SOURCES, INTENSITIES, AND SPECTRAL DISTRIBUTION OF ELECTROMAGNETIC ENERGY FOR PLANT IRRADIATORS

by

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TABLE OF CONTENTS

INTRODUCTION

It has been found that tomatoes grown in a greenhouse do not have the ascorbic acid content of tomatoes grown in the open field (1). Since some of the natural radiation from the sun is absorbed by the greenhouse glass, it seemed logical to assume there was a possibility of increasing the ascorbic acid content of greenhouse tomatoes by irradiation with supplementary artificial light sources. This project was undertaken cooperatively by the departments of physics, horticulture, botany, foods and nutrition, and mathematics.

Previous work indicated that the plant production of ascorbic acid is a photochemical process (2). It was also found that the ascorbic acid content of plants decreased at night but returned to normal when the plants were again exposed to sunlight or artificial light from incandescent radiators (3,4,5,6). Furthermore, Sugawara found that the ascorbic acid content of tomatoes irradiated by white, red, orange-red, green, and blue lights decreased in the order in which the lights are listed (7). This was not substantiated by later work.

Most of the studies of plants grown under artificial light sources have been incomplete in the descriptions of the intensity and spectral distribution of the lights used. Furthermore, recent fundamental developments in the lighting industry have resulted in the production and availability of a much wider variety of sources with high energy in the various regions of the spectrum.

The portion of the work for which the department of physics assumed responsibility was the selection and procurement of the radiation sources, the installation and operation of these sources, and the determination of their energy and spectral distribution. Essentially, this is a report concerning the above; however, related topics which are necessary for an understanding of the basis for certain choices and measurements will be added.

DESCRIPTION AND SELECTION OF RADIATION SOURCES

It is known that the glass in a greenhouse absorbs a part of the radiation in all regions of the electromagnetic spectrum. It has a particularly high absorption coefficient for the near ultraviolet and is opaque to the extreme ultraviolet. This, combined with the fact that previous work does not establish any particular region of the spectrum which is particularly effective in the production of vitamin C, made it seem desirable to include sources rich in several of the individual regions of the spectrum and one source giving a general radiation.

It was impossible to find ideal sources. A brief description of the five selected follows:

Source 1. For the general radiation source a group of four 500-watt clear glass incandescent bulbs was chosen. Each of these emitted 8800 lumens of light flux.

Source 2. As a source near the red end of the spectrum a pair of General Electric Na-9 sodium vapor Luminaires were used. Each of these lights consumed 180 watts of power and emitted 10,000 lumens of light flux.

Source 3. For a radiation source near the blue end of the spectrum a group of four General Electric green fluorescent tubes was chosen. Each one was four feet long, consumed 40 watts of power, and emitted 2800 lumens of light flux.

Source 4. As a near ultraviolet source a group of four General Electric BL-360 black light fluorescent tubes was selected. Each tube was four feet long, required 40 watts of power, and emitted 175 lumens of visible light flux and 4.9 watts in the ultraviolet region.

Source 5. For a source of extreme ultraviolet a group of four General Electric H3-85 high pressure mercury vapor lamps with the glass shields removed were selected. Each lamp consumed 85 watts of power. A large percentage of this power was dissipated as ultraviolet light.

SPECTROGRAMS AND DENSITOMETER MEASUREMENTS

A series of spectrograms of each of the light sources were taken with a Bausch and Lomb medium quartz spectrograph. Each source was placed 20 cm from the entrance slit. This slit was adjusted for 2 mm length and 50 microns width. Five spectrograms with exposure times of 1, 5, 10, 30, and 60 seconds were made for each source. Kodak Panchromatic plates were used. The plates were developed in Eastman DK-20 developer under standard conditions.

Relative intensity measurements were made by means of a Leeds and Northrup recording densitometer. Each plate was passed through the densitometer at a speed of 20 mm/min.

Analyses of the spectra for each illuminant are listed below:

Source 1. The spectrum shown in Plate I of the radiation from the incandescent source is seen to be continuous. The lowest wave length is approximately 3000 Å, and the intensity rises with increasing wave length, probably reaching a maximum in a region beyond the range of the spectrograph.

