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In this Newsletter:

A.J. Both was invited to make a presentation on light uniformity underneath supplemental lighting systems at a recent International Lighting Conference in Quebec. His presentation begins on page 3 of this Newsletter. Electrical installations in greenhouses are major considerations in expanding existing facilities and erecting new facilities. The newly revised Agricultural Wiring Handbook is a valuable reference manual when faced with these circumstances. Page one describes the publication and provides information on how to add it to your library. Don't forget to register for the Greenhouse Design and Environmental Control Systems Short course to be held on January 8 and 9 at Cook College. Check the announcement on the last page of the Newsletter. ***We extend to you and your family the warmest season greetings and wish you all a happy and prosperous new year!***

Agricultural Wiring Handbook Available from NRAES now Revised

Correct design and installation of the electrical wiring system in your greenhouse is important to its smooth, safe and productive operation. For thirty-five years, subsequent revisions of the Agricultural Wiring Handbook have been devoted to planning safe, adequately sized, expandable, and efficient farm wiring systems. The twelfth edition of the 104 page Agricultural Wiring Handbook has recently been published by the National Food and Energy Council (NFEC) and may be ordered from NRAES, the Natural Resource, Agriculture, and Engineering Service.

The twelfth edition of the Agricultural Wiring Handbook has been updated to comply with the requirements of the 1999 National Electrical Code (NEC). The scope of the handbook includes electrical systems inside different types of farm buildings, as well as exterior farmstead distribution and service equipment. Information is provided for both wiring upgrades in older buildings and design recommendations for new construction. Wiring information is included for swine buildings, dairy and beef operations, and poultry facilities, as well as farm shops, machinery sheds, and grain facilities. The book's thirty-four chapters address six major topics: fundamental concepts and requirements; wiring considerations for farm buildings; metering, distribution and services; considerations for motor circuits; grounding; and wire sizing and motor tables. Over thirty-two illustrations and thirty-nine tables are included. New information includes a section on lightning and surge protection, an expanded discussion of wiring materials, new Code rules on service equipment, and updated wire sizing tables.

The Agricultural Wiring Handbook, NFEC-1, is available for $10.45 per copy, plus shipping and handling and sales tax, from:

NRAES,
Cooperative Extension,
152 Riley-Robb Hall,
Ithaca, NY 14853-5701.

For more information or a free copy of their publications catalog, contact NRAES by phone at (607) 255-7654, by fax at (607) 254-8770,
by e-mail at nraes@cornell.edu,
or on the web at http://nraes.org

Insect Exclusion from Greenhouses

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While controlled environment facilities have been used to grow plants for many purposes biological security is not always a design requirement. In recent years the commercial greenhouse industry has shown increased interest in security measures incorporated in the facility to reduce infestations of insects and disease. Some research facilities and government agencies operate quarantine facilities, which have long required biological safeguards with a wide variety of specifications depending upon perceived risk. The design of both commercial production greenhouses and quarantine facilities can benefit by careful integration of some of the principles of both. The authors have experience controlling ingress and egress of insects in either quarantine facilities or commercial greenhouses (Albright & Both, 1990, and Mears & Kahn, 1998). This paper will begin with a discussion of the relatively new concepts for quarantine greenhouse facility design and then review some of the significant developments in insect exclusion from commercial facilities. Finally, some concepts are presented that hold promise to further increase the effectiveness of insect exclusion from commercial greenhouse production facilities.

The paper by Mears and Both will be presented at the ACESYS IV Conference in Tsukuba, Japan on December 4-5, 2000. A complete copy of the paper is available upon request.

