THE EFFECT OF RADIANT ENERGY ON THE GROWTH AND DEVELOPMENT OF RED KIDNEY BEAN

(*Phaseolus vulgaris*)

By

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A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Horticulture

1950

ACKNOWLEDGMENTS

The writer wishes to express his deep appreciation to Dr. C. L. Hamner, professor of horticulture, for his help in the direction and guidance of this thesis, to Dr. R. E. Marshall for his help in the administrative details of this project, and to Professors C. E. Wildon and Paul Krone for their help regarding the use of floricultural greenhouses and their equipment.

The writer further wishes to extend sincere appreciation to Professor Farrall, head of the department of agricultural engineering, for suggestions, encouragement and cooperation, especially in regard to the assembly and designing of all control equipment. Other members of this department who have helped to make this project possible also deserve mention--particularly Mr. F. J. Hassler and Mr. Clarence Hansen.

The writer is grateful to Director V. R. Gardner of the agricultural experiment station, who applied for and obtained the federal funds for this work which was listed as Agricultural Engineering Experiment Station Project Number 65.

The writer wishes to thank the numerous members of the horticultural and agricultural engineering departments and all members of the guidance committee who have given their able assistance.

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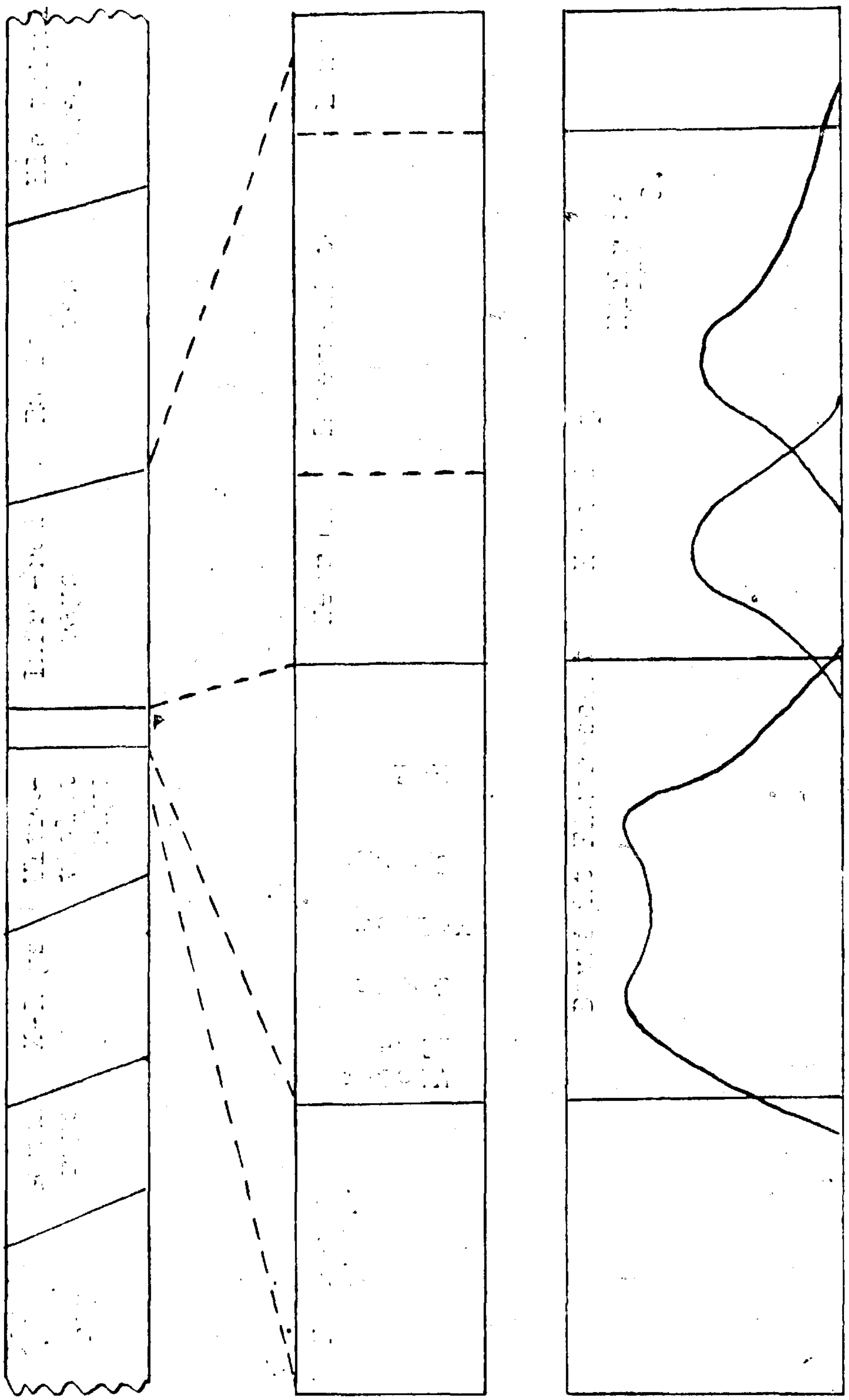
INTRODUCTION

The intentional and controlled use of radiant energy has found few applications in horticulture. Although radiation affects all living forms, little effort has been directed to intelligently apply it where it will do the most good.

Few horticulturists realize how radiation affects the temperature relationship of plant life. It is true that measurements of 10° C. or more above air temperature have often been quoted in the literature, yet the idea that all physiological processes are more or less dependent on plant temperature rather than on air temperature has seldom received the attention it deserves. This is reflected in the mass of horticultural data in which writers use air temperature as the criterion on which they form their conclusions. In fact, few of these temperatures even correspond to the true air temperature since the mercury thermometer or thermograph was used as the measuring or recording device in most of the experiments. These instruments are sensitive to a certain amount of radiant energy, the amount depending upon the extent to which they are protected from bodies of unlike temperature. The relative amount of radiant energy absorbed by a temperature-measuring device seldom or never approximates the amount absorbed by growing plants.

Temperature can be derived in several ways. First, the soil may transfer a part of its temperature to the plant directly through the root system. Second, temperatures may be distributed through convection currents referred to by Foley (49). Third, evaporation of water and other physical changes of state either absorb or emit energy in the form of heat. For example, transpiration, which occurs at all times in rapidly growing plants, lowers the temperature to some extent in plant leaves. Fourth, energy may be lost to colder objects or gained from warmer objects. Fifth, heat may accumulate due to the absorption characteristics of such materials. For example, the difference in the rate of transmission of light of different wave-lengths of the electromagnetic spectrum (Figure 1) through glass causes the heating effect found inside a glass enclosure (Figure 2). Visible light and the shorter infra-red waves pass without obstruction through the glass, while the reradiated heat waves from the plant--in the form of the longer infra-red waves--are reflected instead of being transmitted through that medium. This causes a condition known as a "heat trap", an asset for greenhouse growers in cold weather but a liability in hot weather. The heat trap makes scientific temperature control difficult.

The purpose of this experiment was to investigate how radiant energy may be used by controlled equipment, both as a supplementary source of heat in the greenhouse, and later in control rooms with no solar radiation. Plant material was chosen that was highly responsive to temperature changes and



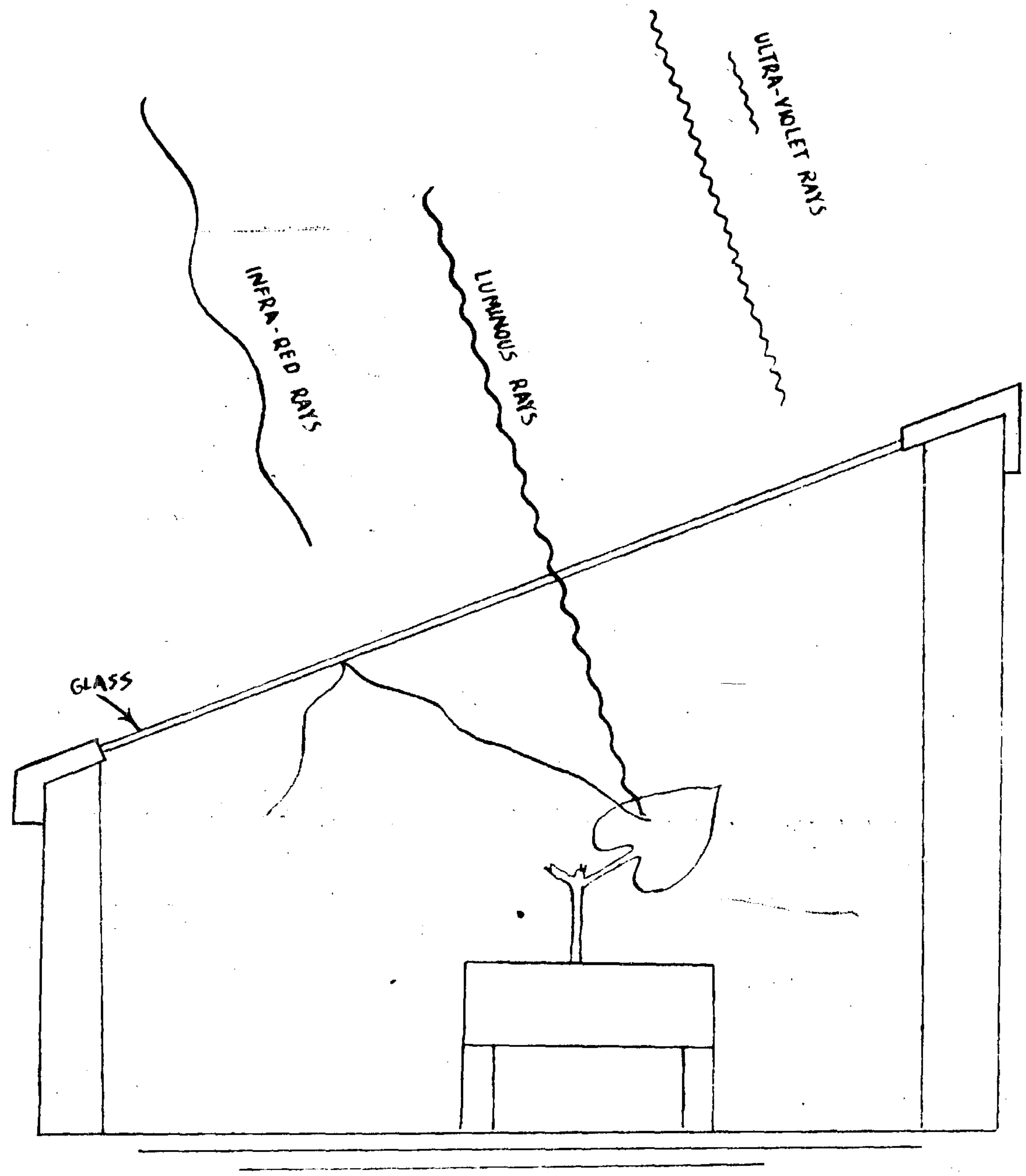


Figure [illegible]. Figure showing how a "heat trap" is created by the relative difference in transmission of radiation and re-radiation through glass.

uniform in its growth under controlled growing conditions. The Red Kidney bean (Phaseolus vulgaris) met these requirements.

REVIEW OF LITERATURE

Terminology

Radiation is the process by which radiant energy is generated and emitted by a source and propagated through space (Withrow, 145); the source is referred to as the radiator. Radiation from the sun is termed solar radiation. Although the term radiant heat is commonly used in the literature, and referred to in this thesis occasionally for purposes of clarification, heat is not radiated but rather heat is produced in an object when radiant energy strikes it, if that object has the proper absorption characteristics. The proper term for the measurement of radiant energy is radiometry, and the instrument so used is a radiometer. A narrow band of electromagnetic waves which produce the sensation of light to man's sense of sight is referred to as luminous energy or light. In a less technical sense, the term <u>light</u> is used by many authors to refer to those waves lying adjacent to both sides of the visible spectrum--namely, ultra-violet and infra-red. Luminous energy emitted by fluorescent low-pressure mercury tubes is also referred to as fluorescent light. It is measured by means of a photometer.

Irradiation is the process of the interception of radiant energy by an object. The re-radiation of some of this energy at a longer wave length is termed fluorescence.

Radiant energy in the visible spectrum extends from .39 micron in length in the violet to .76 micron in the red; the infra-red rays extend up to the region of 100 microns, where radio waves begin. In this thesis the term near infra-red refers to that band in the spectrum from visible red light to waves 2 microns in length. Below the blue light lies the ultra-violet extending down to .01 micron. Below this the X-rays are located, then the gamma rays, and, finally, the infinitesimal cosmic rays. Much of the energy of the sun's rays is absorbed by the atmosphere, especially by water vapor. Those rays penetrating in greatest abundance lie in the region from .3 micron in the ultra-violet to 2.6 microns in the infra-red.

All electromagnetic waves travel through space at a speed of approximately 186,000 miles a second. The frequency of the wave is inversely proportional to the length of the wave. Barnes (12) refers to heat as the frequencies of oscillations of atoms around their positions of equilibrium. These frequencies are of the same order of magnitude as those of infra-red radiations.

Temperature Measurement

Methods

Radiant energy absorbed by matter is measured in terms of the heat generated when it impinges on that matter. Heat is commonly measured by means of the mercury thermometer or some instrument dependent on the expansion of gas, liquid, or metallic plates.

Leaf temperature was first determined by pressing the thermometer against the leaf or by wrapping the leaf about the thermometer. This method may still be used where only approximate results are desired and where the relatively slow response of the ordinary thermometer is of no concern. However, the most accurate and responsive method is to employ the thermocouple. This method, invented by Seebeck (Allen and Maxwell, 4), was first used on plants by Dutochet (Sachs, 116). Blackman et al. (15) made their famous study on cherry laurel leaves by comparing the difference between the temperature in the shade and that in the direct radiations from the sun.

The thermocouple is usually made by twisting together the ends of two fine wires of dissimilar metals, for example, copper and constantan (an alloy of 60% copper and 40% nickel). A difference in potential is set up between the two wires thus brought together. The magnitude of this electrical potential is very nearly directly proportional to the temperature of the thermocouple junction. A reference junction, which is necessary for measuring temperature differences, is usually made by putting a junction into an ice-water bath (Forsythe, 50). This is also called the cold junction.

Instead of an ice-water bath, Shreve (119) used the air inside a thermos bottle and calibrated his readings for that particular temperature. Shreve's innovation merely complicated the process because of the uncertainty of a steady air temperature inside a thermos bottle. Wallace and Clum (136) placed the reference junction underneath the leaves of the plant whose temperature they were measuring to find the magnitude of the temperature difference between the leaf and the surrounding air. It is debatable whether the air temperature they used was accurate or whether it was typical of a true convected air temperature. Their recording potentiometer was built so that the cold junction could be used in this manner.

Since most galvanometers and potentiometers used to measure the electrical potential through the termocouple are read in millivolts, a chart must be referred to in order to calculate the temperature. However, some recent potentiometers are calibrated at the factory to read directly in either the Fahrenheit or Centigrade scale of temperatures; others are built to record either one or a large number of readings simultaneously for an extended period of time.

The technique for making thermocouple junctions varies with the investigator. Miller and Saunders (90) used No. 36 copper and constantan wires braided together and joined securely with acid-free solder. A pair of crucible tongs was fitted with two small wedged-shaped pieces of cork. On one side of these tongs the thermocouple was attached, and the completed device held the leaf firmly while the temperature was read.

Curtis (40, 41) placed the junction in direct contact with the leaf and held it firmly by threading the lower portion of the thermocouple through the leaf.

Wallace and Clum (136) found it more desirable to use several junctions. They assembled a thermopile composed of five junctions, which were mounted on a wire clip within a six mm. square frame. When this clip was opened, pushed across the leaf, and allowed to close, the five junctions were pressed against the lower surface of the leaf and held in place by a similar frame pressing down from the top. Wallace (135) now considers this thermopile obsolete since the five junctions increase the probable error five times.

The placement of the thermocouple has been of considerable concern to investigators. Clum (35) obtained the temperature of the interior of the leaf by inserting the junction into the intercellular tissue of the leaf. This method was very tedious and caused an inner metabolic disturbance of the leaf. Wallace and Clum (136) reported that it was more satisfactory to attach the thermocouple to the lower epidermis of the leaf.

Gibson (55) designed some thermocouples for leaf insertion by filing the thermojunction to a point. This device injured the leaf, being entirely too large for the grass blades used in his frost-prevention studies.

Plant temperature

Plant temperature is governed by a complex group of factors. Miller and Saunders(90) list five that are influential under field conditions: (1) air temperature, (2) supply of moisture in the soil, (3) air currents, (4) evaporating power of the air, (5) light intensity. They reported that the temperature will rise more rapidly in a wilted leaf than in a turgid leaf.

