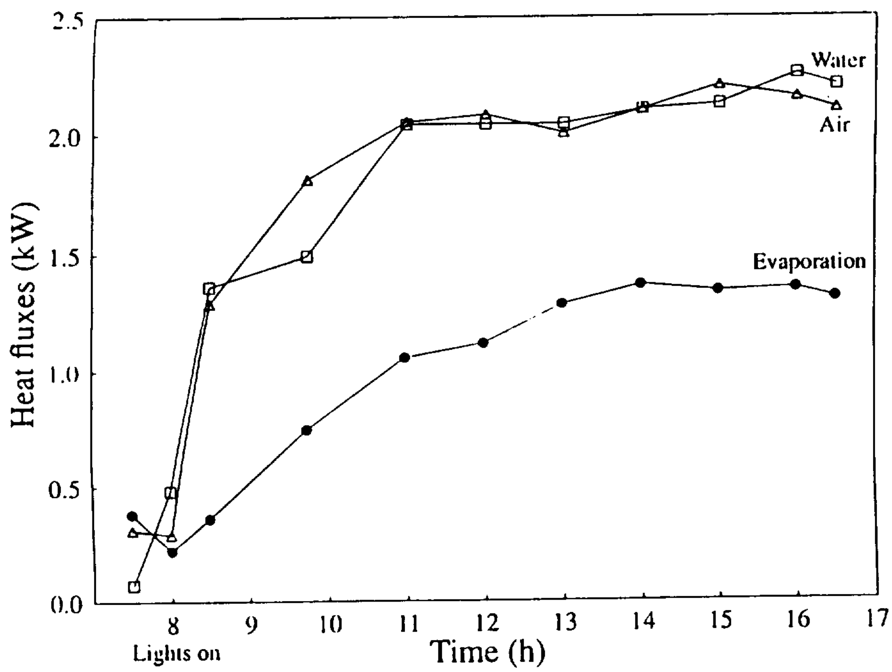

Fig. 3. Heat fluxes (kW) measured in the lamp loft of a controlled environment room with a lighting system comprising 4 x 1000W Sylvania `Metalarc' and 4 x 1000W Philips tungsten halogen lighting. Lights were switched on at 0800 h. The depth of the water on the thermal barrier was 46 mm and the flow 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).

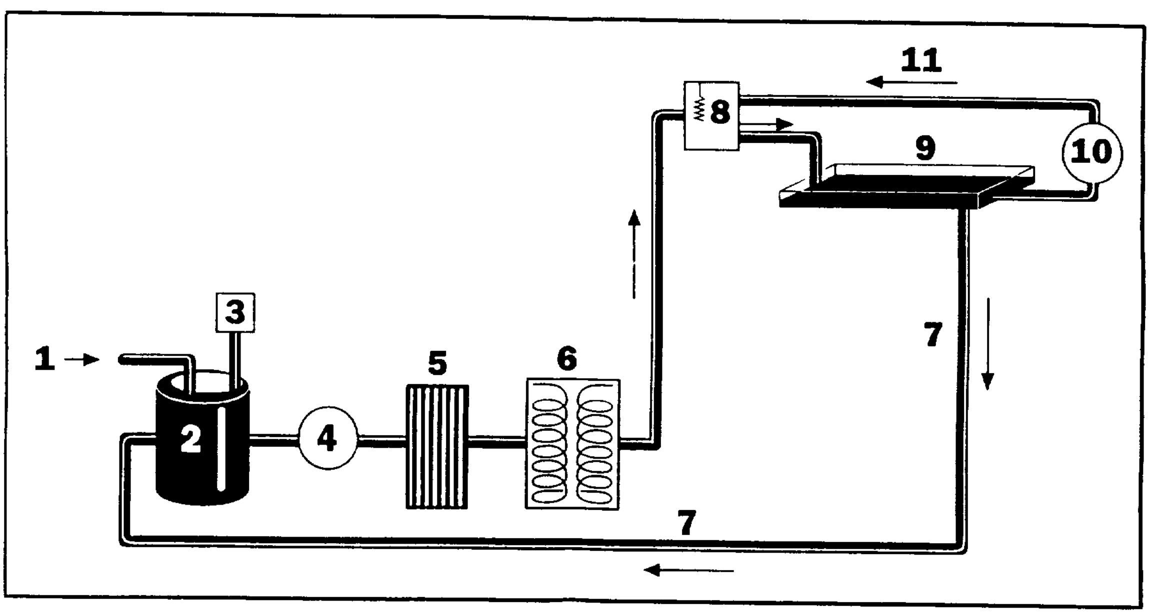

Fig. 4. Schematic diagram of the equipment layout and pipe circuits required for maintaining the temperature-controlled water supply to the plate glass-water thermal barriers used in the National Climate Laboratory (1. Inlet water supply; 2. Supply tank; 3. Injection system for algae control; 4. Circulation 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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