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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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.

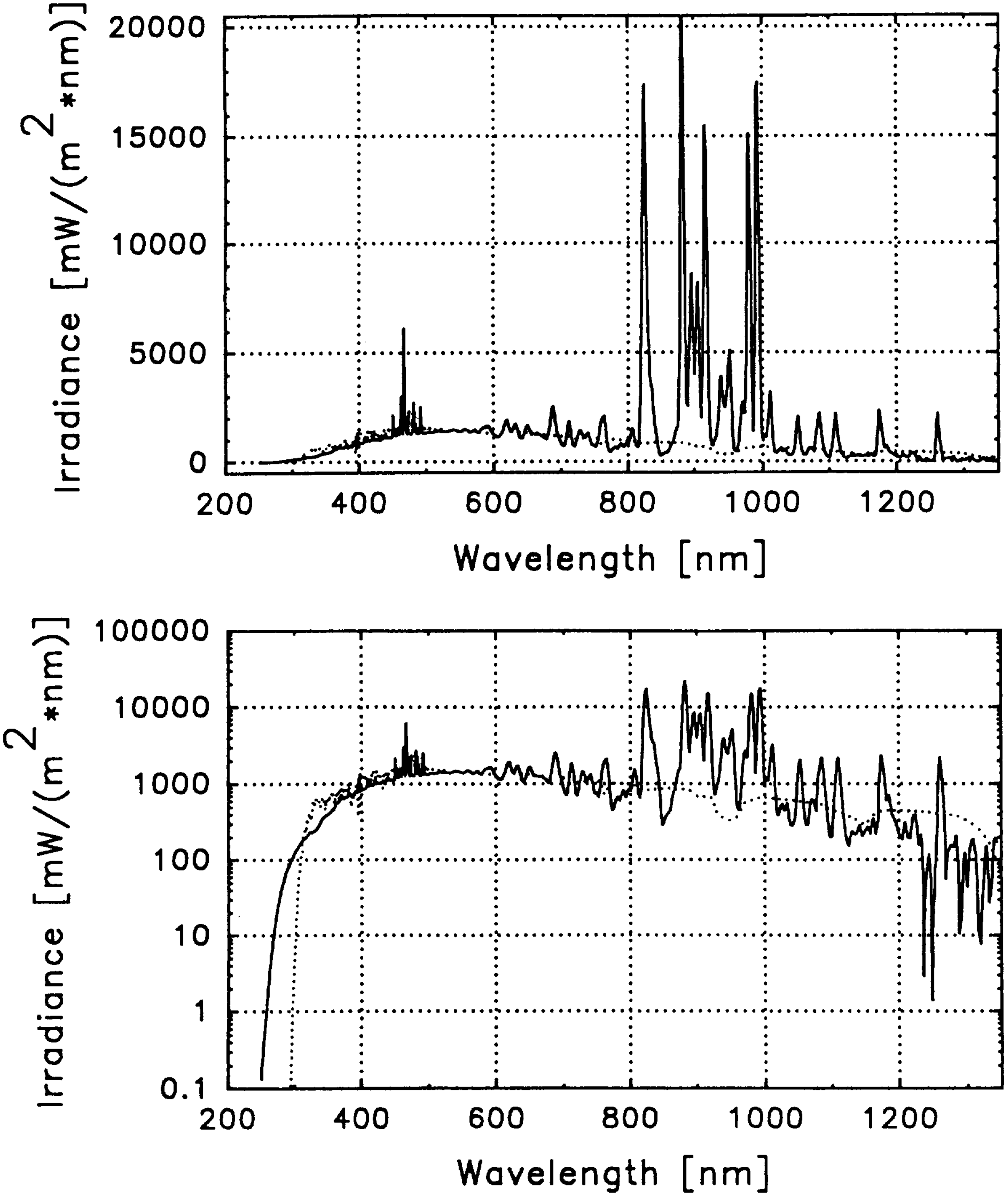

Fig. 1. Spectral irradiance of the unfiltered radiation of a long arc xenon lamp. The data are adjusted to 1940 μmol/(m2 s). The dotted line indicates the spectral irradiance of global radiation for a sun elevation of 60 degrees and an ozone value of 320 DU according to model calculations.
Fig. 1a (top).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

