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

Donald A. MacLennan, Brian P. Turner, James T. Dolan, Michael G. Ury, and Paul Gustafson

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.

* Based on work supported by NASA Small Business Innovation Research (SBIR) Phase 1 Contract NAS10-11978

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.

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.

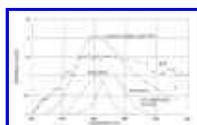


Fig. 1. Spectral Irradiance of 6700° CCT bulb (upper solid curve) with solar spectra (discrete points -- CIE Pub, 85, Table II). Lower curves are scotopic and photopic eye responses for comparison only.

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.

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) of 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.

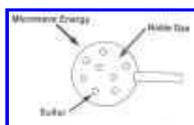


Fig. 3. Microwave Electrodeless Quartz Sulfur Bulb.

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.

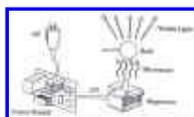


Fig. 4. Microwave Electrodeless Lamp Schematic.

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.

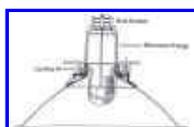


Fig. 5. Microwave Electrodeless Lamp showing Bulb Coupling.

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 effects 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 $M^{-2} \text{sec}^{-1}$ has demonstrated better performance (Sager). Total energy has been postulated as optimized at approximately 600 micro-moles $M^{-2} \text{sec}^{-1}$. By controlling the total energy output to that level, direct comparisons can be made between the 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.

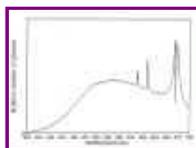


Fig. 6. Sulfur/lithium in the range 400-700 nanometers. The ordinate is proportional to the number of photons per second.

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.

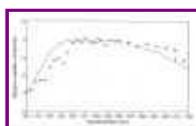


Fig. 7. Sulfur plus X in (continuous line) compared with the sun (discrete points). The ordinate is proportional to the number of photons per second.

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.
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*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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Researcher Comments Supplied By:

Steven J. Britz, Research Leader, United States Department of Agriculture, Building 046A, Room 1 BARC-W, Beltsville, MD 20705-2350

Robert J. Downs, Director, SPE Laboratory, College of Agriculture and Life Sciences, North Carolina State University, Raleigh, NC 27695-3635

Jerry Deitzer, Professor of Horticulture, Department of Horticulture, University of Maryland, College Park, MD 20742-5611

Robert Langhans, Professor of Floriculture, 20 Plant Science, Cornell University, Ithaca, NY 14853

John C. Sager, Advanced Life Support Division, NASA mailcode, MD-RES, Kennedy Space Center, FL 32899

Frank Salisbury, Professor, Plant Science Department, Utah State University, UMC 48, Logan, UT 84322-4280

Theodore Tibbitts, Professor of Horticulture, Department of Horticulture, University of Wisconsin, 1575 Linden Lane, Madison, WI 53706.

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