LIGHT UNIFORMITY UNDERNEATH SUPPLEMENTAL LIGHTING SYSTEMS

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Abstract

The use of supplemental lighting systems is increasing as more growers become interested in shortening the time needed for their crops to reach maturity, and/or in continuous plant production throughout the winter season. The installation and operation of supplemental lighting systems can add significantly to the overall energy requirement of a greenhouse operation. Obviously, the selection of energy efficient luminaires is an important design consideration. In addition, a high degree of light uniformity is required for consistent plant production throughout the growing area. Sometimes, different design criteria are used to characterize the light distribution in plant production facilities. Several of these design criteria are discussed in this study. Other times, the design of supplemental lighting systems for plant production facilities is optimized with the help of sophisticated computer software programs. Depending on the dimensions and characteristics of the plant production area, the available luminaire mounting height, the average height of the crop, and the number and placement of the particular luminaires selected, the software calculates the resulting light intensity and uniformity. Or, based on the desired light intensity, it calculates the required number and placement of the selected luminaires. One such software program is used in this study and its use demonstrates the importance of a careful measurement procedure for the evaluation of installed supplemental lighting systems.

1. Introduction

Lighting for greenhouse plant production is used for two very different purposes: photoperiod control (e.g., to induce flowering by shortening the duration of the nighttime), and supplemental lighting (to increase the instantaneous light intensity when the solar radiation level is low, or to add to the daily light integral). In this paper, we will only focus on supplemental lighting. Usually, high intensity discharge (HID) lamps are used to design supplemental lighting systems in commercial greenhouses. Two examples of such lamps are high- pressure sodium (HPS) and metal halide (MH) lamps. Designing supplemental lighting systems starts with the type and design of the luminaire (see the definitions section for an explanation of underlined words). Each luminaire component has a significant impact on the overall efficacy of the luminaire (Both et al., 1997). Each component is manufactured according to (allowable) manufacturing tolerances, which can result in a significant fluctuation in efficacy from luminaire to luminaire. As a result, each luminaire will perform (slightly) different. Keeping this in mind, three variables will further determine the overall light output and uniformity of supplemental lighting systems: lamp wattage, mounting height, and spacing between luminaires. The most common lamp wattages used for supplemental lighting systems in greenhouses are 400, 600, and 1000 watt (the higher the lamp wattage, the higher the lumen output of the lamp). Furthermore, increasing the mounting height results in decreasing light intensity (inverse square law), but the uniformity of the light distribution usually increases. And finally, decreasing the spacing between luminaires usually increases the light intensity, but also increases the number of luminaires installed. Using more luminaires results in higher electric power consumption, and, depending on their size and shape, more blockage of natural light from reaching the crop underneath.

It is clear from the above description that many factors influence the design procedures for supplemental lighting systems. In greenhouses, the luminaire mounting height has an apparent upper limit and the type of cropping system determines the distance between the top of the plant canopy and the luminaires. Usually, structural elements (e.g., trusses and posts) and other essential greenhouse components (e.g., heating pipes, electrical conduits, shade screens, fans, etc.) limit the placement of luminaires, unless all these elements were considered during the design phase of a new structure. In addition, in order to limit the number of supports (which usually double as electrical conduits) needed to mount the luminaires, luminaire placement is to a certain extend determined by the design of the greenhouse structure (especially the location of the trusses). Also, the type of crop grown and the desired growth rate determine the required light intensity, and to some extend the required light uniformity. Finally, the maximum number of luminaires available to a designer to provide the required light intensity is determined by their combined energy use and efficacy. (Note that although the initial capital expense for purchase and installation can be significant, the electric power consumption of HID luminaires over their lifetime is a much bigger cost factor.) A successful supplemental lighting designer needs to consider all these factors before a final design can be proposed. Inevitably, such a design is a compromise that favors those factors (e.g., light uniformity, or power consumption, or crop requirements, etc.) that are most important for the specific greenhouse application.

1.1. Luminaire mounting patterns

Most luminaires used for supplemental lighting are mounted in multiple rows. In these rows, the luminaires can be positioned in a regular (when the luminaire position in each row is the same) or a staggered grid (when the luminaire position alternates from row to row). Both these grid types can be further divided into a square (when the luminaires are positioned at the corners of an imaginary square) or a rectangular pattern (when the luminaires are positioned at the corners of an imaginary rectangle). In general, the staggered mounting grid provides better uniformity compared to the regular mounting grid, unless the distance between luminaires in the rows is relatively large.