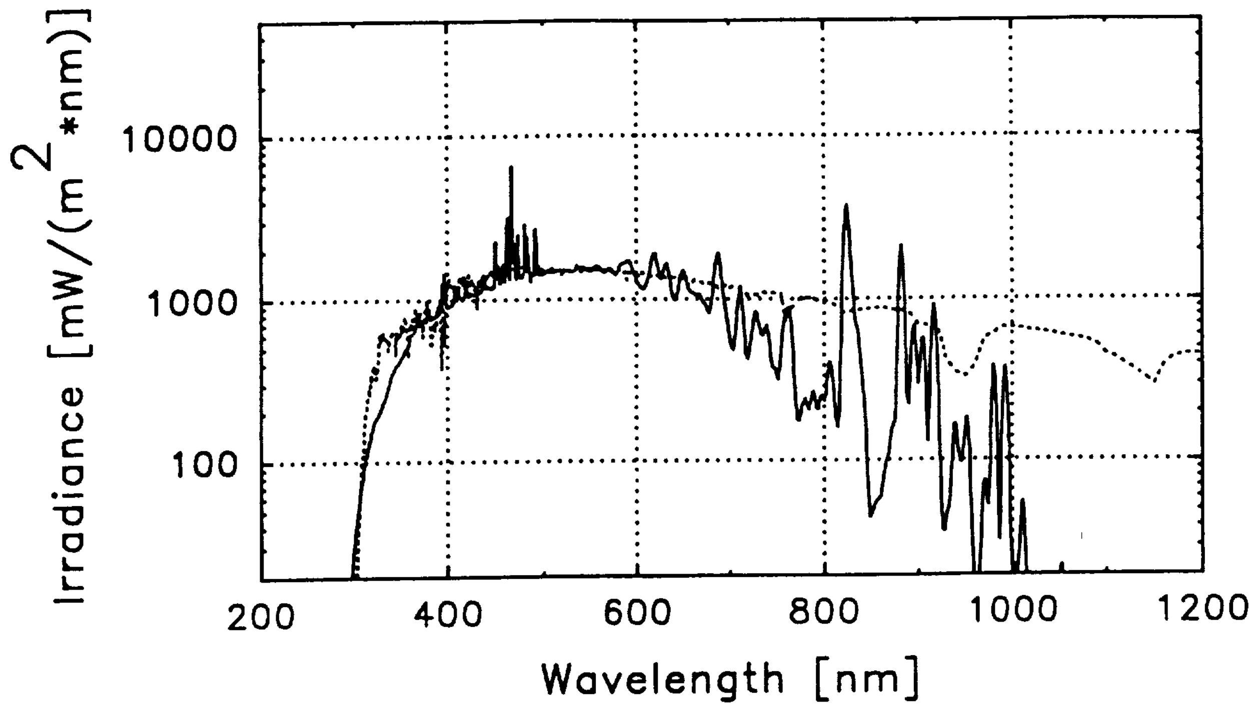

Fig. 2. Spectral irradiance of xenon radiation, filtered by an IR absorbing Schott glass KG 1. Further explanation see Figure 1.

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.