Source 2. Plate II shows the sodium vapor light to be virtually monochromatic. By far the greatest intensity of light emission is at the 5890 Å wave length. Weaker sodium lines are at 3302 Å, 5688 Å, and 6160 Å. A group of lines seen in the red end of spectrograms A, B, and C is caused by a small amount of neon in the tube. For a source of intense yellow light, this sodium vapor luminaire is unparalleled, although the monochromatism may not be desired in certain applications.

Source 3. As seen on Plate III, the spectrum of the green fluorescent tube shows strong mercury lines at 3132 Å, 3650 Å, 4047 Å, 4078 Å, 4359 Å, 5461 Å, and 5790 Å. Superposed over these characteristic radiations is a band extending from approximately 4900 Å to 6100 Å. This band is the fluorescent spectra produced by the zinc silicate phosphor coating on the inside of the tube. Excitation of the phosphor by the 2537 Å mercury vapor radiation causes light to be emitted in the given range.

Source 4. The spectrum of the ultraviolet fluorescent tube, Plate IV, also shows characteristic mercury lines. The superposed continuous radiation from 3200 Å to 4500 Å wave length is the spectra produced from the 360 BL phosphor coating on the inside of the tube. This coating is sensitive to and excited by radiation from 2500 Å to 2800 Å. The highest intensity of the radiation is at approximately 3600 Å wave length.

Source 5. Plate V shows the spectrum of the mercury vapor source. Radiant energy was emitted throughout the entire range of the spectrograph. The "pressure broadening" of the characteristic mercury lines is shown. Obviously, this high pressure arc produces a "cold" light source with some radiation present in all regions from 2450 Å to 6700 Å.

Plate VI shows the spectrum from mercury vapor light passed through a sample of greenhouse glass. Radiation not completely absorbed by the glass was restricted to the range above 3100 Å wave length. The spectral intensity of the radiation transmitted through the glass from 3100 Å to 3250 Å is extremely low. From 3250 Å to 3600 Å the absorption coefficient of the glass decreases still further. From 3600 Å to

7000 Å the absorption coefficient for the greenhouse glass is quite low.

It is recognized that the measurements made with the spectrograph and densitometer are crude and only roughly qualitative. Unfortunately, the accepted experimental procedure necessary for quantitative work was not followed.

ARRANGEMENTS OF LIGHTS AND TEST PLOTS

The irradiations were performed in the end of a greenhouse which was unshaded by other buildings or trees. The plant bed within the greenhouse was 94 feet long and 6 feet wide with an average of 6 feet of space between the top of the bed and the greenhouse roof. Tomatoes in the bed were planted in 42 rows at right angles with the length of the bed and with three plants in each row. This arrangement provided 26 inches of space between both rows and plants.

Lights were arranged over the plants for the two successive crops as shown in Figs. 1 and 2. Each test plot thus contained nine plants directly exposed to each group of lights. The lights, all at the same height, were spaced and provided with reflectors so as to give as nearly equal radiation as possible to the nine plants affected. Tomatoes subjected to stray radiation from the artificial sources were not used in the statistical study.

To determine the geometrical shadow of the artificial light sources, the distribution of light was measured at night with the radiators operating. A Weston photometer, having a sensitivity of 60 foot-candles for full scale deflection, indicated zero intensity three rows and beyond each test plot. This was true even when the plant growth necessitated raising the lights to their full height of five feet above the bed.

For sufficient support with minimum shading, three-eighths inch pipe was used in making the suspension frames for the lights. The method of construction may be seen in Plates VII, VIII, and IX. To keep the sources above the growing plants, each frame could be moved up vertical supports. In the early stages of the development of the plants, the lights were kept one foot above the plants. In the later stages, the plants grew beyond the lights to the roof of the greenhouse.

Wiring of the lights was conventional and followed the manufacturer's specifications for each light.

EXPERIMENTAL PROCEDURE AND RESULTS

The First Crop

The plants used in the experiment were grown by the department of horticulture and transferred to the test bed. When the third cluster of tomatoes began to form on the vines, supplementary radiation was superposed over the natural. Irradiation of the test plots for nine-hour periods each day started October 13, 1947, and ended January 18, 1948. Daylight periods of operation chosen were from 8:00 a.m. to

5:00 p.m.