1.2. Uniformity design criteria

Several uniformity design criteria have been used to evaluate the light distribution from supplemental lighting systems in greenhouses. Albright and Both (1994) described five uniformity design criteria (Table 1):
1) The ratio of the minimum to the maximum measured or calculated light intensity,
2) The ratio of the minimum to the average measured or calculated light intensity,
3) The complement of the average deviation from the mean divided by the mean,
4) The complement of the standard deviation divided by the mean,
5) A frequency graph of sorted (in ascending order) light intensity data.
Ciolkosz et al. (2000) proposed to add another design criterion:
6) Spacing Criterion (SC): the maximum lu-

minaire spacing for a given mounting height such that the light intensity halfway between four luminaires, and due to the light from all four luminaires, equals the light intensity directly underneath one of the luminaires and due to the light from that luminaire alone (Rea, 1993).

2. Materials and Methods

A supplemental lighting system was designed for a 750 m^2 gutter-connected greenhouse equipped with a floating hydroponics lettuce production system (Both et al., 1999). Each of the four greenhouse bays contained a shallow, self-contained pond, allowing a walkway around the entire greenhouse perimeter (except along most of the North wall, see Figure 1). The total lettuce production area measured 25.6 by 24.1 m, or 617 m^2. A luminaire mounting height of 3.2 m was available between the bottom of the luminaires and the top of the canopy (the gutter height was 4.3 m). The design asked for a light intensity of 200 μmol-m^{-2}-s^{-1} with maximum light uniformity. A 600-watt (requiring another 75 watt to operate the ballast) HPS luminaire (PL Light Systems, Beamsville, Ontario, Canada) with medium reflector (designed for a more rectangular illumination area) was selected. With the help of a commercial lighting design software package (Lumen Micro by Lighting Technologies, Inc., Denver, CO) the optimum number and placement of the luminaires was evaluated. The light uniformity was evaluated for both the entire growing area (400 measurement points in an evenly spaced 20 by 20 grid) and for a smaller area indicated by the marked area in Figure 1 (240 measurement points in an evenly spaced 12 by 20 grid). The marked area in Figure 1 represents a lettuce growing area in a greenhouse bay segment contained by successive trusses, 3.7 m wide and 6.1 m long. After installation and initial operation of the supplemental lighting system, a careful measurement was performed in the marked greenhouse area shown in Figure 1. These measurements were performed at the exact same location as previously calculated with the design software (240 measurement points, each measurement in the center of an area of 0.093 m^2).

3. Results

The final supplemental lighting design is shown in Figure 1, in which the location of each of the 144 luminaires is represented by a small square and positioned in a square, staggered mounting pattern. The light intensity and uniformity calculated with the design software and based on the design shown in Figure 1 are shown in Table 2. The measured light intensity and uniformity of the marked area shown in Figure 1 (after installation of the design) are also shown in Table 2. Figure 2 shows the calculated light intensity for the entire lettuce growing area. Figure 3 shows the frequency graph for the calculated light intensities.

Continued on next page

Industry Statistics

The 1999 wholesale value of floriculture crops was up 4 percent from 1998, according to USDA's Floriculture Crops Summary which was released online. Wholesale crop value for growers with $10,000 or more in sales is estimated at $4.1 billion for 99 compared with 3.95 billion in 1998. California was again the leading state with crops valued at $796 million, up 1 percent. The number 2 state listed was Florida, up 7 percent. These two states accounted for 36 percent of the total value. The top five states were California, Florida, Texas, Michigan and Ohio totaling $2.10 billion, 51 percent of the total production in the United States. ***Courtesy of Long Island Horticulture News, June 2000, Ralph Freeman Editor.***

4. Discussion

Due to the daily movement of the lettuce crop through the greenhouse in the East-West and West-East directions, light intensity and uniformity along the North and South wall of the greenhouse was considered more important compared to along the East and West walls (the plants remain in a location along the East and West walls with less uniform light only for one day). Therefore, more luminaires were mounted along the North and South walls to improve light intensity and uniformity along these walls. Using this same technique, the light intensity and uniformity along the East and West wall could have been improved at the expense of installing more luminaires.