Leaf temperature also fluctuates markedly and suddenly when air moves because of the difference in temperature of air pockets. The fact that temperatures may be higher at the tip than at the base of the leaf blade, they suggested, was due to the difference in available water supply. The lower surface of the leaf was usually 1° C. higher than the upper surface. Normal turgid leaves showed a leaf temperature approximately the same as that of the air during the night but slightly lower during the early morning and evening.

Leaf temperature (Meyer and Anderson, 89) may be regarded as conditioned by four influences: (1) thermal absorption, (2) thermal emission, (3) internal endothermic processes, and (4) internal exothermic processes such as respiration. Thermal emission refers to the loss of heat from the leaf by conduction, convection, and radiation (Brown and Escombe, 26). Thermal absorption refers to the gain of energy or heat by the leaf. According to Maxwell (88), all objects tend to come into thermal equilibrium with each other. For this reason the weather bureau uses instrument shelters to screen instruments from objects of higher or lower temperatures (Blair, 16). All objects lose heat to interstellar space when the air is clear.

Tyndall (134) states that the dryness of the air, rather than the clearness, causes the loss of heat. Clear air may contain much aqueous vapor which will intercept radiation even though the sky be dark blue in color. The heat lost by terrestrial radiation is greatest when the atmosphere is dry. According to Farrall et al. (48) and Hassler (67), heat lost by terrestrial radiation is the cause of much frost injury. Frost caused by this means is called "radiation frost."

When a leaf is exposed to the full impact of solar radiation, the temperature of the leaf normally rises markedly above that of the surrounding air. Clum (35) measured leaf temperatures 5 to 10° C. higher than the surrounding air temperatures. Miller and Saunders (90) found little temperature difference with the thinner-leaved plants they were using. Blackman et al. (15), using detached leaves, in direct sunlight detected a rise in temperature of 4 to 13° C. over that of the surrounding air; in the shade the leaf temperature rose only 1 to 1.5° C. higher than air temperature. The maximum temperature was recorded by Wallace (135), whose potentiometer registered a gain of nearly 20° C., although an earlier paper (Wallace and Clum, 136) showed only a maximum 13° C. increase outdoors and 16° C. increase in the greenhouse over air temperature. Moreland (92) measured the leaf of the sugar cane and found a maximum temperature differential over air temperature of 8.5° C. on a still day and 4.5° C. increase on a windy day.

Solid fruit can accumulate more heat than thin leaves, as demonstrated by Brooks and Fisher (22), who found that the temperature of the exposed side of an apple may rise from 12 to 25° C. higher on the exposed side than on the shady side. Anderson (4) reported that the internal temperature of cotton balls usually followed the general air curve but might exceed the air temperature by 5 to 10° C. in direct solar radiation. At night the balls were usually below air temperature. He remarked that respiration can produce very little heat. Miller (91) suggested that absorption of radiant energy is increased in thicker-leaved plants. He quotes Askenasy (12), who found that leaves of Sempervivum attained a temperature 18 to 25° C. higher than that of its surroundings.

Leaf temperature is also governed by air movement. Brown and Wilson (27) stated that air velocity increased the emissivity of the leaf. Smith (120) observed that breezes reduce the temperature of the leaves in solar radiation from 2 to 10° C. and that thin leaves are more responsive to temperature fluctuations than thick ones. Similar results were reported by Miller and Saunders (90).

Curtis (40, 41) claimed that transpiration is of great importance as a cooling agent in leaves because of the change of water from the liquid to the vapor state. But he also made the statement that some of the benefits of cooling by this means were greatly exaggerated. Curtis suggested that higher leaf temperature relative to air temperature in humid regions, usually ascribed to diminished transpiration, is due in part to the humidity of the atmosphere in preventing loss by thermal emission. He also stated that the angle of exposure to radiant energy, or the angle of incidence upon the leaf surface, greatly affects the capacity to absorb heat. He urged that all measurements of temperature should be made with reference to leaf position, or, unless otherwise mentioned, the leaf position should be understood to be at right angles to the incident rays of the radiator whether it be the sun or some artificial source.

Transpiration, according to Brown and Escombe (26), is responsible for 80% of the total heat given off by the leaf. Clum (35) found little correlation between transpiration and leaf cooling, because major temperature changes may occur within a few seconds.

Copeland (36), working with chaparrel, concluded that transpiration decreased the heating of the leaves by solar radiation, and observed that the cooling of actively transpiring leaves amounted to more than 10° C.

Watson (138) concluded that transpiration and thermal emission from the leaf surfaces were the only significant factors that tend to lower the temperature of the leaf. Watson (139) later reasoned that transpiration accounted for more than 50% of the heat loss of <u>Liriodendron</u> leaves only when both of the following conditions obtain: (1) the transpiration rate exceeds .71 gm./dm^2/hr, and, (2) the difference in temperature between leaf and air temperature is less than 7° C. Thus, it is evident that thermal emission becomes increasingly important with an increase in temperature differences.

The influence of transpiration on temperature changes in still air is not clear. Martin (85, 86) found that transpiration increased in a linear relationship with the incident energy absorbed by the leaf, but varied with relative humidity. Thut (131, 132) found that the relationship between relative humidity and water loss is more or less linear, but falls below the expected value at low relative humidity. It also varied with wind velocity.

The Influence of Light on Plants

Although the sun is considered to be absolutely essential for plant growth, man has been able to grow plants under artificial conditions with artificial lights only, but the most satisfactory growth still results from solar radiation (Parker).

Artificial light for experimental plant studies may be used for one of the following purposes: (1) to serve as the sole source of light, (2) to lengthen the day, (3) to serve as an additional source of light in the middle of a dark period, as used in some photo-periodic experiments, (4) to serve as the source of minute amounts of light to which seedlings grown entirely in the dark are exposed, and (5) to serve as a source of light of different wave lengths.

Light, like all forms of radiant energy, varies in intensity, quality, and duration, and these factors have a profound influence on the growth and development of plants.

The intensity of solar radiation varies with the altitude, the clarity of the atmosphere, and the angle of incidence of the sun's rays upon the recipient of that radiation. It may exceed 10,000 foot-candles at times and yet be extremely weak on the forest floor of a tropical rain forest (Oosting, 98). Plants vary in their ecological adaptability to different environmental habitats, and survive where they can suitably compete with existing weather and biological factors. The observed light conditions under which shade plants grow may not indicate the most favorable growing conditions for those plants, since many of them will grow better where they receive a higher intensity of solar illumination. On the other hand, many plants of the xerophitic type have developed a tolerance for high light intensities which are not necessary for their optimum growth. Holman (71) and Emerson (46) found that injury to the photosynthetic mechanism may result from exposure to intense radiation. They found that there existed a maximum point where the starch ceases to be deposited and then disappears. This phenomenon was called "solarization" because its reversal nature reminded the authors of a similar response known in photography by that name. Solarization is probably associated with the CO_2 concentration in the air. Hoover et al. (72) found that increases in light intensity accelerated the photosynthetic process up to the point where CO_2 became the limiting factor. At relatively low light intensities, as long as the carbon dioxide is not the limiting factor, the rate of photo-synthesis was approximately proportional to the light intensity. According to this study, light was not the limiting factor under conditions of intense solar radiation.

On the other hand, Heinicke and Childers (70) showed that the above statement did not apply to the normal apple tree, probably because of the decreased light intensity in the interior of the tree where the heavily shaded leaves reduced the light intensity to one per cent of the total direct solar radiation.

Brackett (21) found that CO_2 became a limiting factor for plant growth of wheat at high light intensities and that the optimum CO_2 concentration these plants could use varied with the intensity of light available.

Matthaei (87) discovered that the utilization of CO_2 by plant tissue varied not only with light intensity but also with the temperature.

Harvey (64) found that many plants grew and set seeds in light intensities from 400 to 10,000 foot-candles. Shirley (118) grew redwood seedlings under light intensities varying from 33 to 300 foot-candles, and found that all intensities above 100 foot-candles had a similar effect on their growth, while plants growing at lower intensities gave a less favorable growth. Geum showed a gradual reduction in growth as the light intensities fell from 470 to 41 foot-candles. The author concluded from his experiments that all plants with which he experimented, except sunflowers, can survive on less than

40 foot-candles of light. At light intensities below twenty per cent of total solar radiation, the increase in dry weight of plants so exposed was proportional to the light intensity. At higher light intensities there was an increase in dry weight which was not proportional to light intensities.

Guthrie (63) and Shirley (118) both found that chlorophyll concentration increased with decreasing light intensities until the low light intensities threatened survival.

Post (107) reported that floricultural crops, especially those of bronze and pink shares, show poor color development at low light intensities. At high levels of light intensity, there is doubtless a reduction in color intensity of the petals as well as in that of the leaves of most crops.

Naylor and Gerner (95) found that 600 foot-candles of fluorescent light for 16 hours duration a day caused excellent growth in Red Kidney beans.

When lights were used to lengthen the day for long-day plants, Withrow and Benedict (147) found that from .1 to .3 foot-candle illumination was sufficient to cause flowering stimulation in the China aster. They found that other long-day plants require a higher initial light intensity. This was substantiated by Porter and Lee (103), who recommended the use of 5 to 15 foot-candles of illumination for the lengthening of the day period of a short-day plant.

The most economical utilization of light used to prevent floral initiation in a short-day plant was to interrupt the dark period by giving brief periods of illumination about the middle of the night. Time intervals of only a few seconds were effective (Parker et al., 99). Later studies (Parker et al., 101) showed that the total amount of illumination used in the experiments was the same regardless of the time of exposure or intensity of light.

Quality of light is classified as to color temperature (79). The numerical value indicates the predominating light wave in the spectrum which is emitted by a black body when heated to the Kelvin temperature of that number. The color temperature is often referred to as being either warm or cool depending on the physiological response or psychological reaction of the observer.

Solar radiation changes its color temperature with the angle of incidence, being warmer when the sun forms a more acute angle with the horizon. On the other hand, light radiated from clouds or similar objects of white color will be cooler to the visual sense. Note the influence of a white background in Figures 10, 11 as contrasted to a black and non-reflective background in Figures 12 and 13. However, when light is reflected by a colored object or filtered through the trees, it does not conform to the true color temperature scale.

Plant pigments differ in the relative proportion of different wave lengths of light absorbed or reflected. Chlorophyll (Miller, 91; Frank and Loomis, 51) showed five absorption bands. The two which predominated were the red rays of

Figure 10. Rad Kidney beans, at the age of 45 days, after growing in the radiation room for 30 days. Photographed March 16, 1950.

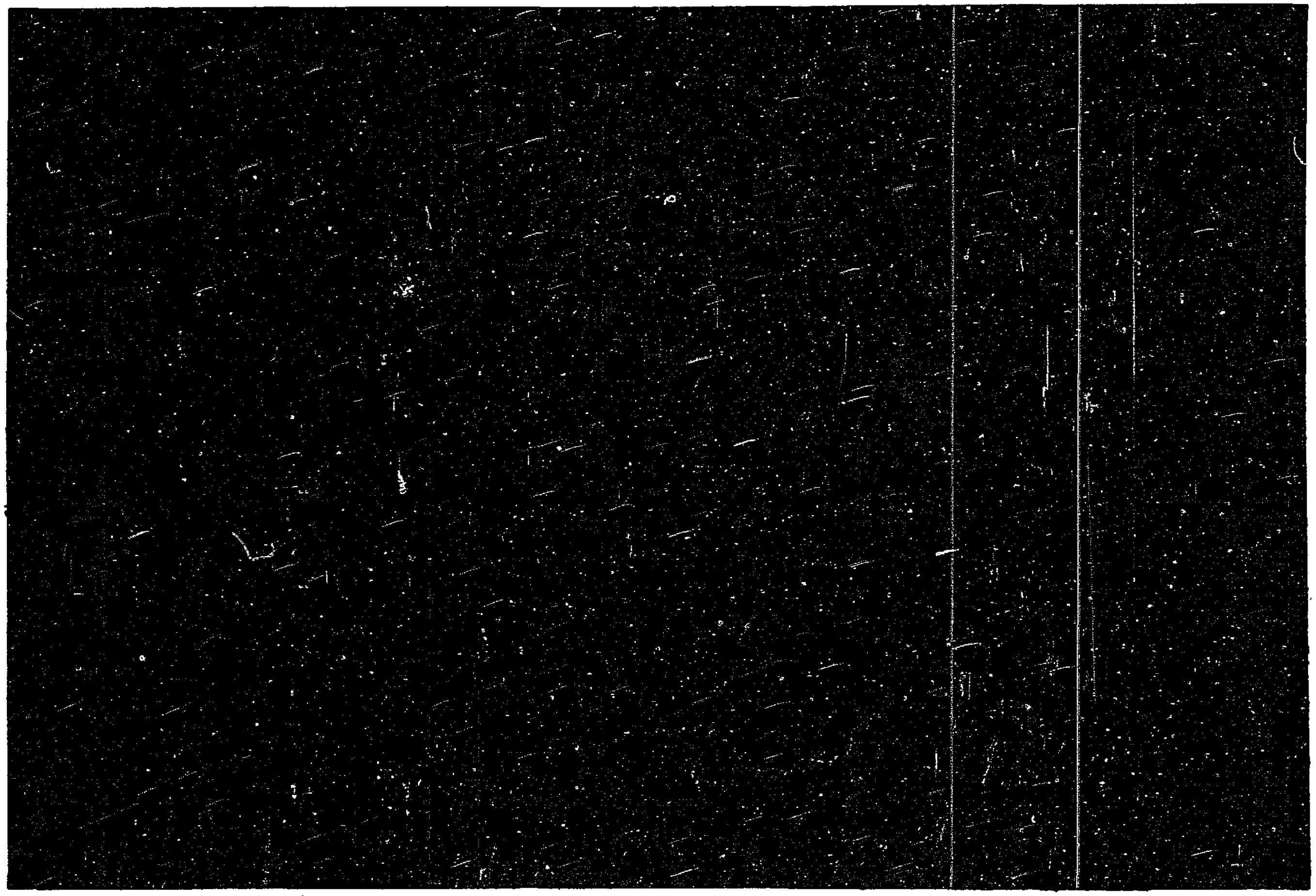


Figure 11. Red Kidney beans, at the age of 45 days, after growing in the control room for 30 days. Photographed March 16, 1950.

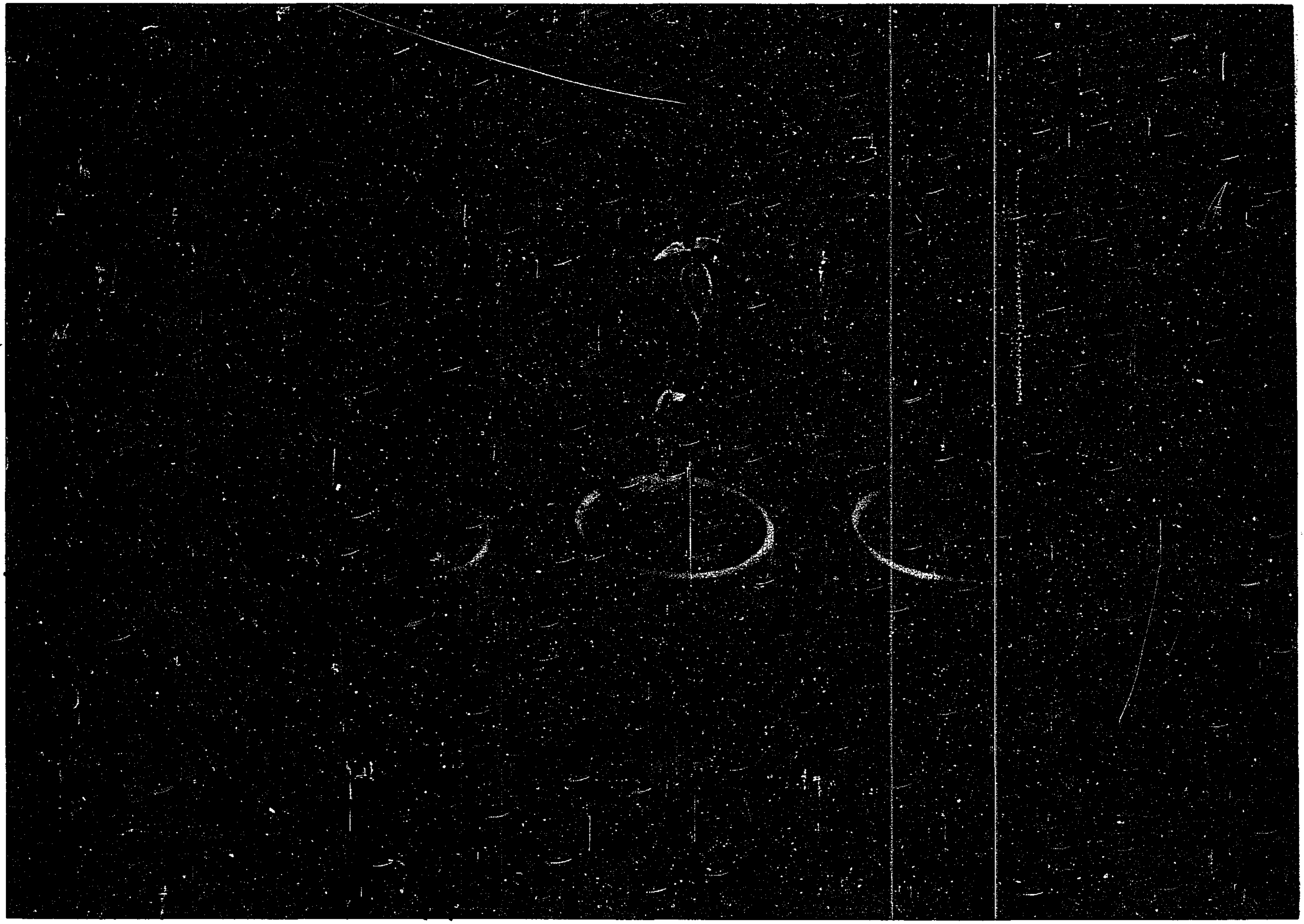


Figure 12. Red Kidney beans, at the age of 29 days, after growing in the radiation room (converted cold storage) for 14 days. Photographed February 28, 1950.