Three groups of lights were used for the first irradiation: four incandescent bulbs, four green fluorescent tubes, and two sodium vapor luminaires. The arrangement of these lights is shown in Fig. 1. After the lights were installed, intensity measurements were made with a Weston Illumination Meter, Model 603. These data are shown in Table 1. A "Viscor" filter was used, and consequently the measurements represent "eye response" intensity.

During the early stages the lights were manually operated. Later a Tork time clock switch was installed. Incandescent and fluorescent lights were practically instant starting, but the sodium vapor luminaires required approximately 30 minutes to come to full brilliance.

At the time the plants reached three feet in height, photometer readings around the third cluster of fruit on each plant in the test plots were made. These readings are plotted in Fig. 3. The data were taken at night and represent only the supplementary radiation. Variation of the readings because of non-uniform shadowing is quite marked.

At intervals during the experiment, Dr. H. C. Fryer, statistician for the Kans. Agr. Expt. Sta., and Dr. J. C. Frazier, botanist for the Kans. Agr. Expt. Sta., selected the fruit whose ascorbic acid content was to be found. Determinations of the ascorbic acid content were made under the direction of Dr. Leah Ascham. The resulting data were analyzed statistically by Dr. Fryer.

In passing, it is interesting to note that the total production of tomatoes was considerably below normal. It is possible that this should be associated with the fact that meteorological records kept by the department of physics at Kansas State College indicate only about 50 per cent sunshine during that interval.

The Second Crop

After the first crop had matured, the plant bed was sterilized and certain deficient chemicals were added. New plants of the same variety as the first irradiated crop were transferred to the bed. When the third cluster of tomatoes began to form on the vines, irradiation was begun. This second irradiation was for the same time interval each day as that for the first crop and was made from March 7, 1948, to June 17, 1948.

Four groups of lights were used for the second irradiation: four incandescent bulbs, four green fluorescent tubes, four ultraviolet fluorescent tubes, and four unshielded mercury vapor bulbs. Figure 2 shows the arrangement of these lights. The incandescent and fluorescent light sources were practically instant starting, but the mercury vapor bulb required approximately 20 minutes to come to full brilliance.

At the end of five days of irradiation, the plants beneath the mercury vapor bulbs exhibited severe burns, so three of the light sources were removed. To prevent further destruction of the plants, the remaining mercury vapor bulb was operated only **four** hours each day. Although the plants still showed some burns, they recovered sufficiently to bear fruit.

Measurements of intensity for this group of lights, similar to those shown in Table 1 for the group used in connection with the first crop, are given in Table 2.

Again the ripened fruit was systematically picked and analyzed for ascorbic acid content.

DISCUSSION

It is not the purpose of this thesis to discuss the over-all results of the cooperative experiment. However, it should be stated that statistical analyses of all data obtained indicate that the ascorbic acid content of tomatoes grown in the plot under the ultraviolet fluorescent lights was slightly higher than for any other tomatoes, and statistically significant. This leads one to suggest that, if possible, a light source rich in the spectral region from 2800 Å to 3200 Å should be used in future experiments.

It is also desirable that measurements of absolute intensity be made for all the lights. A sensitive thermopile should be obtained for this purpose.

EXPLANATION OF PLATE I

Spectrograms and densitometer measurements of the incandescent light:

A. For 60 seconds exposure time

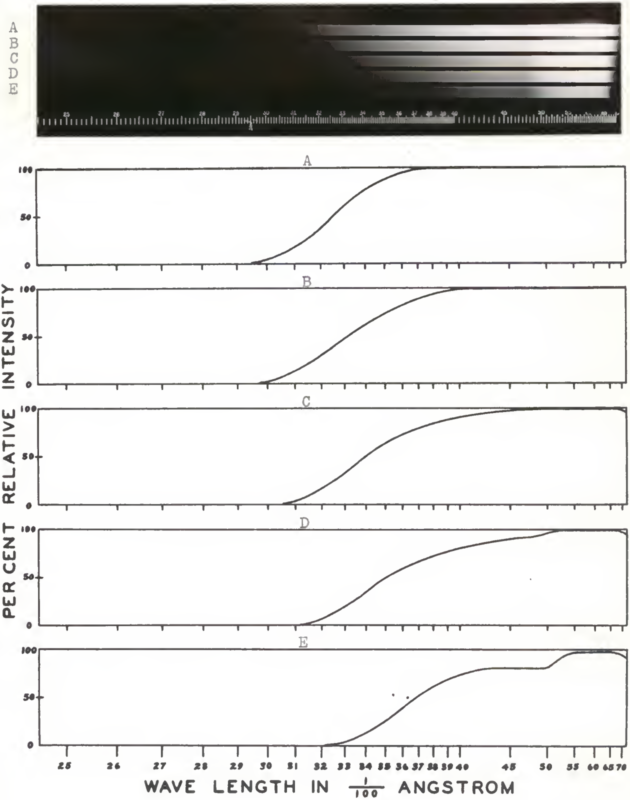
B. For 30 seconds exposure time

C. For 10 seconds exposure time

D. For 5 seconds exposure time

E. For 1 second exposure time

PLATE I


A
B
C
D
E
PERCENT RELATIVE INTENSITY
100
50
0
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
45
50
55
60
65
70
WAVE LENGTH IN 1/100 ANGSTROM

EXPLANATION OF PLATE II

Spectrograms and densitometer measurements of the sodium vapor light:

A. For 60 seconds exposure time

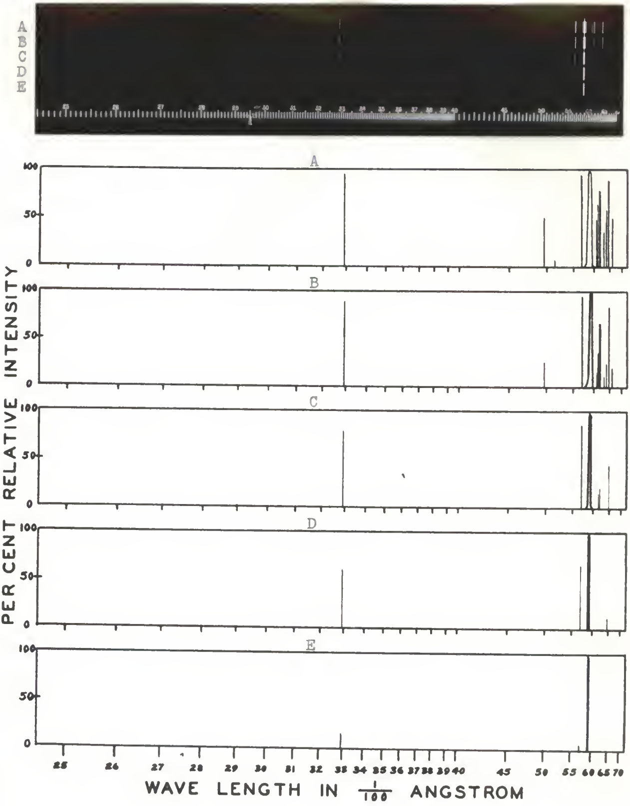
B. For 30 seconds exposure time

C. For 10 seconds exposure time

D. For 5 seconds exposure time

E. For 1 second exposure time

PLATE II


A
B
C
D
E
PER CENT RELATIVE INTENSITY
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28
29
30
31
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33
34
35
36
37
38
39
40
45
50
55
60
65
70
WAVE LENGTH IN $\frac{1}{100}$ ANGSTROM

EXPLANATION OF PLATE III

Spectrograms and densitometer measurements of the green fluorescent light:

A. For 60 seconds exposure time

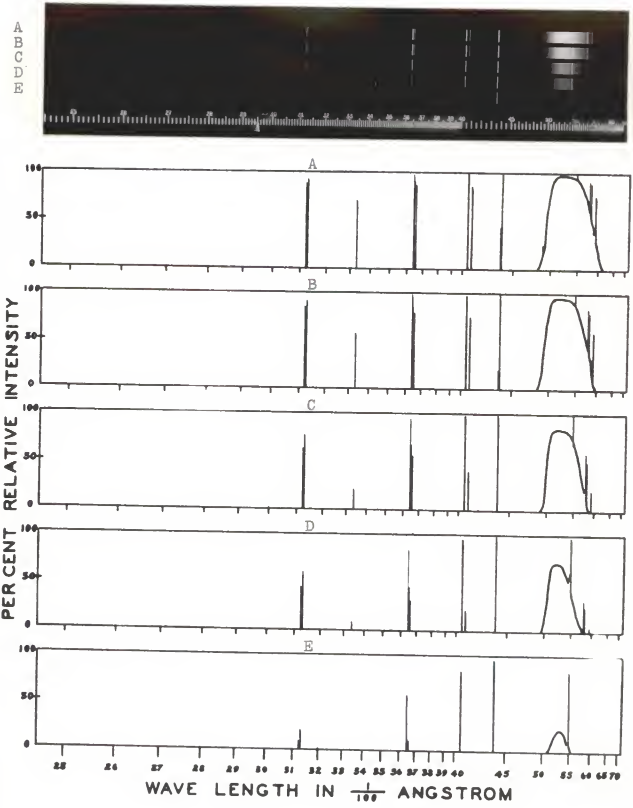
B. For 30 seconds exposure time

C. For 10 seconds exposure time

D. For 5 seconds exposure time

E. For 1 second exposure time

PLATE III


A
B
C
D
E
PERCENT RELATIVE INTENSITY
100
50
0
WAVE LENGTH IN 1/100 ANGSTROM

EXPLANATION OF PLATE IV

Spectrograms and densitometer measurements of the ultraviolet fluorescent light:

A. For 60 seconds exposure time

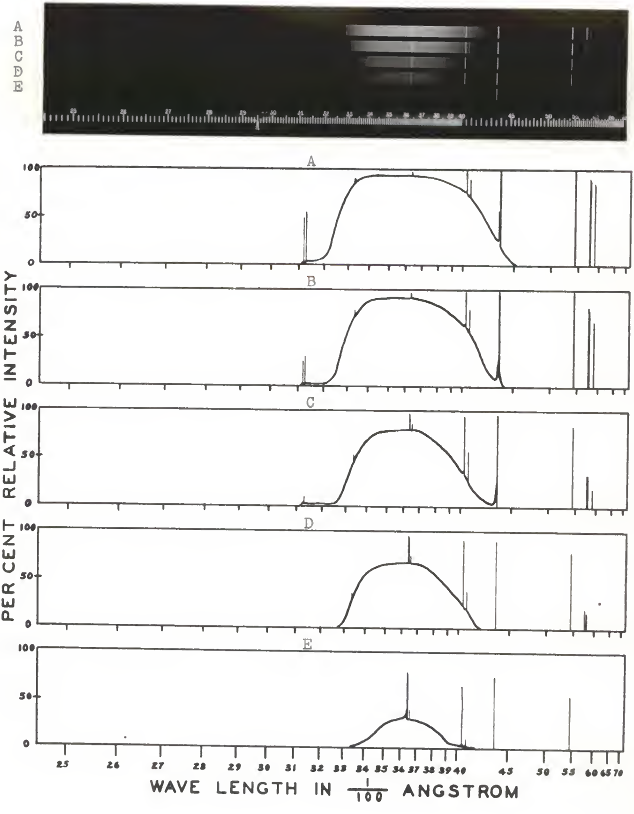
B. For 30 seconds exposure time

C. For 10 seconds exposure time

D. For 5 seconds exposure time

E. For 1 second exposure time

PLATE IV


A
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A
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E
PER CENT RELATIVE INTENSITY
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WAVE LENGTH IN 1/100 ANGSTROM

EXPLANATION OF PLATE V

Spectrograms and densitometer measurements of the mercury vapor light:

A. For 60 seconds exposure time

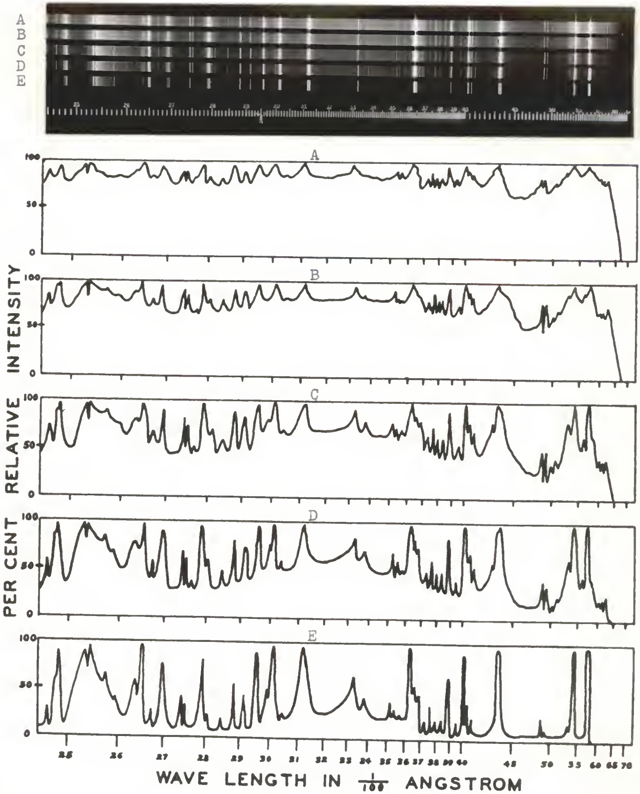
B. For 30 seconds exposure time

C. For 10 seconds exposure time

D. For 5 seconds exposure time

E. For 1 second exposure time

PLATE V


A
B
C
D
E
100
50
0
RELATIVE PER CENT INTENSITY
25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 45 50 55 60 65 70
WAVE LENGTH IN $\frac{1}{100}$ ANGSTROM

EXPLANATION OF PLATE VI

Spectrograms and densitometer measurements for mercury vapor light transmitted through a sample of greenhouse glass:

A. For 60 seconds exposure time

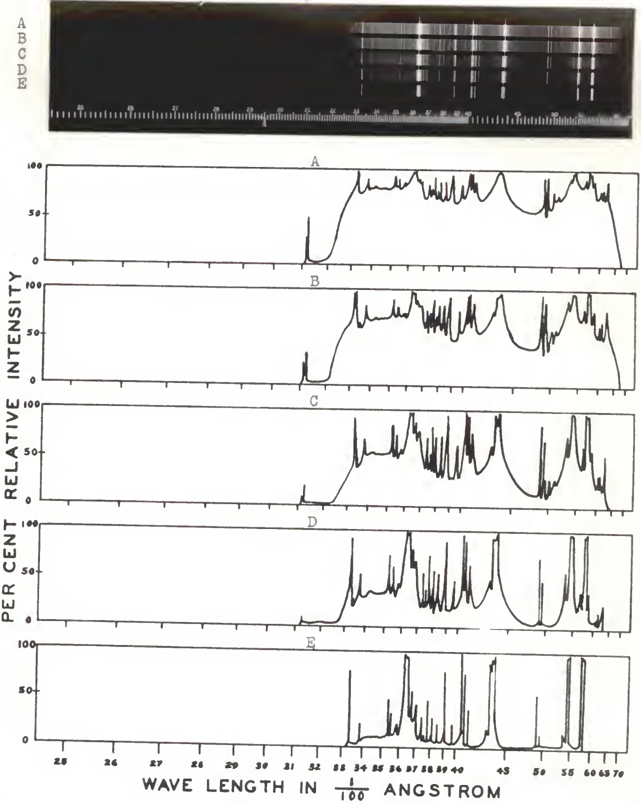
B. For 30 seconds exposure time

C. For 10 seconds exposure time

D. For 5 seconds exposure time

E. For 1 second exposure time

PLATE VI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0
PER CENT RELATIVE INTENSITY
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38
39
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45
50
55
60
65
70
WAVE LENGTH IN $\frac{1}{100}$ ANGSTROM

EXPLANATION OF PLATE VII

Photograph of incandescent light source in place above the tomato plants

PLATE VII

EXPLANATION OF PLATE VIII

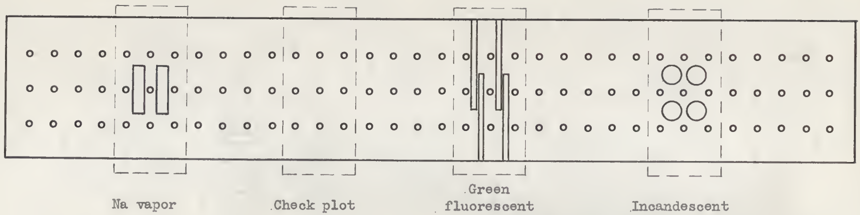
Photograph of fluorescent light source in place above the tomato plants