Most lighting design software packages use standardized photometric data as input for their calculations. These photometric data are usually obtained from careful measurements of a single (representative) luminaire. However, such data was not available for the particular luminaire used in this study. Therefore, photometric data for a similar 400 watt HPS luminaire were used and scaled (using a multiplier) to represent the 600 watt luminaire. It is important that all luminaire manufacturers provide photometric data for all their luminaire models to lighting designers. It is also important to realize that because the designs are based on photometric data from a single luminaire, usually higher light uniformity is predicted compared to what is obtained after installation (see Table 2 for a good example).

Designing supplemental lighting systems for tall greenhouse crops (e.g., tomato) creates a dilemma: for what height of the crop should the light uniformity be optimized? As the crop grows, the distance between the luminaires and the top of the plant canopy decreases, usually increasing light intensity (especially close to the luminaires) and decreasing light uniformity. In most cases, the designer will focus on the height of the top of the plant canopy, without worrying about light uniformity within the canopy. Light uniformity within a plant canopy is very difficult to obtain due to the absorption, reflection, and transmission of light by the plant leaves.

When evaluating the light uniformity of supplemental lighting systems, it is important to carefully consider at which locations the light intensity should be evaluated. As can be seen in Figure 2, the light intensity usually drops rapidly near the perimeter of the design. Whether and how much of the perimeter is included in the analysis will have a significant impact on the overall uniformity evaluation. As stated before (Both, 1994), when the area under consideration is less than 20 m^2, the light intensity in the center of each 0.25 m^2 (0.5 by 0.5 m) should be considered. When the area is more than 20 m^2, the light intensity in the center of each m^2 (1 by 1 m) should be considered. The fewer the number of data points and the further away from the perimeter of the design, usually, the more favorable the uniformity analysis.

Table 1 lists six uniformity criteria. Uniformity Criterion (UC) 1 uses only two data points and is thus deemed less suitable. UC 2 included all data points (to calculate the average) and is therefore an improvement. UC 3, 4, and 5 are the most suitable for a careful uniformity analysis, with little difference between UC 3 and 4. The Spacing Criterion (UC 6) can be used to estimate the number of luminaires required to uniformly light a particular growing area. However, for the design of supplemental lighting systems in greenhouses, the last part of the definition used by Rea (1993) should be modified to read: "…, equals the light intensity directly under one of the luminaires and due to the light from *all surrounding luminaires*". This modification is needed because in most greenhouse supplemental lighting systems most locations receive light from several (sometimes many) luminaires.

Definitions

The inverse square law states that the light intensity decreases with the square of the distance from the light source (moving twice as far away reduces the light intensity by a factor of four). Note: this law is valid for point light sources only, but can be used for greenhouse supplemental lighting systems when the distance between the measurement location and the light source is at least five times the maximum diameter of the source (i.e., when the measurement is at least 1.5 m away from most commonly used HID luminaires).

The lumen is the unit of luminous flux, representing the power (brightness) of visible light (1 lux equals 1 lumen-m^{-2}; 1 foot-candle equals 1 lumen-ft^{-2}).

A luminaire consists of a current-regulating ballast, a lamp bulb, a reflector, and sometimes a lens or shield.

Luminaire efficacy relates the light output from a luminaire to the electric power input.

Mounting height is the distance between the bottom of the luminaire (or the center of the lamp bulb) and a measurement plane underneath (usually the top of the plant canopy).

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ACESYS IV International Conference

Dr. David Mears and several former faculty colleagues are invited speakers at this international conference being held in Tsukuba, Japan. They include, Dr. K.C. Ting, now Chairman of the Bio and Ag Engineering Dept at Ohio State Univ., Dr. Gene Giacomelli Director of the Controlled Environment Ag Program at Univ. of Arizona, and Bill Roberts Emeritus Professor of Rutgers. The Conference will be held Dec 4-5, 2000

Table 1. Design criteria for the evaluation of the uniformity of light distribution from supplemental lighting systems in greenhouses.