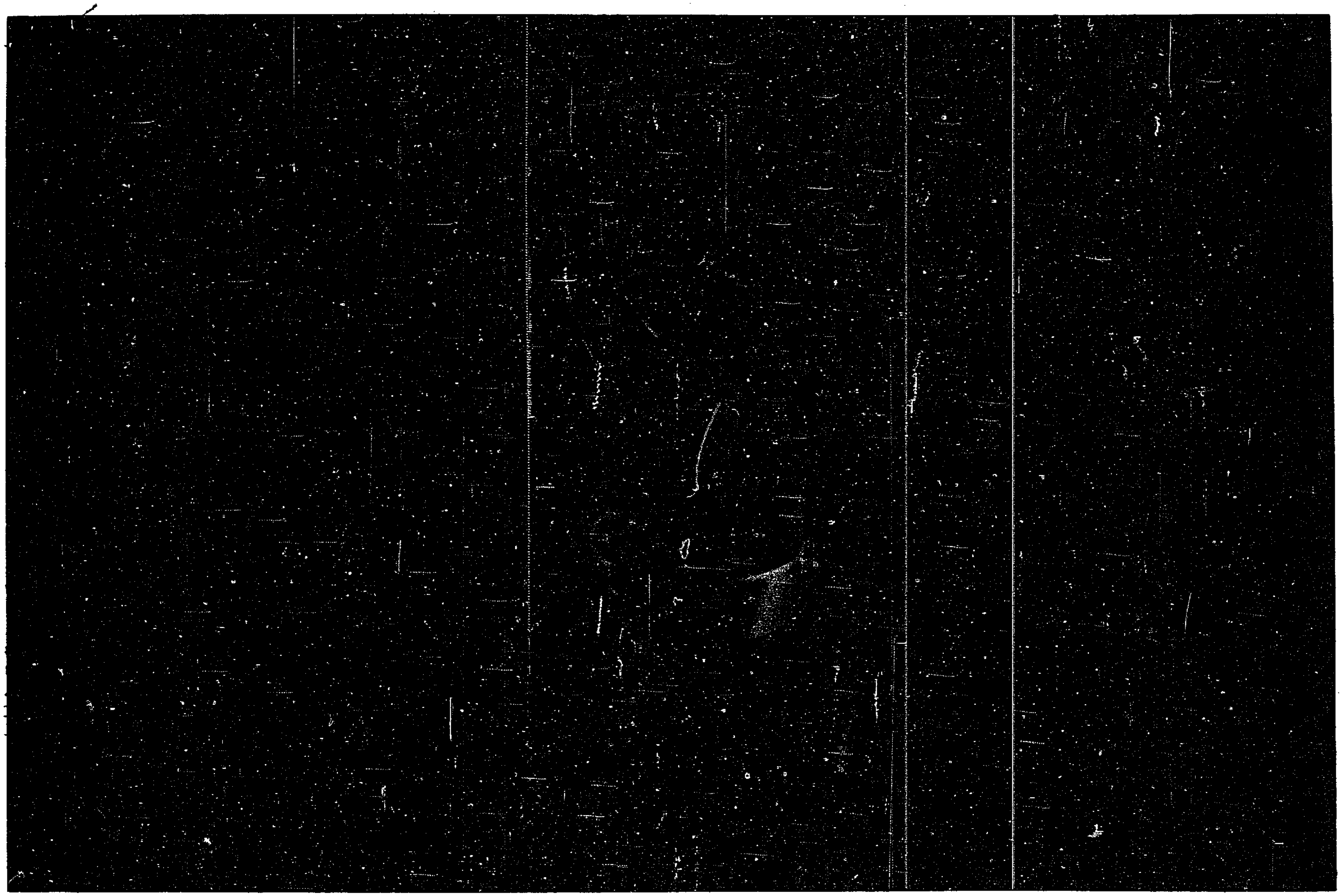


Figure 13. Red Kidney beans, at the age of 29 days, after growing in the control room (converted cold storage room) for 14 days. Photographed February 28, 1950.

.651 micron to .680 micron and the blue, indigo, and violet rays of .44 micron to .510 micron. The blue band shows a slightly higher absorption coefficient (Meyer and Anderson, 89).

The relative rates of photosynthesis also differ with the different regions of the spectrum. Hoover (73) found that the maximum photosynthesis occurred at the wave length of .655 micron in the red, and the secondary maximum at .440 micron in the blue region of the spectrum.

In the spectral greenhouses at the Boyce Thompson Institute, Popp (102) grew a number of different plants in light under filters of different absorptive capacities. His general conclusion was that plants growing in red light and the long end of the spectrum were spindly, had weak stems, had good development of chlorophyll, and had small thin leaves which tended to roll or curl. Plants grown in the short end of the spectrum were sturdy, with well-formed leaves, but low stature.

Etiolation occurs when plants with sufficient storage of food materials are grown for some time in total darkness. Went (141) described another type of etiolation which is produced by plants grown under red light only. This etiolabion is typical of plants without reserve food storage, and is entirely different anatomically from true etiolated plants. Under conditions of true etiolation, the red rays are most effective in inhibiting elongation. Went prefers to call etiolation of plants developing under red light without food supply "excessive growth."

Went and Thimann (144), speaking of the effect of light on plant hormones, state that its influence is twofold: it is first required to form the auxin precursors, and later it causes destruction of the auxin produced from this precursor. Apparently the longer wave lengths favored the production of an auxin precursor, thus enabling plants to grow taller when kept in red light. Yet the results seemed to indicate that those same red and yellow rays were also the most effective in auxin destruction.

Went (142) grew peas in darkness and then exposed them for various time intervals to dim red light. The longer the exposure to the red light before the return to darkness, the greater the decrease in the length of the pea stems. The effect was traceable to that state of growth in which the exposure was made; for example, if the plants were retained in total darkness until the third internode started to elongate, then subjected to a small amount of red light, the third internode would later show a reduction in length while the first two internodes would remain their original length; furthermore the effect did not carry over to the fourth internode. Blue light did not produce as marked a reaction, and green light was practically ineffective in reducing stem elongation.

Went (140) concluded that cotyledons contain hormone-like factors which are indispensable for leaf growth and which are rendered effective when subjected to the presence of small amounts of light.

Priestly (111) found that very brief exposures of light to etiolated seedlings caused them to become less elongated even when such exposure was insufficient to produce green color. He concluded that there must be a photocatlytic reaction in which substances of the nature of hormones were produced.

Gortikova (58), exposing germinated seeds to high intensity colored lights for ten days at 25 to 30° C. found that both vegetative and reproductive development were stimulated by red and orange-yellow light. Blue light had the least effect. Rohrbaugh (115) found that daylight fluorescent and the blue fluorescent light gave equal elongation to the hypocotyl and first internode of Red Kidney beans. When a light source of sufficient purity of color was used, he found that red light showed the greatest effect in inhibiting elongation. This accelerated growth is what Went prefers to call "excessive growth."

Goodwin et al. (57) showed that small quantities of monochromatic light inhibited growth on the first internode of Avena sativa seedlings growing in darkness. The effect was most pronounced in the red .623 micron region and secondarily in the yellow light at .577 micron wave length. Goodwin (57) found that ultra-violet light had an inhibiting effect on the length of Avena sativa; infra-red light had a slight effect on length, though its primary effect was the heat generated in the plant tissue. Wave lengths over 1.6 microns gave no measurable growth difference.

Lubimenko (82) found that the greening process of etiolated seedlings takes place within definite limits of temperature, which do not depend on length of light exposure.

The initial work on photoperiodism was announced by Garner and Allard (54) in connection with their work on tobacco. Porter (103) reported that the intensity of light necessary to lengthen the day period lies in the neighborhood of ten foot-candles of illumination.

Razumov (114) used different colored light to extend the duration of several short-day plants. He found that radiation of red and yellow light, when used to lengthen these short natural photoperiods, was equivalent to solar radiation in its photoperiodic reaction, whereas the shorter wave lengths were ineffective.

Kleshnin (75) found that all parts of the visible spectrum gave photoperiodic reactions, but that the required intensities differed from one region to another. Differences in growth were most noticeable when the intensity of monochromatic light was small.

Withrow and Benedict (147) found that orange and red light produced earlier and more profuse blooming of pansies, stocks, and asters. Although asters responded to all types of light, stocks and pansies gave little reaction to the shorter wave lengths. Withrow and Biebel (148) found that the red band was also effective in preventing flowering of short-day plants. Withrow and Withrow (149) studied the effect of colored light in more detail by eliminating all extraneous light. Their results showed practically no effect of blue radiation and reaffirmed the effectiveness of the red region.

Parker et al. (100) studied the effectiveness of light derived by spectrographic methods and reported that the most effective region of the spectrum for preventing flowering of cocklebur and soybeans extended from .6 micron to .68 micron in the red band of the spectrum. The least effective region for preventing flowering was located at .48 micron; effectiveness increased again at shorter wave lengths in the violet region. Irradiation with infra-red light located at the .7 micron to .9 micron band proved ineffective in preventing formation of floral primordia of soybeans.

<u>Ultra-violet radiation</u>

Stewart and Arthur (124) found that ultra-violet radiation of plants grown in soil under low light intensity or during cloudy weather caused an increased absorption of ash, including calcium and phosphorus. But under high light intensity there was no response to ultra-violet exposures. The effective rays lie between .9 micron and .313 micron, coinciding with the effective antirachitic rays for animals. The ability of plants to form vitamin D seems to be associated with their capacity to absorb and deposit calcium and phosphorus. Later Stewart and Arthur (125) found that the relative absorption of calcium and phosphorus of irradiated tomato plants depended upon the ratio of the two elements in the nutrient solution.

Arnold (18) found that ultra-violet rays do not apparently kill chlorophyll on Chlorella, a green algae, but that the injurious reaction to these cellular plants caused by these rays may be due to the destruction of another substance in these plants.

The Use of Radiant Energy

Prior to man's arrival at the stage of intellectual maturity though he was unaware of the fact, he nevertheless was emitting radiant waves which centered in the 10 micron area of the infra-red portion of the spectrum. He was likewise receiving radiations whose spectral characteristics depended upon the nature and temperature of the objects about him. Even today man is not always aware of these temperature relationships.

In an early stage of history he became aware that the sun produced heat, and, later, that a fire could also produce the same sensation in his body. Realizing the great benefits to be derived from such heat-producing sources, he felt that a great power must reside therein. Thus history records the religious adventures of man in which both sun and fire play an important part. He has sought to deify and personify them, e. g., the ancient Hindu god for fire, Agni, and the great god of the sun in Egypt, Ra.

Although modern man does not usually deify the sun, he recognizes its great source of power, and has at times tried to capture some of this energy to heat water (Brooks, 23) and to heat his homes (Telkes, 128, 129). Solar radiation has a great influence upon the terrestrial temperature of the earth, and even local disturbances on the sun known as sun spots may have far-reaching effects. Burkholder (28) stated that 60% of the energy from the sun is in the infra-red region of the spectrum, and that plant growth is roughly doubled for every 10° C. rise in temperature.

Adlam (1) and Chase (32) both suggest that the earliest man-made form of radiant energy should be attributed to the Romans, who ingeniously designed the first form of artificial heating, the hypocaust system. The Romans built masonry ducts behind and within side walls or beneath floors through which hot flue gases were made to flow. This system heated the adjacent walls or floor surfaces, which, in turn, heated the buildings the Romans wanted heated. The remains may still be seen today at the Roman Baths at Bath, England, and at the Baths of Caracolla in Rome; these baths probably date back more than 1500 years.

The modern use of radiant heating for homes began a few miles from where the Romans built their famous baths in England. This system, more appropriately called "panel heating", spread from England to continental Europe (Adlam, 1; Byers, 30) and to the United States, and is now one of the accepted methods of heating homes. In this design hot-water pipes are usually imbedded in plaster, concrete, etc. The temperature of the panels is low since the temperature of the water circulated seldom exceeds 135° F.

The advocate of panel heating stresses comfort. He describes how man loses heat by a complex combination of respiration, evaporation, and radiation. Radiation is usually responsible for three times as much heat loss as respiration and evaporation combined. The rate of radiation loss depends upon the average temperature of the surroundings. When the temperature of the air is reduced and the average wall temperature increased, man loses less heat by radiation and proportionally more by respiration and evaporation. Increased heat loss due to respiration tends to give man an invigorating feeling similar to the sensation of walking briskly on a cool morning. In panel heating, heat, usually in the form of hot water, is conducted through one or a combination of walls, ceiling and floor to attain an average wall temperature about 5° F., more or less, above the so-called comfort temperature of man, while the air temperature is usually reduced proportionately as much below this temperature. A typical panel-heated room has an air temperature of 65° to 68° F. (18° C.), with the relative humidity registering 55 to 65%.

Comfort conditions during the summer months can be attained by radiant cooling in the home. In this system reducing the relative humidity of the air increases the rate of respiration and evaporation from the skin. A lower moisture content in the air creates a cooling sensation even when the air temperature is above the usual comfort level. By this means man can move in and out of such an environment into hot summer weather without the feeling of entering an oven or a refrigerator. This system of cooling is effective regardless of the propaganda of air conditioners who advocate increasing the water content of the air by washing it. The botanist would like to know whether the relationship between radiation and transpiration under these different conditions affects plant growth.

Low-efficiency radiation has long been used by gardeners, whether they knew it or not, when they planted a vine or espalier next to a warm building. Hotbeds also give off some radiation, and all greenhouses which use glass or its equivalent in their construction accumulate an excess of radiant energy (Figure 2). Steam pipes and other radiators give off a small amount of radiation, but since radiation travels in straight lines, the usual design of greenhouses (Wright, 150; Post, 107; **Laurie** and Kiplinger, 80) does not permit much of this energy to travel to the plants directly. Some attempts to heat greenhouses by aerial pipes can be seen in the Hill Greenhouses at Richmond, Indiana, and the new greenhouse range at Michigan State College. The efficiency of heating by radiation is extremely low at the temperature of these pipes because most of the heat is transferred by means of convection. The low temperature of most steam or hot water pipes emits waves in the 8 to 9 microns region of the spectrum, according to calculations from Wein's law.[1]

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1. Weins law = $= \frac{2884}{T \text{ (Kelvin)}}$

An adaptation of the usual panel-heating system through the concrete floor is used in one of the rooms of the greenhouse range of Michigan State College. In this room hot water is run through pipes imbedded in the concrete. The efficiency of heating by radiant means as compared to other sources of radiation is well demonstrated by the Stefan-Bolzman law[1] as illustrated in Figure 3. The efficiency of this system cannot be shown on this graph, which starts at the boiling point of water. It is difficult to ascertain the true efficiency at such low temperature levels because so many factors distort the picture. It is suggested that this type of heating be known simply as floor heating or its equivalent, and that the name radiant heating, should that name be acceptable, be reserved for a system in which the surface temperature of the heated object is above 100^{o} C.