PLATE VIII

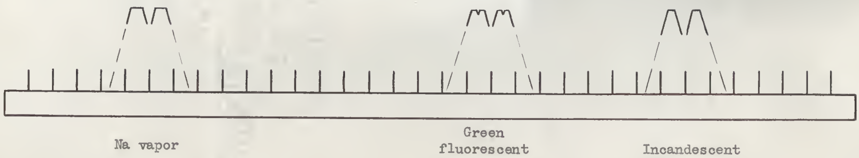
EXPLANATION OF PLATE IX

Photograph of single mercury vapor source in place above the tomato plants. The sodium vapor light was suspended in a similar manner.

PLATE IX

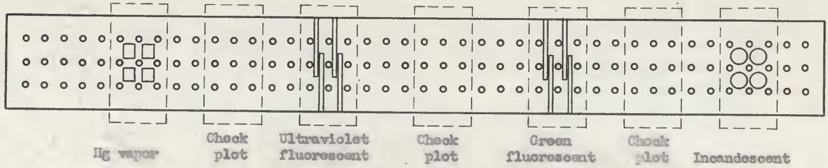


Top view of plants (indicated by circles) and lights.

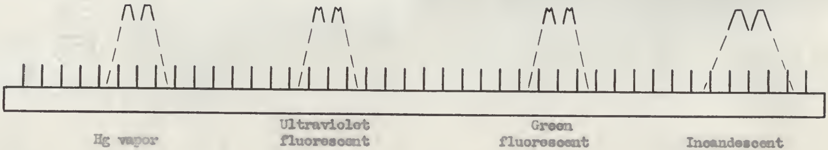


Side view of plant bed and lights showing geometric shadow of lights.

Fig. 1. Arrangement of lights for first crop.



Top view of plants (indicated by circles) and lights.



Side view of plants (indicated by circles) and lights.

Fig. 2. Arrangement of lights for second crop.

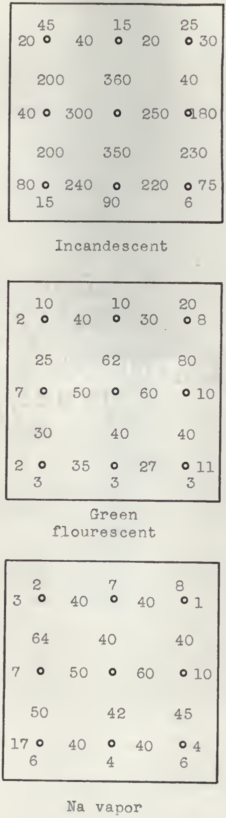


Fig. 3. Distribution of photometer readings around plants (indicated by circles) for first crop.

Table 1. Illumination measurements of sources irradiating the first crop of tomatoes.

Light source	Distance from source in feet	Photometer readings in foot-candles
Incandescent	5	255
	4	380
	3-1/2	445
	2-1/2	590
Green fluorescent	5	39
	4	53
	3-1/2	56-1/2
	2-1/2	77
Sodium vapor	5	90
	4	130
	3-1/2	155
	2-1/2	225

Table 2. Illumination measurements of sources irradiating the second crop of tomatoes.

Light source	Distance from source in feet	Photometer readings in foot-candles
Incandescent	3-1/2	310
	3	400
	2-1/2	530
	2	760
	1-1/2	1280
	1	3700
Green fluorescent	4	59
	3-1/2	72
	3	90
	2-1/2	100
	2	125
	1-1/2	155
	1	215
Ultraviolet fluorescent	4	28
	3-1/2	34
	3	41
	2-1/2	49
	2	61
	1-1/2	80
	1	110
Mercury vapor	4	6-1/2
	3-1/2	8
	3	9
	2-1/2	10-1/2
	2	11-1/2
	1-1/2	12-1/2
	1	20

ACKNOWLEDGMENT

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Appreciation is also expressed to the large number of people associated with the project.

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