Uniformity Criterion (UC)	Equation	Acceptable Range
1. Ratio of the minimum to the maximum measurement	Y_{Min}/Y_{Max}	> 0.7
2. Ratio of the minimum to the average measurement	Y_{Min}/Y_{Ave}	> 0.8
3. The complement of the average deviation from the mean divided by the mean	$1 - ((\Sigma\lvert Y_i - Y_{Ave}\rvert)/(nY_{Ave}))$	> 0.75 (preferably > 0.9)
4. The complement of the standard deviation divided by the mean	$1 - (\sqrt{(\Sigma(Y_i - Y_{Ave})^2/(n-1))})/Y_{Ave}$	> 0.75 (preferably > 0.9)
5. Frequency graph	see Figure 3	at least 90% of the measurements within ±15% of the average
6. Spacing Criterion	see text for definition	--

Where:

Y_i	=	light measurement at location i
Y_{Min}	=	minimum light measurement over the growing area
Y_{Max}	=	maximum light measurement over the growing area
Y_{Ave}	=	average light measurement over the growing area
n	=	number of light measurements taken over the entire growing area

Table 2. Calculated (with the lighting design software package Lumen Micro) and measured light intensity data (in $\mu mol\text{-}m^{-2}\text{-}s^{-1}$) for the entire lettuce production area, and for the area marked in Figure 1.

	Growing area (calculated)	Marked area (calculated)	Marked area (measured)
Average	187.2	202.6	201.7
Maximum	210	206	209
Minimum	100	198	188
St. Dev.	26.5	2.09	4.13
n	400	240	240
UC 1	0.476	0.961	0.900
UC 2	0.534	0.977	0.932
UC 3	0.888	0.992	0.984
UC 4	0.859	0.990	0.979
UC 5	84.5%	100%	100%