Meteorologists, geographers, and ecologists study the effects of solar radiation and how it affects plant life (Oosting, 98). Dinger (42), who measured the spectral absorption pattern of near infra-red radiation, concluded that plants absorb those rays, namely 1.5 and 2.0 microns most strongly in a pattern similar to the absorption pattern of water. In Dover, Massachusetts, an attempt has been made to store solar energy in a house which collects its heat by black-surfaced plates and transfers this heat to cans containing sodium sulphate, a

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1. Stefan-Bolzman law = Calories per sec per cm^2 = $1.36 \times 10^{-12} T^4$.

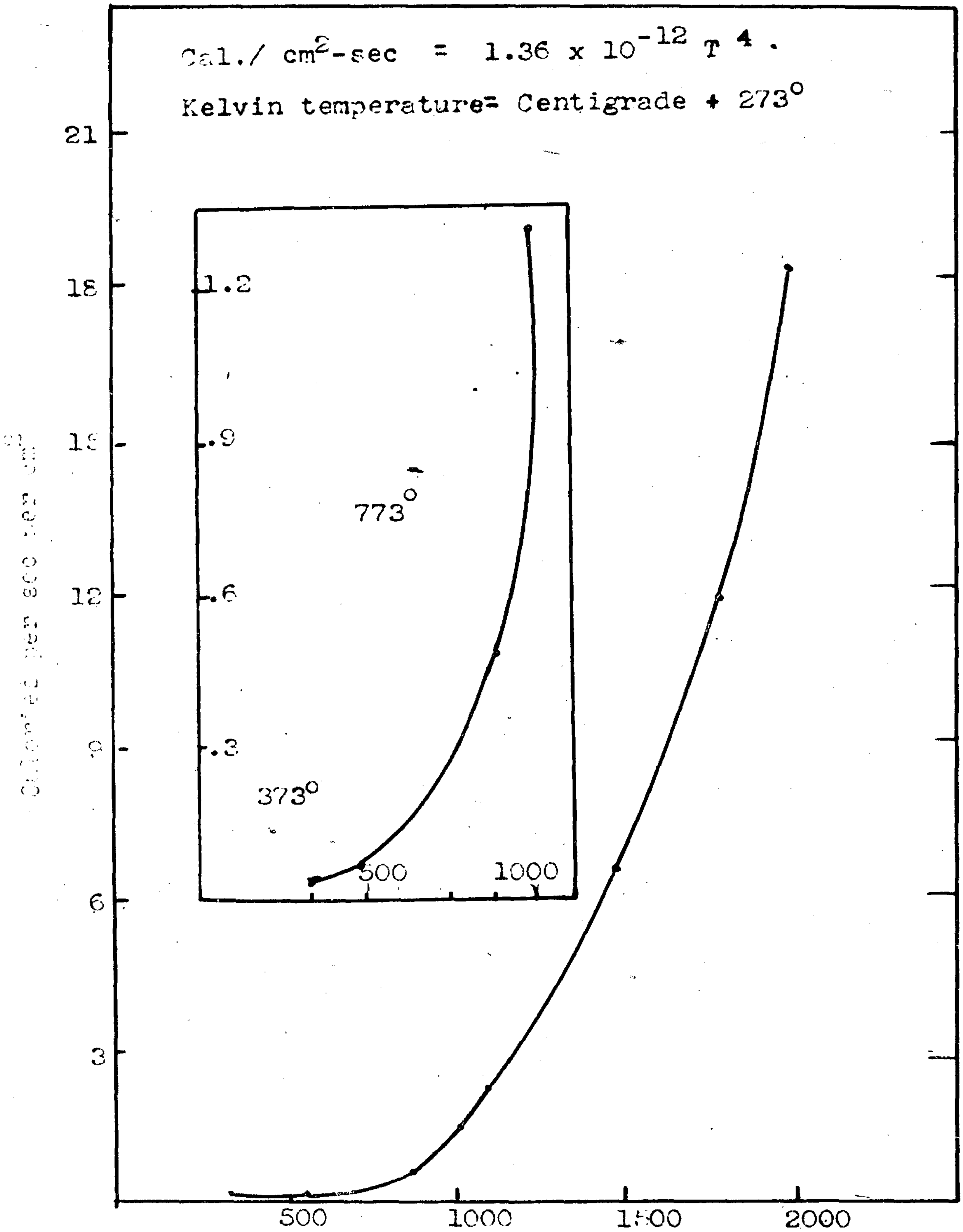

Figure 3. Graph showing the principle of the Stefan-Bolzman law which states that the total radiation from a black body varies as the fourth power of the absolute temperature.

substance well suited to this purpose since its heat of fusion is about 88° to 90° F. (Telkes, 128, 129). Perhaps the same method could be used for storing heat for growing plants.

The earliest attempt to study the radiation of plants by heated panels was published by Bigeault (16) and Chauard (33). Their panels were spaced 20 inches apart and located in a greenhouse at Saint Agnan near Oise, France. Inside these panels were installed steam pipes for heat. The radiation was slightly more efficient than the panel type of heating previously mentioned which is used in the building industry; however, it lacked the efficiency that a high-temperature radiator possesses. While the roots were heated by the use of soil heating units, the leaves were partially heated by radiation from the sides and overhanging surfaces which shaded out part of the light from the sky.

Gray (59) built a similar panel heater using lead heating cables for the heat source. Two thermostats were used, one for the two coils which operated at temperatures below 60° F. and the other for the two additional lead coils set at 55° F. Temperatures of 5° to 30° F. above air temperature were recorded by means of a thermocouple. The test plant, a geranium, was killed by a heavy snow at an air temperature of 8° F. The most noteworthy observation was the rapid drying of this plant.

Professor Farrall was instrumental in starting the first large project on high-efficiency radiation. His work with frost protection commanded world-wide attention. The first tests with a rod-shaped electrical heating unit (Figures 4, 7) showed definite promise of protecting plants from frost on a still night (Farrall et al., 48; Gibson, 55). Later tests made with more practical gas-burning units offered promise to orchardists, truck gardeners, and other horticulturists (Farrall et al., 48; Hassler, 67; Hassler et al., 68). The plants can be protected from radiation frosts when the temperature descends to approximately 26° F.

Other types of electrical resistors were tried by Gibson (55). Of particular interest was a heating element with its coil wound on a cylindrical refractory form which was mounted in an aluminum reflector. Heat lamps (1700° C.; 2000° Kelvin) prevented frost on a dahlia plot at Lakeside Gardens, New Baltimore, Michigan. The visible light emitted by this type of radiator makes it unsuitable for use on plants in the dark period in photoperiodic studies when not suitably filtered. Otherwise, if breakability is no objection, it is a highly efficient source of heat producing rays.

Controlled Conditions

In scientific research, as in the solving of an algebra problem, the experimenter tries to reduce the number of unknown factors to the very minimum. The perfect method is one variable with perfect control of all other unknowns. In biological science this can never be completely accomplished, although the probable error may be reduced by careful control of all

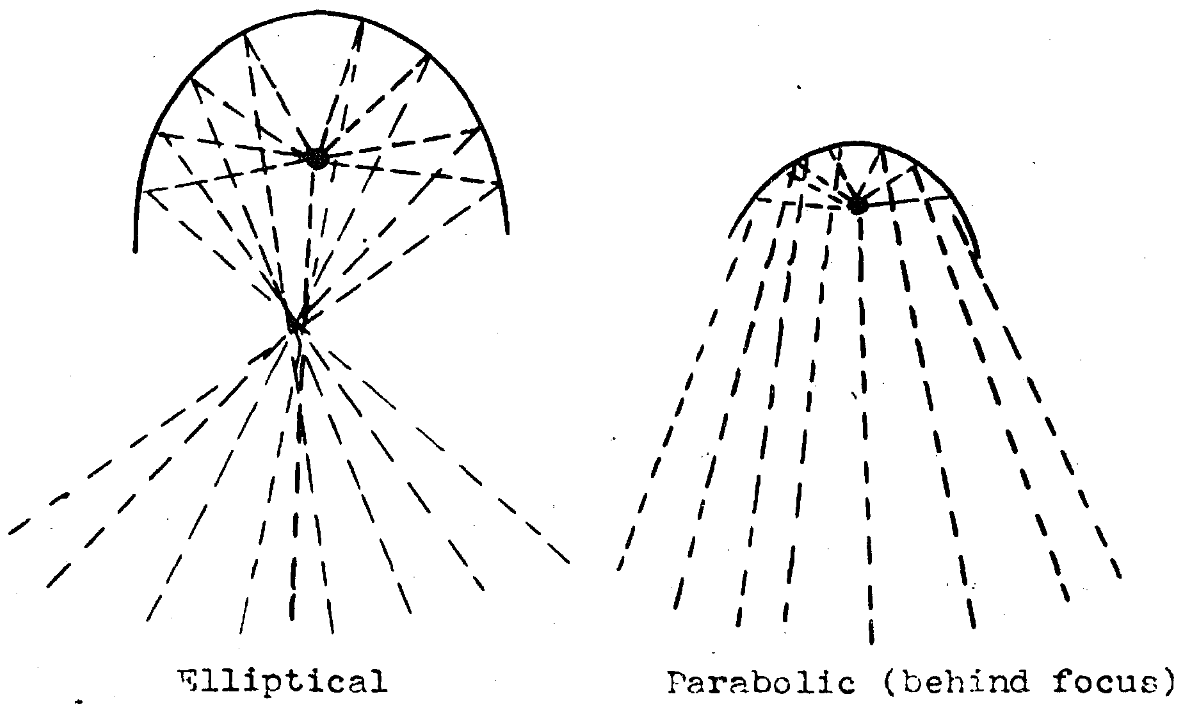

Figure 4. Types of reflectors used in these radiation studies and their respective distribution patterns.

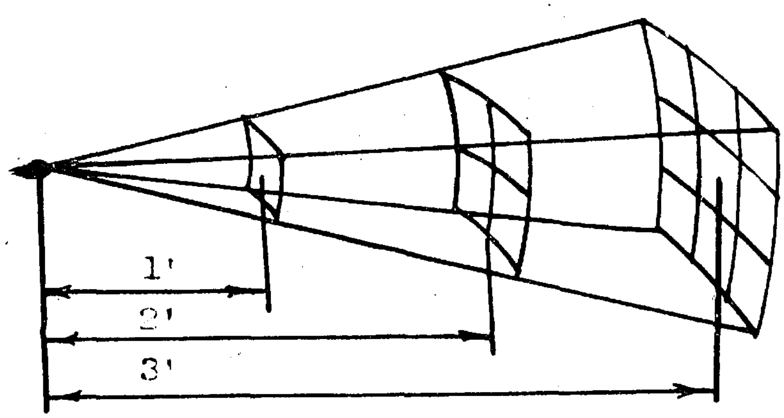

Figure 5. Diagram showing the principle of the inverse square law of radiation distribution from a point source of origin.

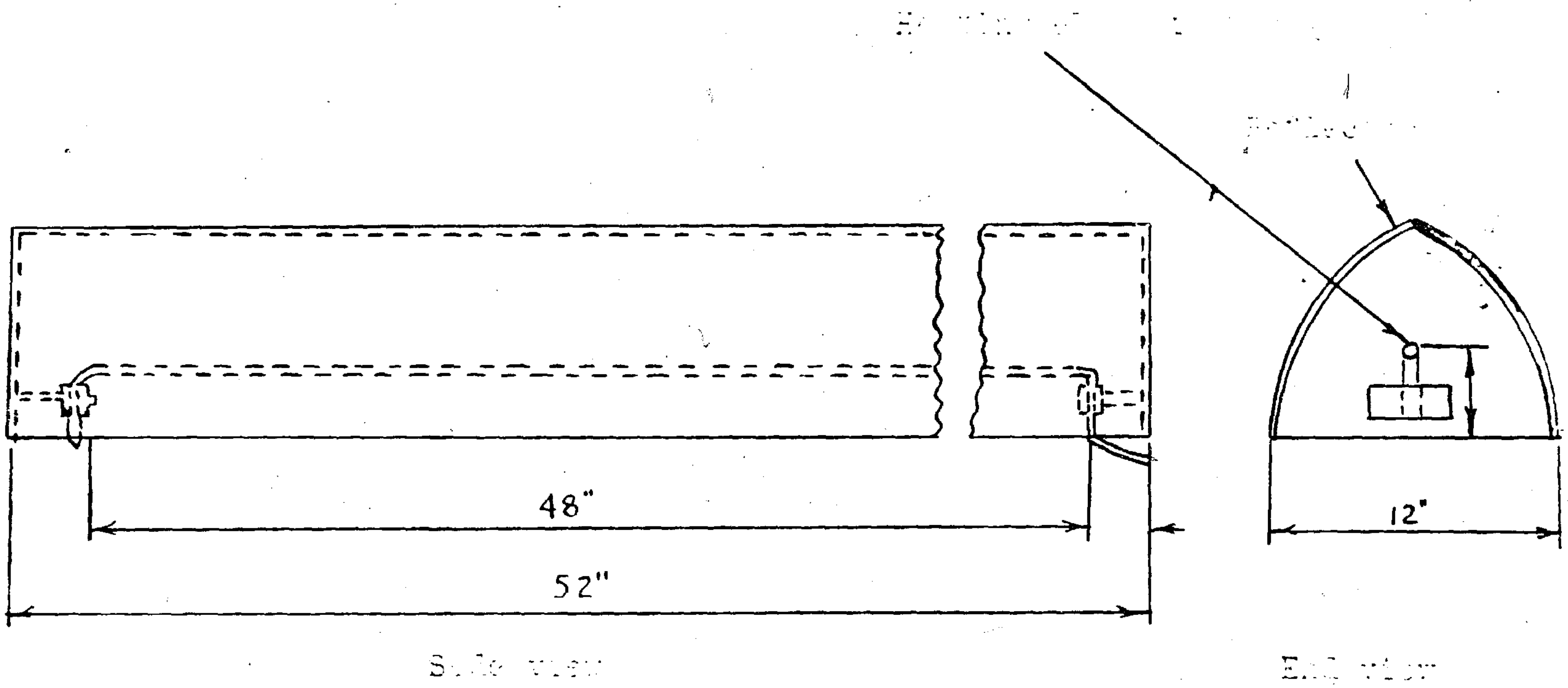

Figure 7. Construction details of electrical heating unit used for insect infestation and later used for radiation studies on Red Kidney beans.

environmental factors. If the investigator starts with homozygous plant material of the same size and age and also can control all exterior influences, he is likely to realize some benefit from his investigation.

Crocker (38) described the effort of the Boyce-Thompson Institute to control the living conditions of plants. Two constant-condition rooms were built, one with continuous illumination and the other without light. Photoperiodic studies were made by shifting plants from one room to the other. In these rooms temperature was accurately controlled; all lights were cooled by means of circulated water behind a plate-glass ceiling. The rooms were air-conditioned with air in which the CO_2 concentration could be enriched and regulated and the relative humidity controlled. In the two 11 x 11 foot rooms the light intensity was held at 900 foot-candles.

Boyce-Thompson Institute also uses (1) two greenhouses equipped with a movable gantry crane having a battery of lights which can be moved over the greenhouse when additional light is needed to lengthen the day, (2) an insulated greenhouse (Arthur and Porter, 9), which is used to keep out unwanted temperature differences, and (3) a spectral greenhouse (Popp, 102) designed for plant study with different-colored lights.

At the California Institute of Technology, Went (142) described two air-conditioned greenhouses each of which was joined to a dark laboratory. The temperature was accurately controlled, the greenhouses being heated by air circulated through controlled baffles and being cooled by a circulatory system of cold water which flowed over the glass on the roof of the greenhouse. The thermostats were actuated by a photoelectric light meter at a 200 foot-candle light intensity reading which changed the setting of the thermostats from that for the night temperature to that desired for the day temperature. The air supply was also humidified to the proper degree of relative humidity. With these controlled conditions, Went did some exacting experiments.

The Smithsonian Institute built several small plant growth chambers for studying the effect of different colored lights on plants (Brackett and Johnson, 20). The octagonal cylinders, 15 inches in diameter and 22 inches high, were surrounded by a water jacket for accurate temperature control. The same tank supplied all the water used in this circulatory system; the same air supply was forced into all chambers. The nutrient solution was also heated and circulated throughout all chambers.