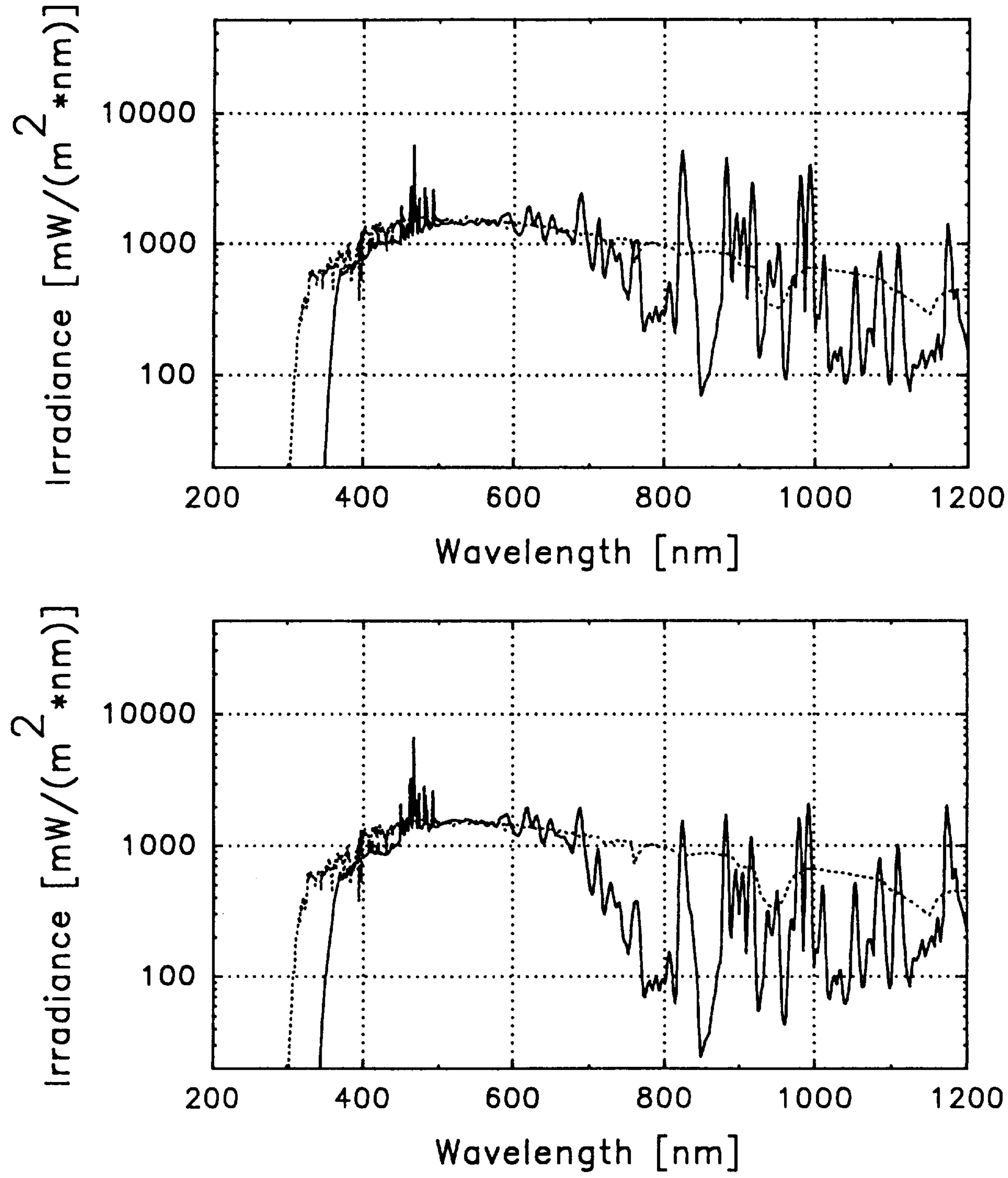

Fig. 3. Spectral irradiance of a xenon radiation, filtered by heat reflecting glass.
Fig. 3a (top). Schott type 112 filter.
Fig. 3b (bottom). Schott type 113 filter. For further explanations see Figure 1