North Wall, shared with an adjacent headhouse

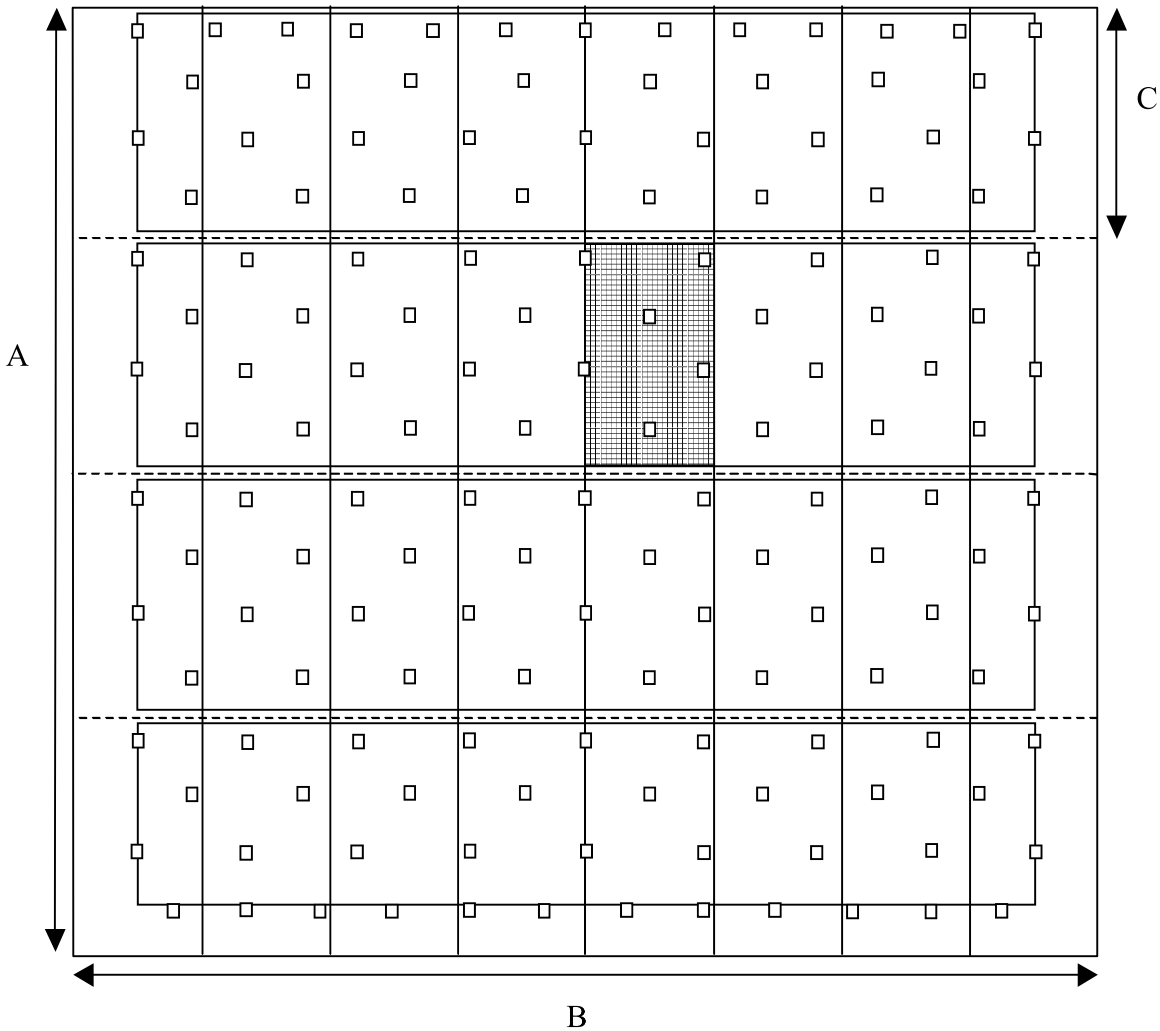

Figure 1. Design of a supplemental lighting system using 144 HPS luminaires (with 600 watt lamps) to provide a uniform light intensity of 200 μmol-m^{-2}-s^{-1} over the entire growing area (mounting height = 3.2 m, A = 25.6 m, B = 29.3 m, and C = 6.4 m).

WWW

In a research study by AgWeb.com, Inc. it was found growers are indeed online looking to the Internet for information to enhance their purchasing power.

Amongst 400 mid-western farmers who each averaged over 1500 acres Internet access is now mainstream with an expected 20 percent growth in online usage by 2001. While it is not surprising that Internet access is highest among younger, more-educated growers with large acreage, the study uncovered new information on what drives Internet usage and the potential for e-commerce. The study found that computer adoption today appears less motivated by record keeping and more by Internet access. This is a major shift from a few years ago when Internet access was an afterthought to owning a personal computer. E-commerce plays a growing role in management decisions such as buying online as well as using online information for price discovery. Growers are still testing the waters and exploring how the Internet can be a management tool.

Long Island Horticulture News 6/2000

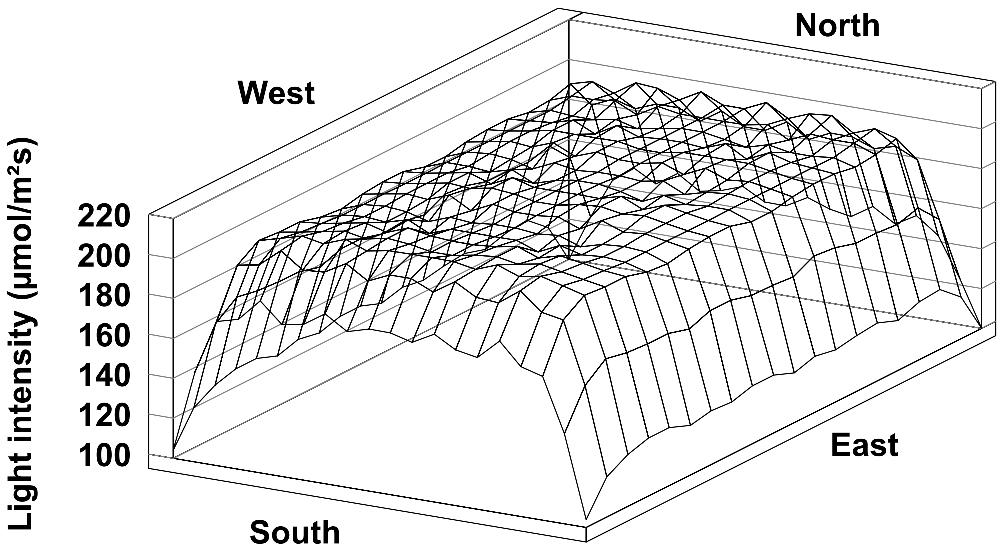

Figure 2. Light intensity for the entire lettuce growing area (25.6 by 24.1 m) as calculated with the lighting design software package Lumen Micro. The 400 light intensities were calculated in steps of 1.35 m in the E-W direction and 1.27 m in the N-S direction.