The United States Plant, Soil and Nutritional Laboratory at Ithaca, New York, installed in a basement-room 10½ x 16½ foot eight panels of fluorescent lights, each of which contained twelve 30-watt 36-inch cylindrical lamps (Hamner, 65). The reflection from these panels was slightly increased by painting the under surface with white paint. By the close arrangement of lights the laboratory was illuminated by a light intensity of 2000 foot-candles, which grew better plants during the months from November to April than the greenhouse did at the same season of the year. Heat from the fluorescent tubes was reduced by means of a fan and the humidity was regulated by a humidistat. Temperature and relative humidity were held within a few degrees of the desired setting. A combination of white and daylight fluorescent light gave the best results for most plants, including the Red Kidney bean. It was suggested that more uniform temperature conditions could be maintained if the lights could be made to burn continuously rather than intermittently; the experimenters had found intermittent light necessary to simulate the duration of solar radiation or the particular duration of light required for any particular photoperiodic crop.

In Oklahoma, Chester (34) installed a temperature regulator in two greenhouses. An elevated heater in the center of each house supplied the heat by means of a series of steam coils mounted in an enclosure; a fan circulated the heated air through anemostats or diffusers with cone-shaped baffles. The heater was operated by a thermostat; when the temperature rose above a predetermined level, the ringing of a bell called an attendant to open the ventilators.

Hartman and McKinnon (66) described an environmental control cabinet built at Davis, California, for the study of the relationship between temperature and the photoperiodic response of plants. Four cabinets, 3 x 4 x 5 feet, constructed adjacent to a refrigerator, supplied cool air for reducing temperatures around the lights, which were mounted in a compartment over the glass-roofed cabinats. The twelve 40-watt fluorescent light tubes supplied a light intensity of 500 foot-candles to the plants, although it was suggested that a higher intensity would be more suitable for the two cabinets which were heated to a higher air temperature. Relative humidity was raised in the warmer compartments by keeping water on the floor until sufficient water was absorbed so that the relative humidity equaled that in the cooler rooms.

Withrow and Withrow (149) grew plants in air-conditioned chambers controlled within a variation of .5° to 3° C. The relative humidity was maintained within a variation of 70 to 80% saturation at the temperature studied. In each case the rooting medium was subirrigation gravel culture. All lights functioned satisfactorily, but the incandescent lamps were most difficult to cool because of the high infra-red radiation. Most of the lights were mounted behind water-filled cells five inches deep.

Parker (100) worked with plants in many controlled experiments and came to the conclusion that the population of plants is limited in a control chamber, but that the results regarding light and environmental reactions are of great value.

Naylor and Gerner (95) and later Naylor (94) found that fluorescent lights gave them the best results of all lights tried, and that 600 foot-candles gave good growth to Red Kidney beans. Both white and daylight fluorescent lights appeared to be equally effective with little heat being dissipated. Various colored fluorescent light tubes, they said, were also available for special purposes.

Recently the greenhouse industry has become interested in control equipment. Thermostats for heat control, and the trombone style of heating pipes, which are more responsive to regulation, will make greenhouse heating easier. Automatic ventilation will help to solve the cooling problem, and automatic watering will aid the growers in maintaining an even water supply at the roots of their crop.

EXPERIMENTAL

Selection of a Radiant Energy Source

As previously stated, the primal source of radiant energy is the sun. Its illumination is indispensable for the process of photosynthesis as well as the heat it produces in plants. The energy utilized by plants directly or indirectly from the sun enables them to carry on their normal physiological reactions--to grow, develop, and reproduce.

Radiant energy is being transferred from and to all places and at all times, but the rate and wave-length may not be easily recognized. Wherever there is a temperature difference--such as between a fireplace and the objects surrounding it--there is a transference of energy between the two objects with the major share of energy leaving the hotter object. The hotter the radiator in relation to the plant, the more effective the radiator will be as a heating agent. Panel heating should be called a low-efficiency radiator because the temperature of the panels or walls is only slightly above the objects which it surrounds. The heating panel of Bigeault (16) and Chauard (33) and those of Gray (59) were slightly more efficient than most panels as a radiant source.

To compare the efficiency of radiators at different temperatures, reference to Figure 3 will show the relationship between the energy produced at all temperatures from 372° K. (100° C.) to 2000° K. It is evident that the efficiency increases almost directly with the fourth power of their Absolute (Kelvin) temperature.

Because of the difference of temperature the most highly efficient source of radiant energy that might be used for plant radiation studies is the heat lamp (74). When new, this lamp burns at slightly above 1700° C., and its spectral pattern extends well into the visible spectrum (Figure 1). But because it gives off a measurable quantity of illumination, which is present at all hours of the day that it is used for heating, it is not beneficial to plants which demand a certain period of darkness; i. e. a short-day plant, like some varieties of soybeans, will not produce seed when the number of hours of the light period exceeds an amount known as the critical period. If these plants are exposed to light more than this number of hours they will remain in the vegetative condition.

In this problem a radiator was needed whose radiation included no visible light, or one whose illumination was so negligible that it would produce no light stimulus in the plants studied. It was desired to eliminate all effect of photoperiodism, and at the same time to heat the plants by a radiator of the most efficient type which still emitted no light. This requirement indicated an emitting surface of 500° C. Since both the electrical and gas-burner types of radiators used by Farral et al. (48) for frost protection were used at this temperature and higher temperatures, they were considered ideal for this experiment.

A gas-burning radiator, however, is undesirable at close quarters with plants, since gas injures plants. Until an efficient gas-burner is designed without the danger of escaping gas, it will be of questionable value for the heating of plants.

The electrical design was therefore the most practical of these two heaters; the heat output could also be more readily controlled. The design used by Farrall (48) was based on an electrical cromolox heating rod 4 feet long mounted in an elliptical reflector. Its heating capacity could be regulated by a change in wattage in the electrical circuit. Therefore it was decided that, by using this heater, the emitting surface could be regulated by the suitable manipulation of a Variac. At an amperage of 12.5 coulombs per second and an average voltage of 120 volts the wattage was 1500, which, when divided by the conversion factor 4.18[1] gives 358 calories per second.

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1. There are approximately 4.18 watt-seconds per calorie.

Selection of an Adequate Reflector

The electrical cromolox heating element which was mounted in an elliptical reflector used for frost-prevention studies (Figures 4 and 7) was the logical choice for the study of radiant energy on the growth and development of Red Kidney beans. The distribution pattern of this reflector, with its polished aluminum undersurface, was studied by means of an Eppley thermopile (130) and a radiation meter (Figures 6[1] and 14). Although the distribution of radiant energy was satisfactory for all purposes, uses in this problem, the 12-inch wide design shaded the plants considerably. Therefore a 3-inch elliptical reflector was made, modeled upon the 12-inch one. This miniature model was not so satisfactory as the larger one but permitted more of the sun's rays to fall on the plants when it was used. However this elliptical reflector had one undesirable feature; i. e., the radiation distribution pattern covered too wide an area. A narrower and more concentrated pattern was needed so that one could place the reflector at a greater height above the plants and thereby decrease the difference in temperature between the upper and lower parts of the plants.

This need led to the design of the near-focus parabolic reflector (81; Figure 4), with the help of F. J. Hassler. Made

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1. Used by permission of Mr. F. J. Hassler.

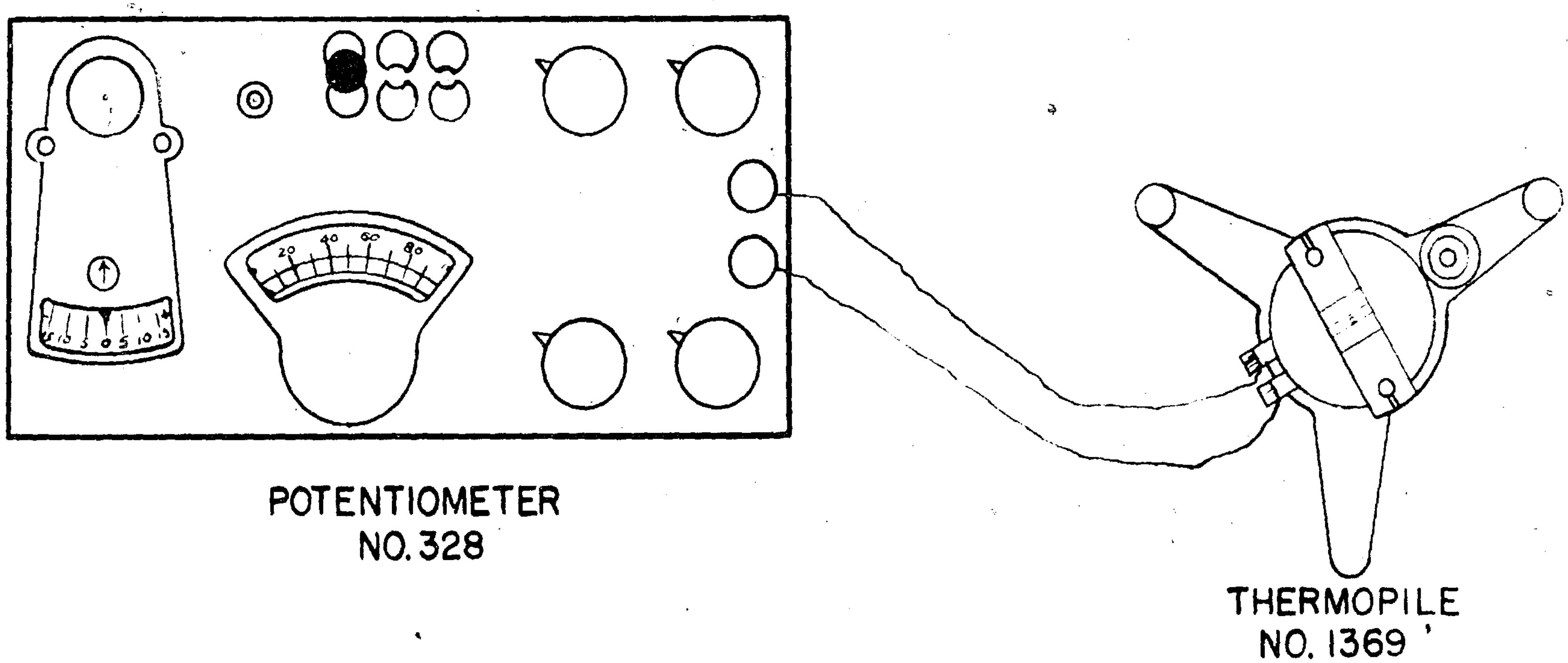

FIG. 6 EPPLEY RADIATION METER

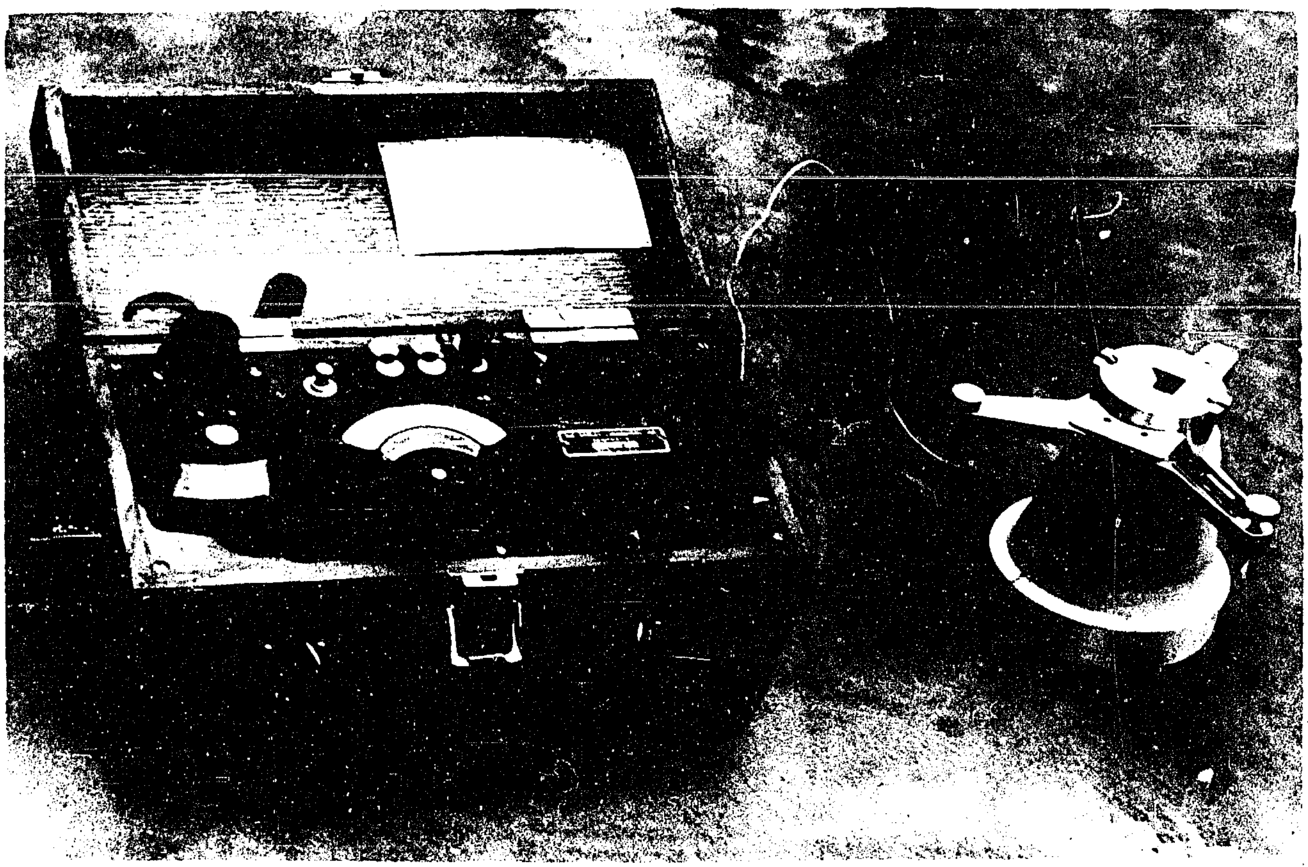

Figure 14. Radiation meter and thermopile used for measuring radiant energy directly.

from double-weight sheet aluminum with an anodized center, on the under side, this reflector was six inches wide, and the radiation house (Figure 8) used in the greenhouse was designed with the correct width at the top to hold this particular reflector. Besides being used in the greenhouse during 1948, it was mounted on a frame in the cold storage room during 1949 (Figure 15). Several irregularities developed in its distribution pattern known as "hot spots", while other areas had a lower-than-desired exposure to radiant energy. The main reasons for this irregular distribution were: (1) the faulty design due to the difficulty of designing a reflector which would give a good distribution pattern; (2) the failure of the metal to hold its original shape because of its lightness.

While the elliptical reflector was being used, it was necessary to move the potted plants frequently to avoid local overheating of some plants and underheating of others. Pots were also moved to prevent the roots from growing into the sand beneath the pots.

The principal reason for returning to the parabolic reflector in 1950 (Figure 16, 17) was to use its more even rate of energy distribution. The main disadvantage found was the necessity of lowering the reflector to within fourteen to sixteen inches of the tops of the plants.