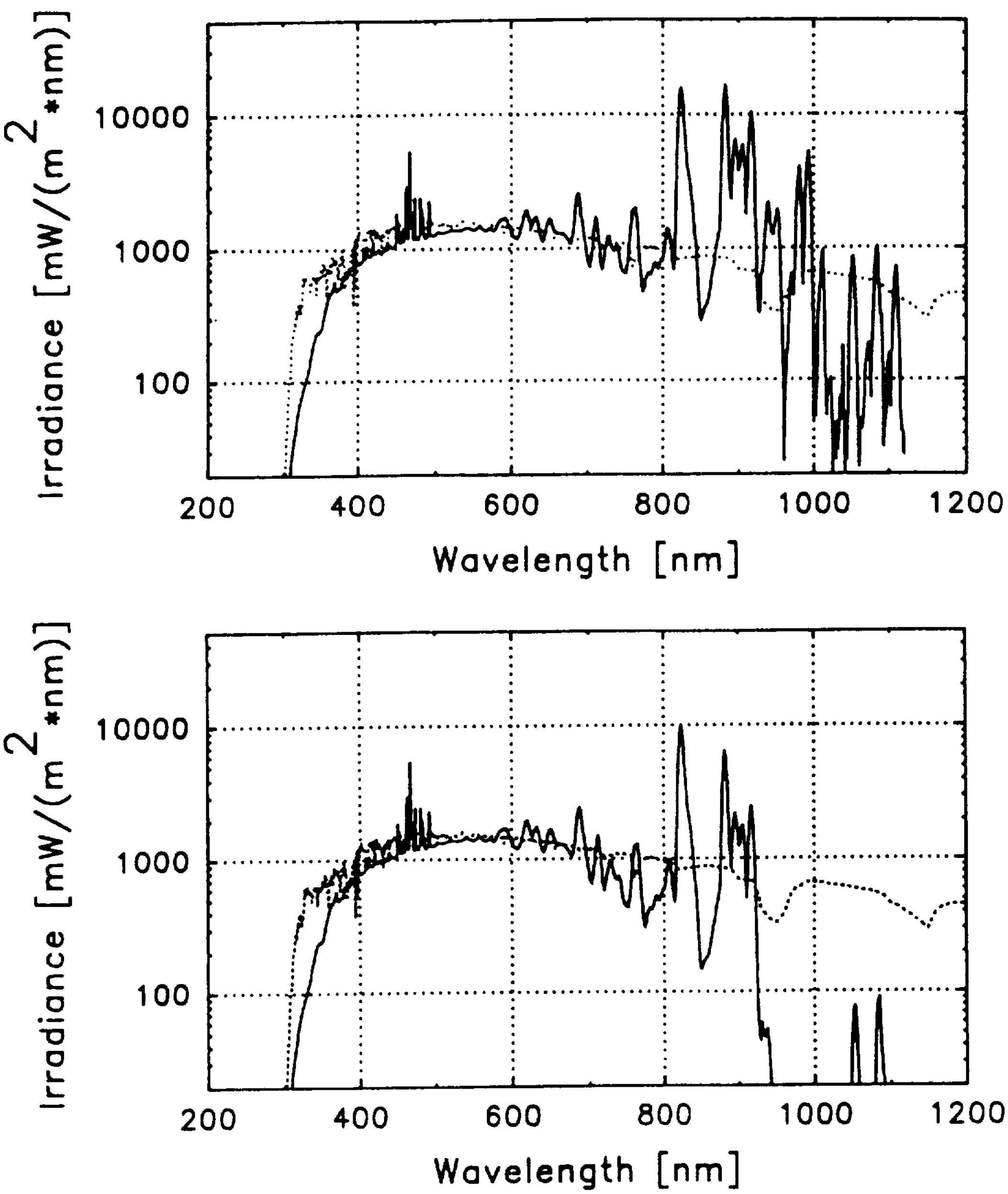

Fig. 4. Spectral irradiance of a xenon radiation, filtered by water contained in Tempax glass (Schott).
Fig. 4a (top). Water layer of 2 cm
Fig. 4b (bottom). Water layer of 20 cm. For further explanations see Figure 1.

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.

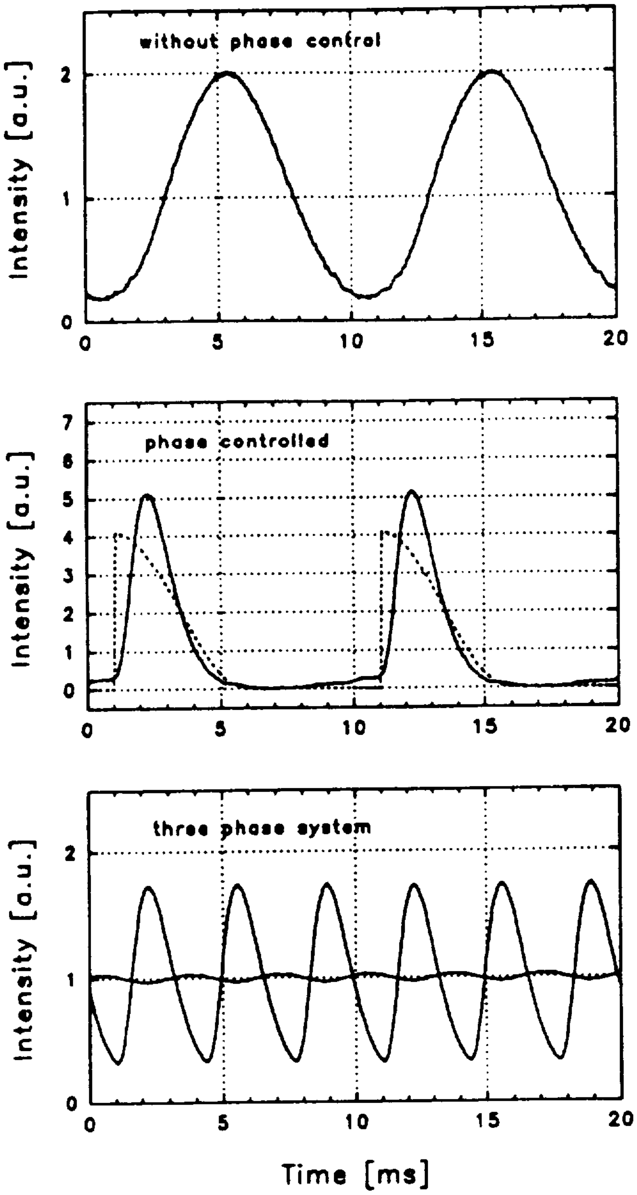

Fig. 5. Light ripple of an AC operated xenon lamp under different modes of operation
Fig. 5a (top). Single phase operation without phase control Imax/Imean = 2.
Fig. 5b (middle). Single phase operation with phase control (solid line), Imax/Imean = 5. The dotted line shows schematically the phase control 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	continuous + polychrome, > 6000K
Xe long-arc (XQO)	3000	25	500	
Xe long-arc max	?	30	4000	
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.

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