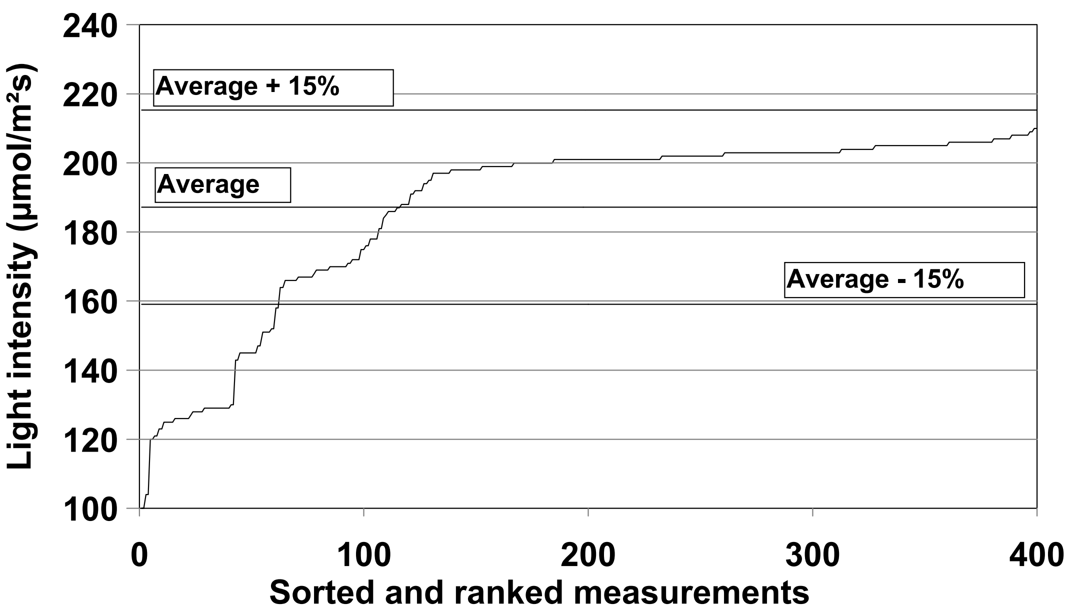

Figure 3. Frequency graph for the calculated light intensities (using the lighting design software package Lumen Micro) for the entire lettuce growing area. A total of 62 measurements had a value of less than 159.1 µmol-m^{-2}-s^{-1} (the average minus 15%).

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HORTICULTURAL ENGINEERING

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Horticultural Engineering on the Web

This Issue of Horticultural Engineering, like previous ones, will soon be available on the internet at:

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We will send an e-mail announcing each Horticultural Engineering Newsletter as it is posted on our web site.

Thanks to those of you who have elected to receive this newsletter via the Web. We appreciate you helping us save the duplicating, postage, and handling costs in our department particularly since our staff has been greatly diminished.

Environmental Control and Design of Greenhouse Systems

January 8 and 9, 2001

This popular greenhouse engineering and environmental control short course will again be offered. Dr. A.J. Both is the course coordinator and he will be giving several presentations during the 1-1/2 days of lectures and demonstrations. The entire course scheduled was published in an earlier edition of this newsletter. The one-half day **tour** is the feature of the program and will include visits to our new open-roof demonstration greenhouse, Kube Pak Corporation, and the Burlington County Resource Recovery Greenhouse which is operating on methane gas produced at the adjacent landfill.

Contact Margaret Stegmann in the office of Continuing Professional Education at Cook College for registration information. 732 932 8451. General information about the course is available from A.J. Both. Mark these dates and plan to attend this very informative course.