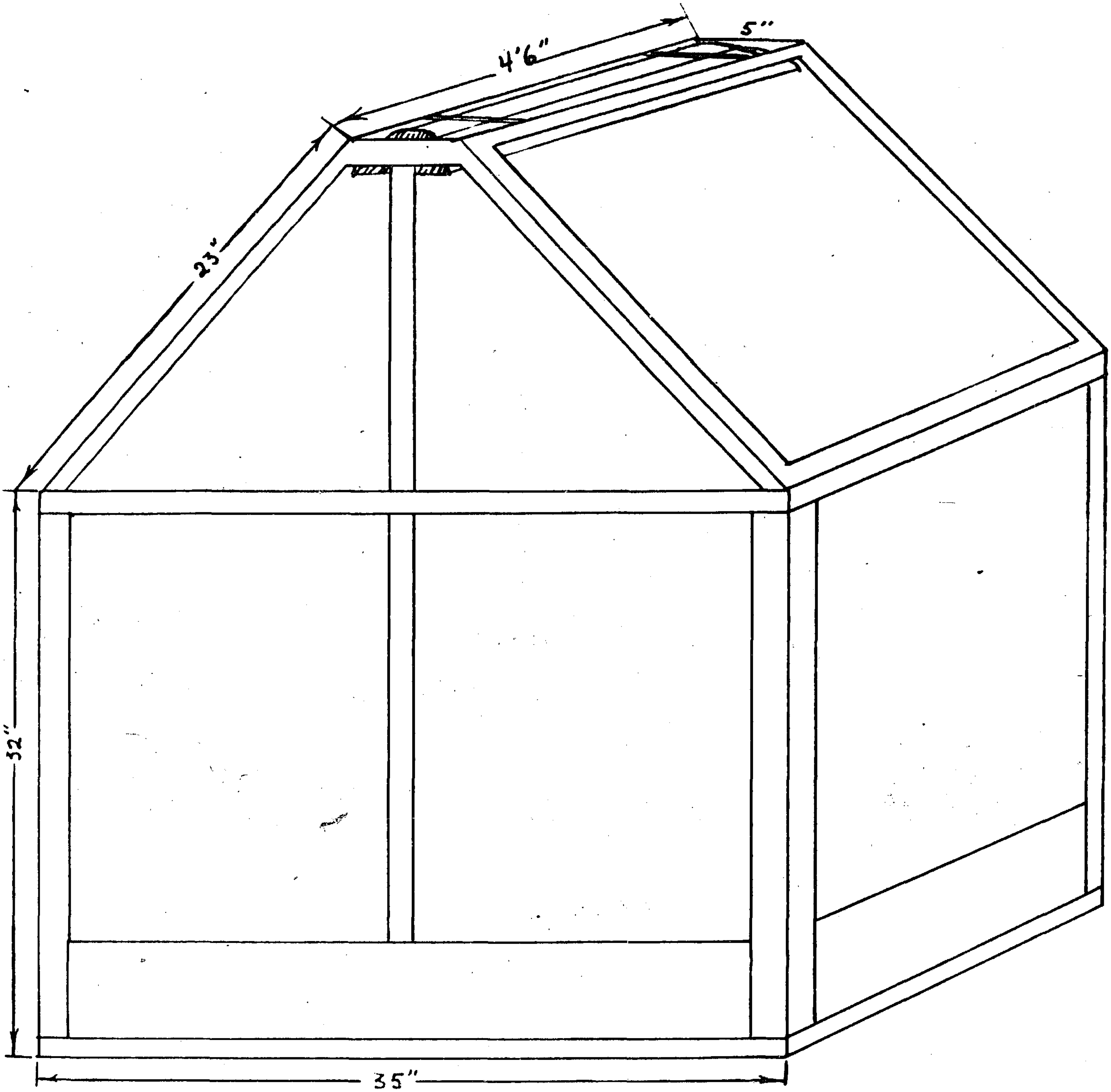

Figure 8. Design of radiation house used for radiation studies in the greenhouse during 1948. Another house of same design without reflector served as a control house.

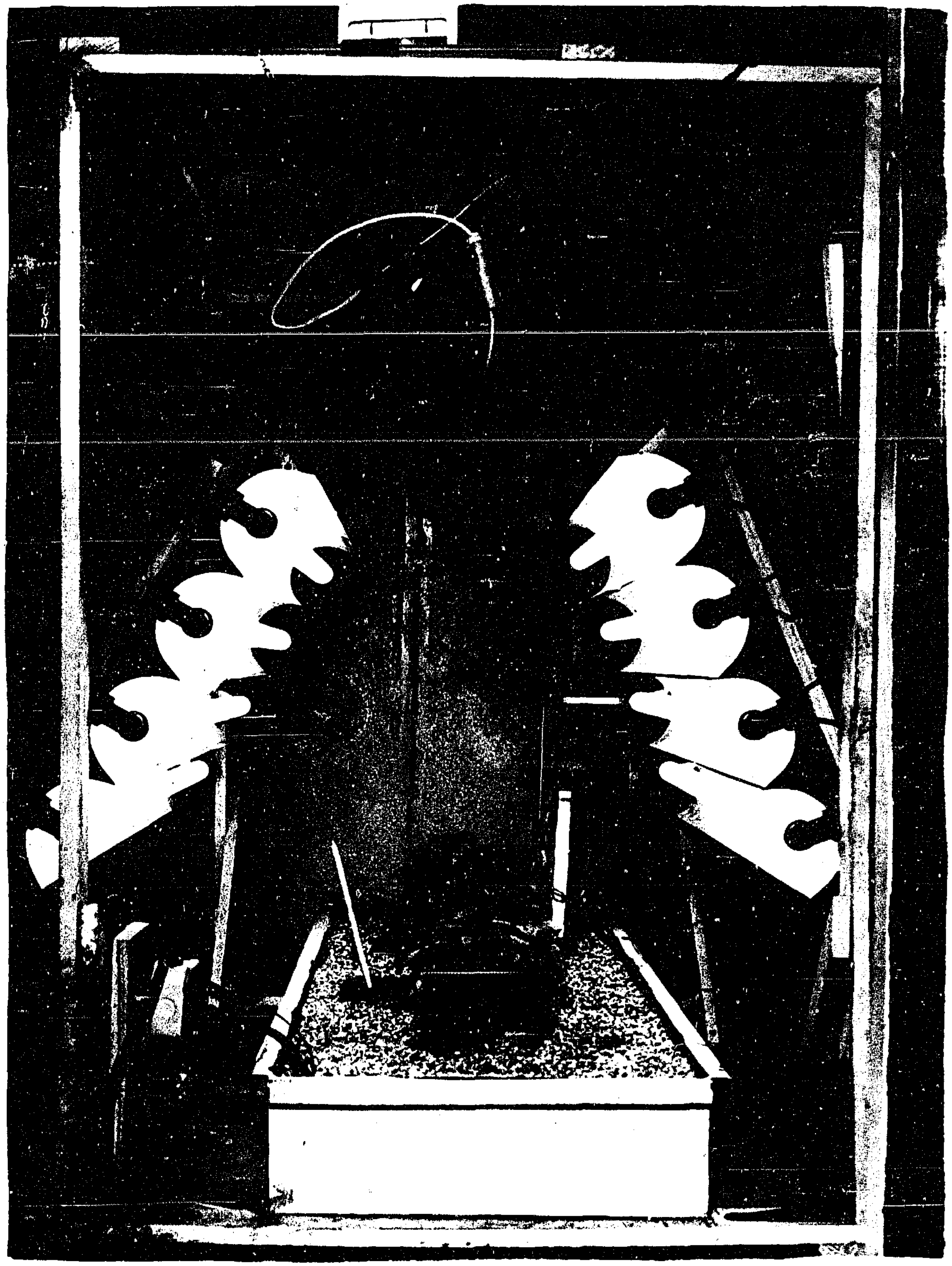

Figure 15. Radiation room (converted cold storage in which the air temperature was held at 40° F.) during 1949, showing six inch wide, parabolic reflector. (Note framework supporting assembly of lights, reflector and tank. Two rows of Red Kidney beans were used due to the narrow width of radiant energy distribution.)

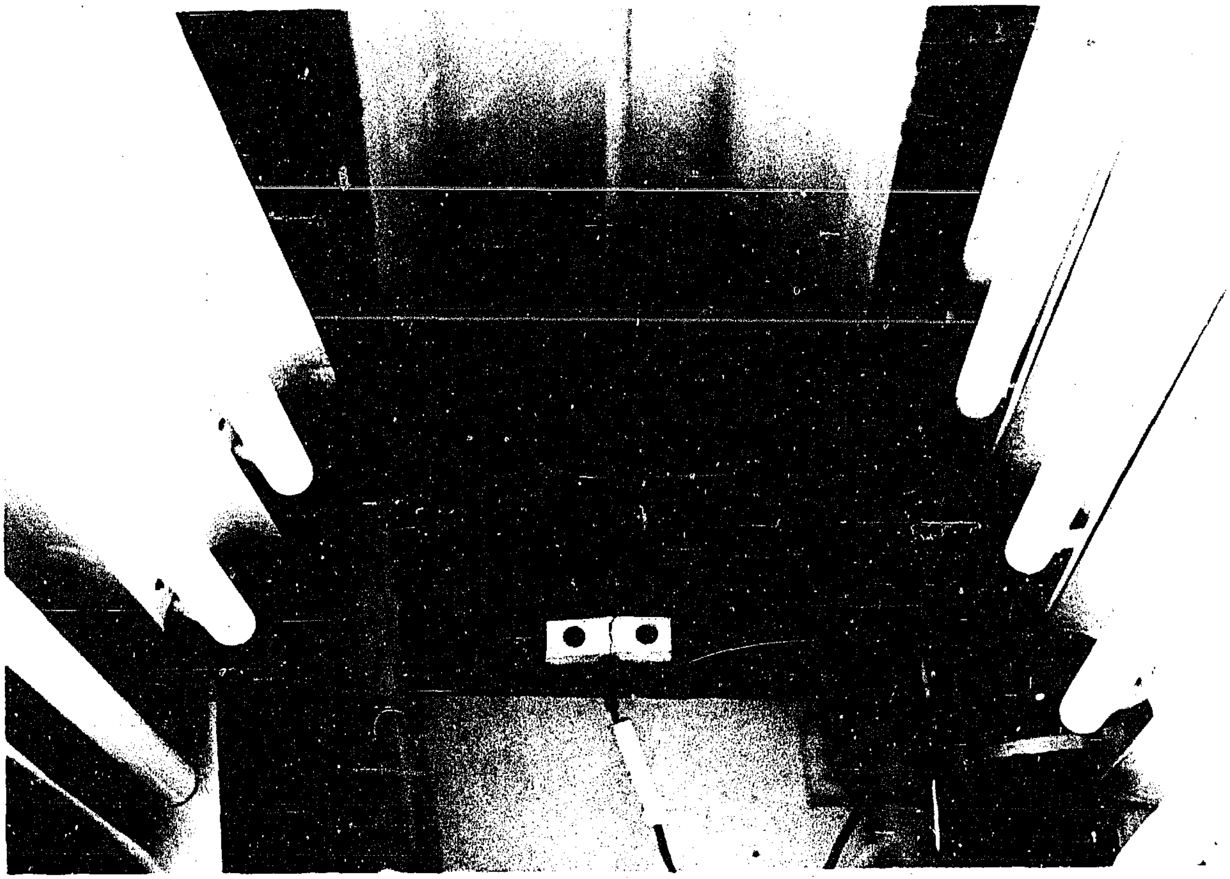

Figure 16. The 12-inch wide elliptical reflector with the cromolox heating unit mounted between two banks of flurescent lights in the cold storage room during 1950.

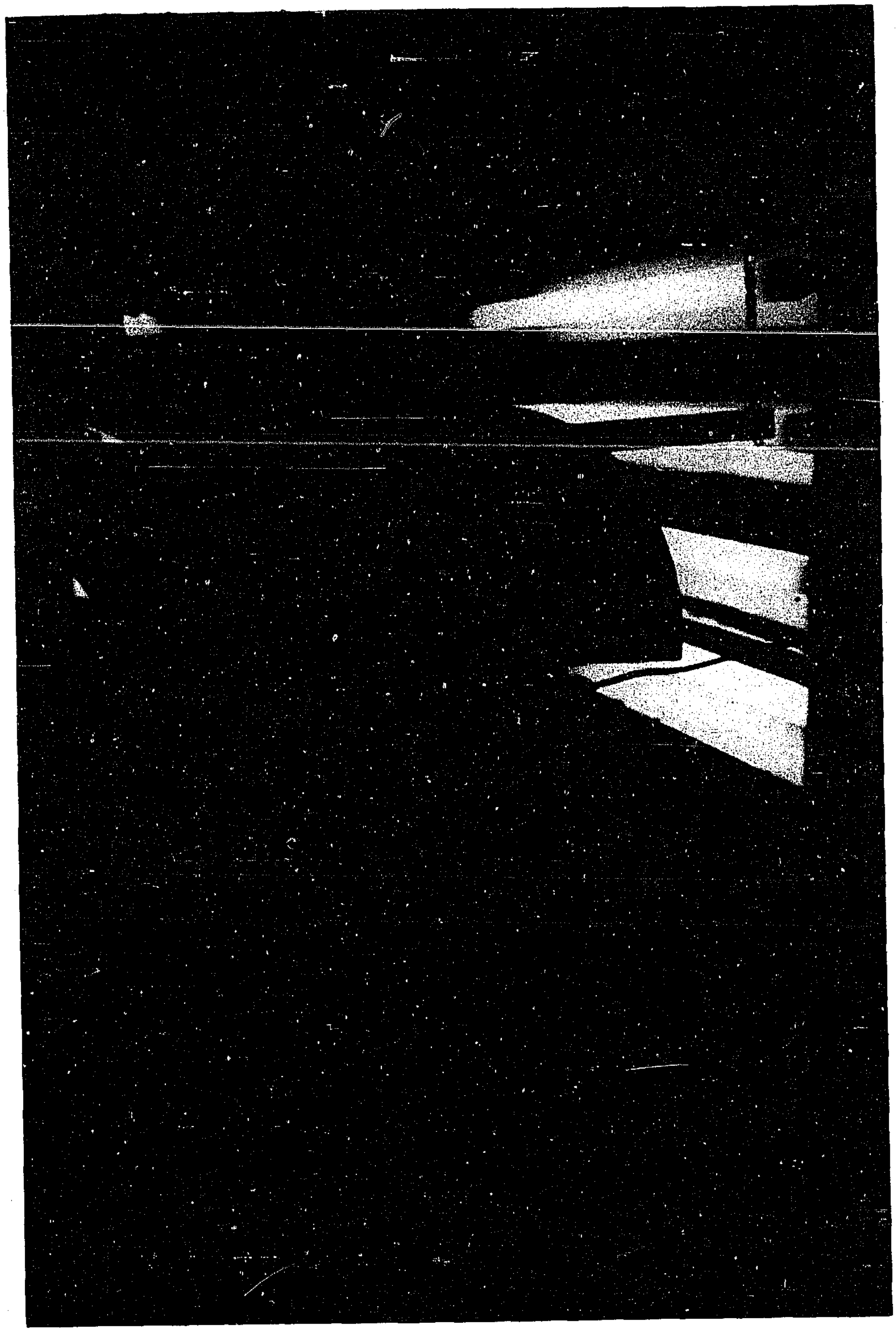

Figure 17. View of radiation room (converted cold storage) in which the air temperature was maintained at 40° F. The twelve-inch elliptical reflector here shown was used during 1950. Red Kidney beans on sixth day under radiation treatment. Taken Feb. 20, 1950.

Nutrient and Watering Requirements

The quantity of water lost through transpiration of the aerial parts of the plant and by evaporation from the soil is extremely high when the plant is continually exposed to radiant energy. This high water loss was mentioned by Gray (59) and was verified in the present experiments on begonia and geranium potted plants during the early testing period in which radiant energy was used. Radiated plants used from two to six times as much water as control plants in all of these experiments.

When infra-red radiation was used, to prevent wilting, it became imperative to adjust the water supply at the roots of the radiated plants to approximate the supply to the control plants. It would be difficult to hand-water plants frequently enough by casual observation to insure an adequate and uniform supply.

It was necessary then to look for an artificial means of supplying a continuous and uniform supply of water. Two systems of supplying water were mentioned by Post and Seeley (109) and Post (106): injection and automatic watering. Later Post and Seeley (110) reported on an automatic watering system for pot plants. Seeley (117) discussed in detail the watering of pot plants by this system. The Post and Seeley method seemed acceptable for the conditions of the present experiment. Therefore it was used throughout all of these studies.

This method depends upon the principle of capillarity of water. In the case of pot plants where the pot is not over four inches in diameter, a water level an inch of two below the bottom of the pot was reported satisfactory. This distance between the pot and the water level will vary, however, with the size of pot, the size of plant, the type of soil in the pot, the type of medium in which the water table is immersed, and the compactness of the soil. (In short it will depend upon the capillarity of the soil used.)

In the experiments reported in this thesis, it was necessary to raise the water level slightly higher in the radiation room because of the more rapid loss of water. In the method followed, recommended by Post and Seeley, a layer of gravel was placed in the bottom of the bench, or, in the case of the cold storage experiments, in the bottom of an asphalted, painted, galvanized tin tank. In the first group gravel was used altogether with the pots immersed in this medium (Figures 13, 14, 15, 46). Since a few pots dried out, the gravel was later covered with sand, in which the pots were pressed about a half inch deep. Water was applied at one end of the tank automatically by the constant level system (Figures 9, 18, 19).

To insure better contact with the water and to maintain capillarity, all pots were filled with soil without the customary drainage material in the bottom as suggested by Cornell research workers (37). A guard row of pots was added to each of the cold storage experiments to replace any that failed to establish good capillarity in the tank. (Observe first row in Figure 17). At the time the pots were installed at the beginning of each experiment, they were watered from overhead

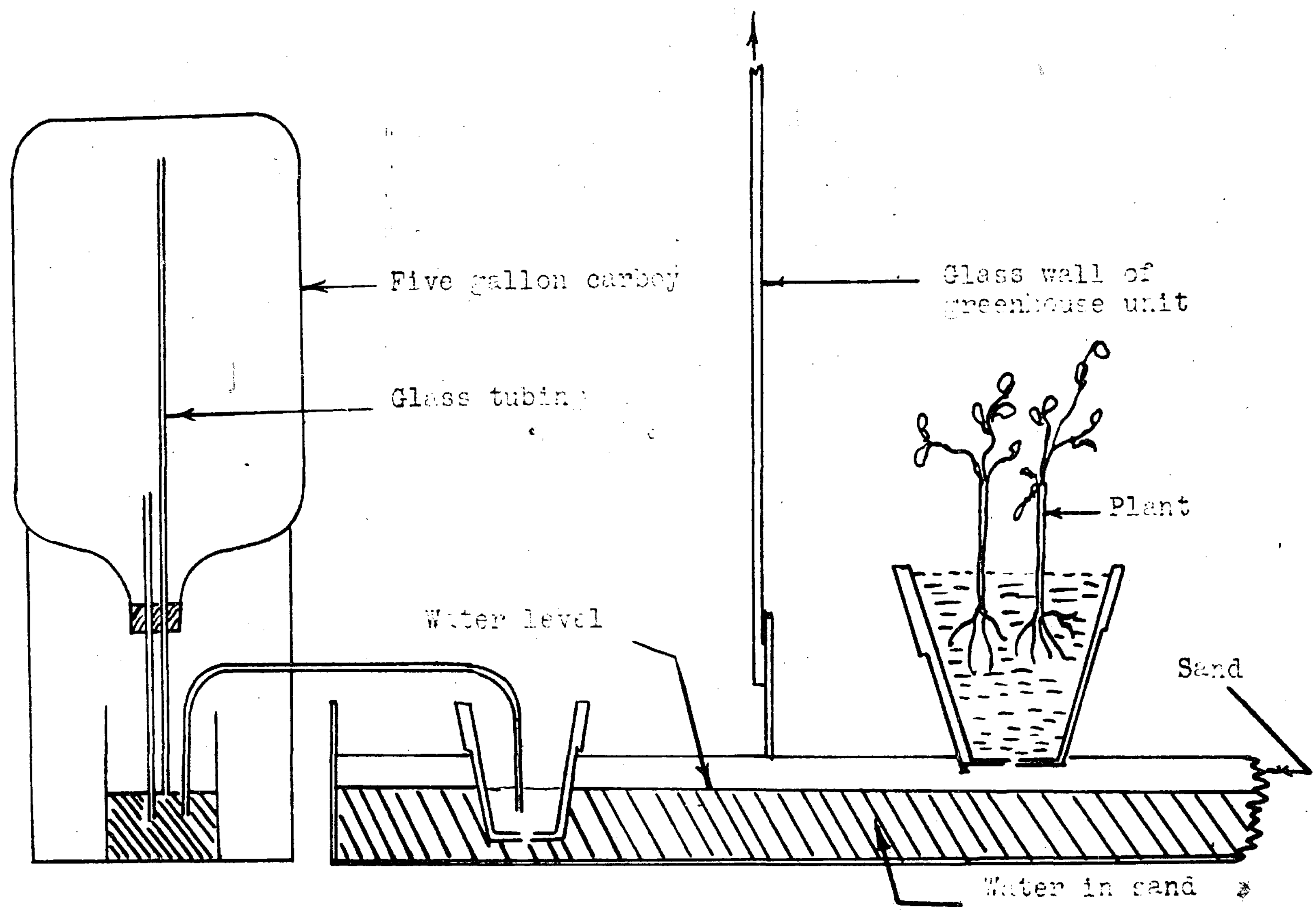

Figure 9. Method of automatic watering by the constant-level method used for these radiation studies. Diagram showing use in the greenhouse.

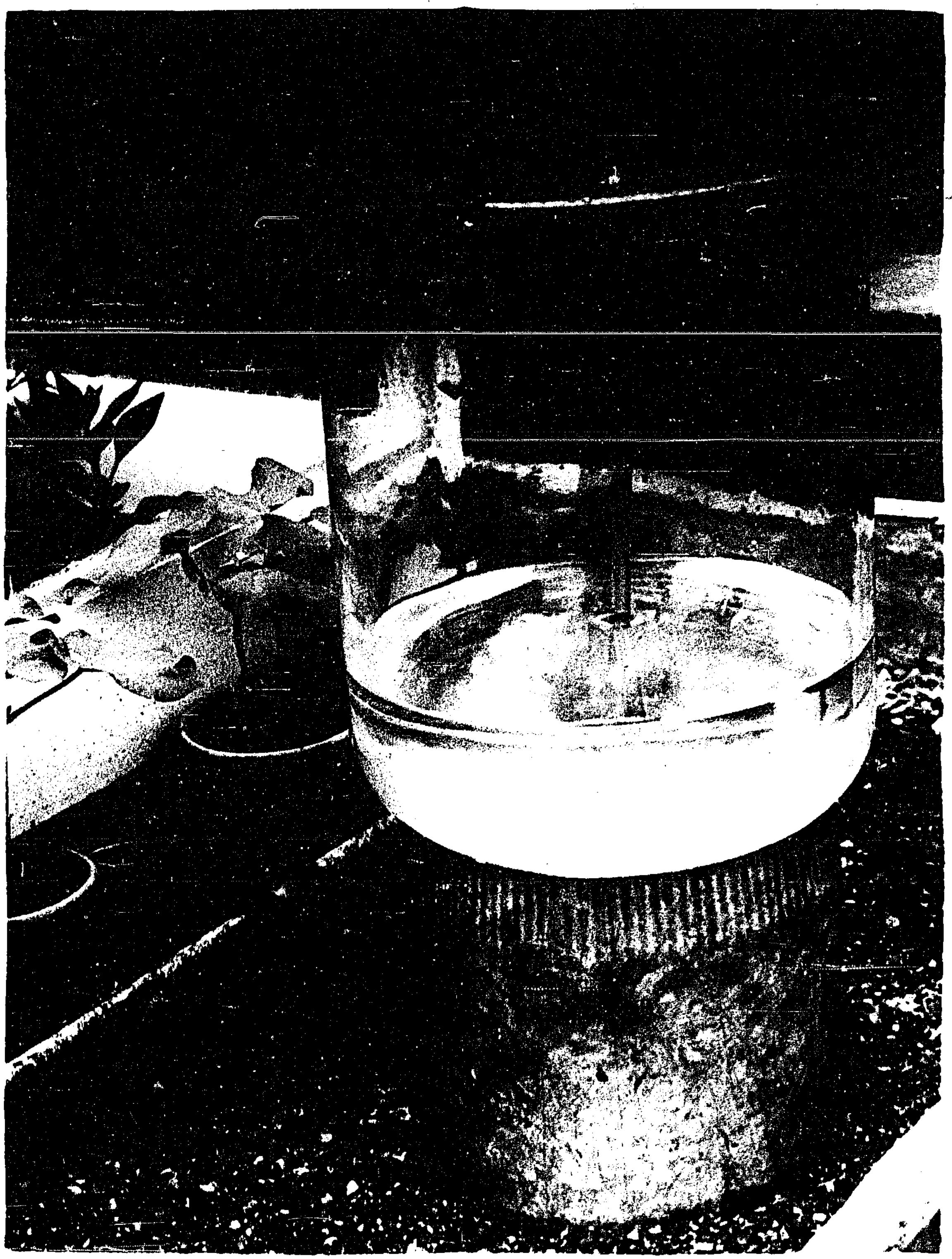

Figure 18. Automatic watering system used for the radiation house in 1948. The Red Kidney beans outside the house were used as checks.

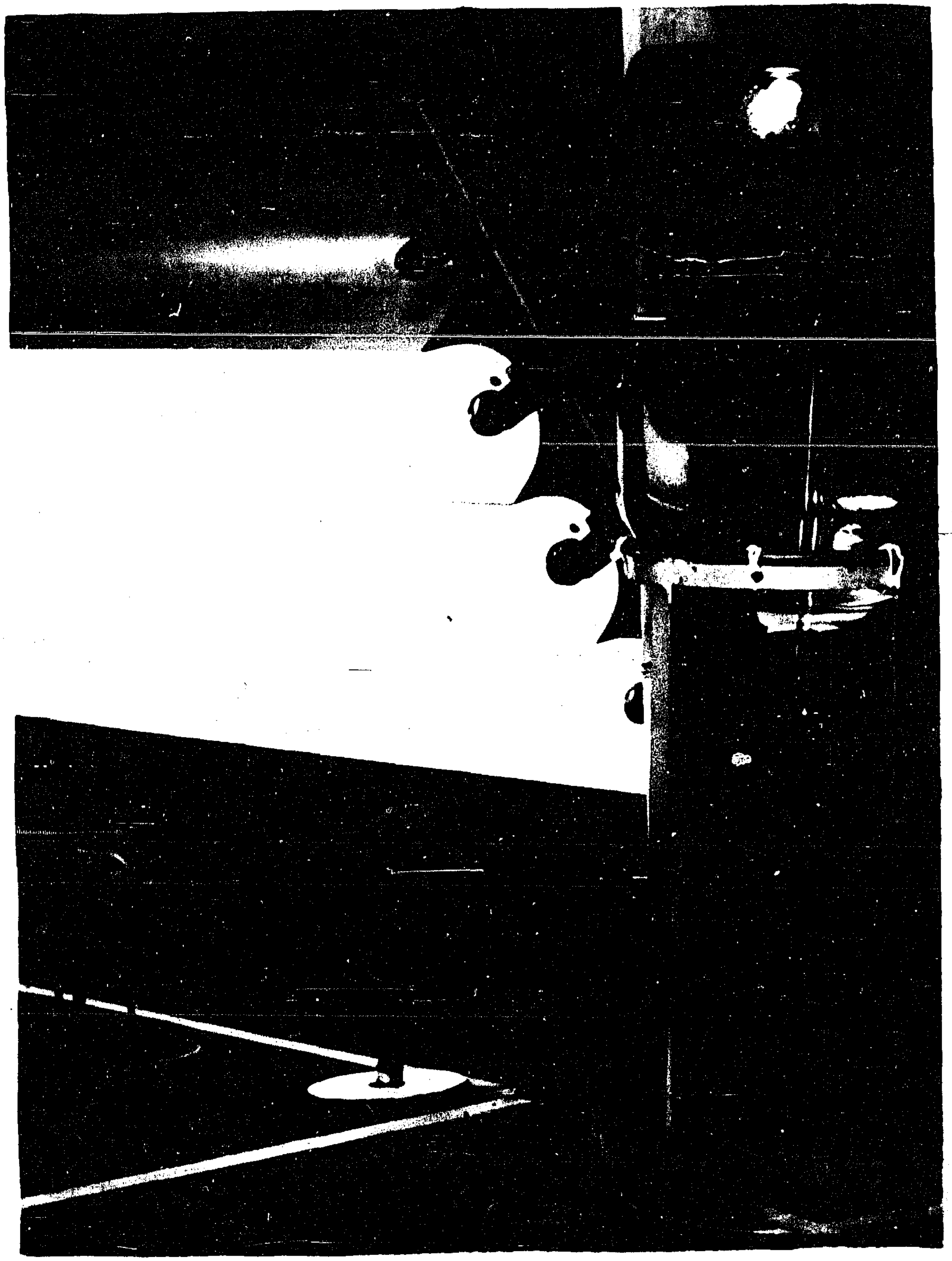

Figure 19. Automatic watering system used in the control room (converted cold storage room) during 1950. Some of the fluorescent tubes were removed to balance the light intensity in the radiation room.

until they were completely saturated. To initiate capillarity during the first two weeks after seeding, the pots of bean seedlings which were started in the greenhouse were watered by hand with a sprinkling can. This was true both for the four-inch pots planted in 1948 and the three-inch pots in 1949 and 1950. The root system developing under hand watering conditions was slightly more branched and had more root hairs than the root system of those plants developing under automatic watering conditions. Both root systems are equally beneficial to the plants growing under those conditions. The fleshy condition of the roots is especially noticeable when plants are growing under water culture or "hydroponics" (Eastwood, 44). In the experiments reported herein, the seedlings were moved at the age when the new set of leaves were just assuming their full size, about two days after they first unfurled (Figure 20). They were selected at this age because they could be chosen for uniformity of age and development and also because the immature root system could easily produce the more fleshy root system which is more suitable for constant watering conditions.

The nutrient level of the soil in all pots was approximately equal in each experiment, since the soil was always mixed in one large pile before each seeding. A good grade of greenhouse loam was mixed with a small proportion of sand and peat (approximately 15% each), with superphosphate added. No further nutrients were added after the bean seeds were sown.

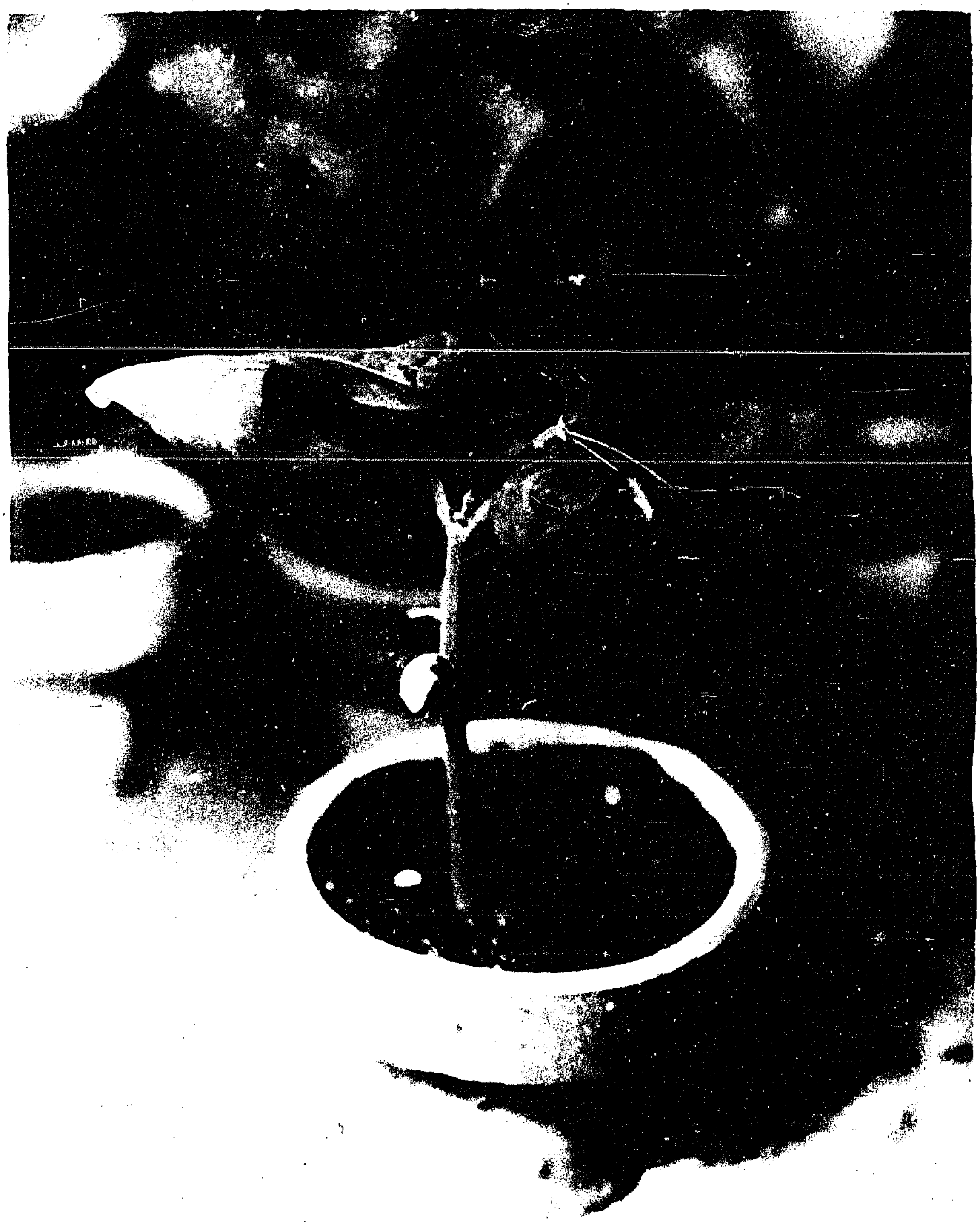

Figure 20. Example of Red Kidney bean seedling selected for experimental work, photographed the same day it was brought into the cold storage room. All seedlings were chosen at this age, just as the first leaves were approaching full size.

Temperature Measurement and Control

Thermocouples

The unreliability of the mercury thermometer and the other methods of measuring temperature which depend on a change in volume or pressure makes necessary the thermocouple when one wishes to learn the precise temperature. The thermocouple can measure the thermal conditions in a minute spot within a few seconds. Its use is particularly helpful when it is necessary to record the rapid fluctuations existing in the leaf under intense radiation.

The sensitiveness of a thermocouple depends on its size; the higher numbers correspond to the smaller diameter. Finer wire than number 40 is not required for measuring leaf temperatures. In fact, in this experiment all sizes from number 24 to 32 were used. Numbers 28 and 32 seemed to be the best sizes both for accuracy and for a sufficiently firm attachment to the lower surface of the leaf.

The earliest measurements in this study were made with a minute thermocouple inserted within the leaf. This thermocouple had to be made very small so that it could be inserted within a leaf blade from .015 to .018 inch in thickness. To do this the smallest wire available at the time had to be rubbed down with crocos cloth and, after being soldered with non-acid solder, again smoothed down until a diameter of .010 inch was produced. If the wire were smaller it was likely to break. Particular care had to be exercised to push the thermocouple all the way into the leaf until the first contact of the copper and constantan wire was located where a temperature reading was desired. Throughout this work particular attention was always given to this first meeting of these two wires, for the difference in electrical potential is measured on the potentiometer at the place where the two wires first make contact. All work had to be carefully executed with the aid of a magnifying glass.

It is questionable whether the internal leaf temperature derived in this manner represents the true plant temperature as accurately as the temperature taken on the lower epidermis of the leaf blade. The injury to the leaf increased with time so that the contact could be used only for a few hours. It positively could not be used where a continuous reading was needed. Since the point of insertion was not sealed from air movement, there might have been a lowering of the true temperature because of the evaporation of cell sap on the thermal junction.

After the preliminary testing period with the injection type of thermocouple, it was decided that these experiments should be based on temperatures taken from the lower surface of the leaf. As mentioned in the literature, the contact on the lower surface of the leaf seemed to be the most feasible. This system of recording temperature causes no injury to the plant and can be used for long periods of time. Regarding the temperature relationship of different parts of the leaf, Miller and Saunder (90) indicated that the lower surface was 1° C. higher than the upper surface.

Thermocouples for use on the outside surface of the leaf were made by twisting the copper and constantan wires as in the insertion type of thermocouples; larger-sized wire was used. A few were made with the contact point slightly flattened to insure better contact against the leaf surface. To attach these thermocouples to the leaf or leaves, the wires were bent around both sides of the leaf (Figures 21, 22, 23, 24 and 25) to insure the best contact with the junction.

Representative leaves--those that represented the average heat absorption for the group of plants--were chosen for all temperature measurements. Other leaves were chosen for the study of temperature variations within a given group of plants to determine the length and breadth for each experimental plot, and to discover any variations in temperature produced at different heights and leaf positions. Most readings were made with the leaf in the horizontal position--that is, with the leaf at right angles to the direction of radiation and at a height representative of the group of plants. These readings were made in approximately the center portion of the leaf. A location on one of the leaves was selected to serve for temperature control after careful comparisons of numerous temperature readings. This was necessary to insure the best possible temperature regulation of the radiator in the radiation room, so that the radiated plants would be heated as nearly the same as the control plants in the control room.

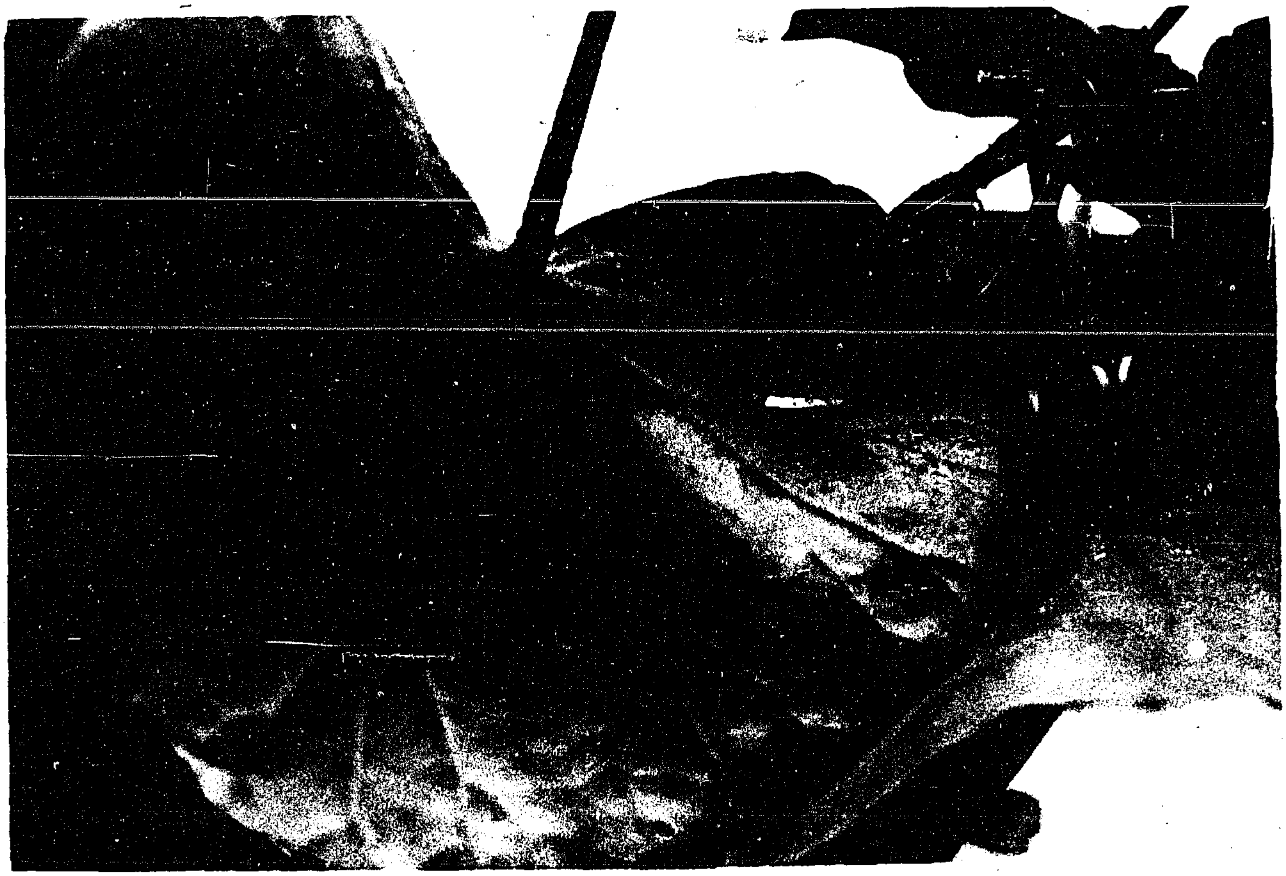

Figure 21. One method of attaching thermocouple to lower surface of geranium leaf for temperature measurement. A spring-like tension was created by bending the wire into a clip-like attachment. 1948.

Figure 22. Upper surface of geranium leaf showing attachment of three thermocouples by the loop-clip method of attachment.

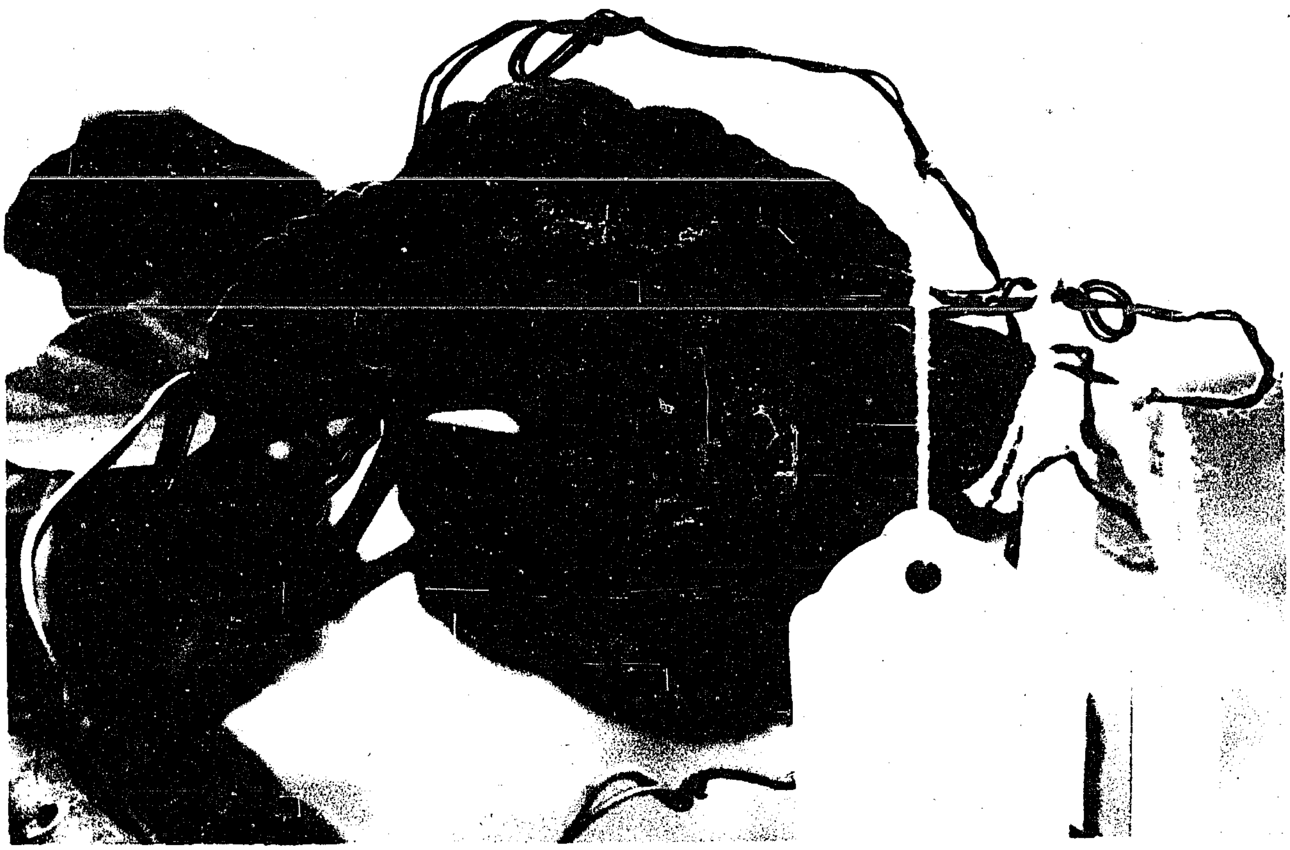

Figure 23. Lower surface of geranium leaf showing the same three thermocouples illustrated in Figure 19.

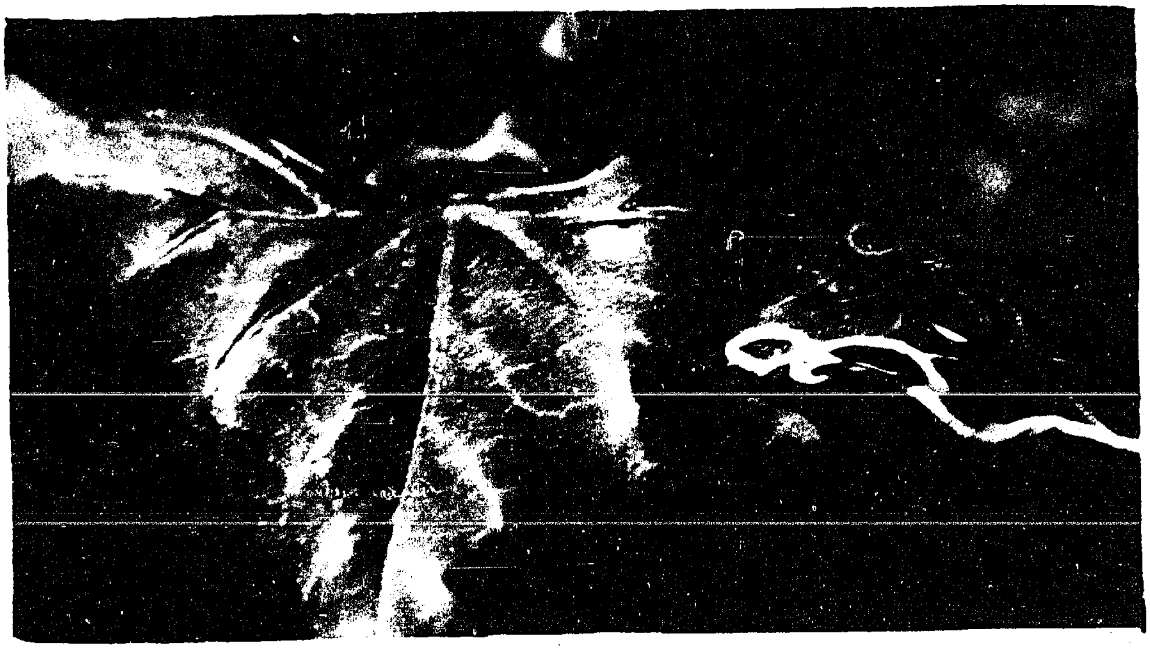

Figure 24. Method of mounting thermocouple in 1950. Control leaf six days after moving into storage room.

Figure 25. Method as above. Thermocouple attached to radiated leaf.

When the parabolic reflector (Figure 15) was used, only two rows of plants were inserted in the tank, for the distribution from this reflector, as measured with the radiation meter and thermopile (Figure 11), showed that the distribution fell off rapidly on the sides. With the elliptical reflector (Figures 16 and 17) it was possible to use four rows of Red Kidney beans (Figure 17).

After the twisted type of thermocouple was used for two years, Clarence Hansen suggested the use of a new type of thermocouple made by silver soldering two wires end to end. After this thermocouple was tested and found not only to compare favorably but to have some advantages over the twisted design of thermocouple, it was decided to use this new junction during the 1950 experimental studies.

The technique for making these junctions was difficult, but the following procedure was found to be the most satisfactory. With the use of a magnifying glass, the two ends of the thermocouples were filed or sanded at right angles to the length of the wire. Silver filings were made by filing some silver wire. The two wires were joined by melting a small quantity of flux on the end of each wire, then melting a small amount of silver filings on top of the flux. The two wires were then mounted in a suitable clamp which could bring the wires together. The wires were held in the flame for a second or two, sufficient time to join the wires together with the silver solder. When properly made, the thermocouple was as strong as a single piece of wire. The junction could only be identified by the difference in the color of the copper and the white constantan wire.

The ten thermocouple junctions made with the silver solder proved satisfactory for all the 1950 experiments, and no breakage occurred. They were easy to attach to the leaves at the desired location.

All thermocouples were calibrated while they were immersed in a 32° F. ice-water bath in which the mixture was stirred to produce an even temperature. The proper correction, which was less than .5° F. in all cases, was made to all readings of thermocouples which did not check with the expected reading. No variations were noted in the silver-soldered thermocouples. Variations in readings are usually due to the length and size of wire used, although it may be caused by the way the junction is assembled.

Potentiometers

Several devices for measuring potential difference in the thermocouples were used. In the early tests a manually operated potentiometer was connected to the two open ends of the copper and constantan wires which were scraped to remove all insulating material. Readings were calibrated in millivolts; thus it was necessary to refer to the proper tables to find the correct temperature. An ice-water bath in a thermos bottle was used for a reference junction with this potentiometer. During the 1949 and 1950 season, another manually controlled potentiometer for making temperature measurements was loaned by the vegetable crop section of the horticulture department. This instrument, with its ten point selector switch (Figure 26), was calibrated at the factory for copper-constantan thermocouples to read directly in Fahrenheit degrees without the need of an external reference junction. With this apparatus it was possible to estimate the temperature to within .1° F. on the temperature-indicating dial. Thermocouple wires were attached to each of the ten wiring posts of the selector switch.

Several recording potentiometers, based on the potential difference between copper and constantan in a thermocouple, were also used. The twelve-step Brown Electronik recording potentiometer #153Z65 (Brown 25; Figure 27, 28), which could record simultaneously twelve different temperature readings from as many thermocouples, was loaned by the department of agricultural engineering. A Brown circular-chart air-operated air-o-line Electronik potentiometer controller was acquired for use in this experiment (Brown 24; Figure 28, 29, 30, 31). It was adjusted to operate within two or more degrees variation in temperature (Figure 58). It could be set to any desired temperature by means of a pointer hand (Figure 30) and the temperature recorded by a pen carrying enough ink to last for more than a month.

Helpful suggestions for the use of the aforementioned controller, to determine the amount of energy used by the radiator, were made by Wallace of the University of Connecticut,

Figure 28. Manually operated potentiometer with ten-point selector switch for measuring temperatures from ten different thermocouples.

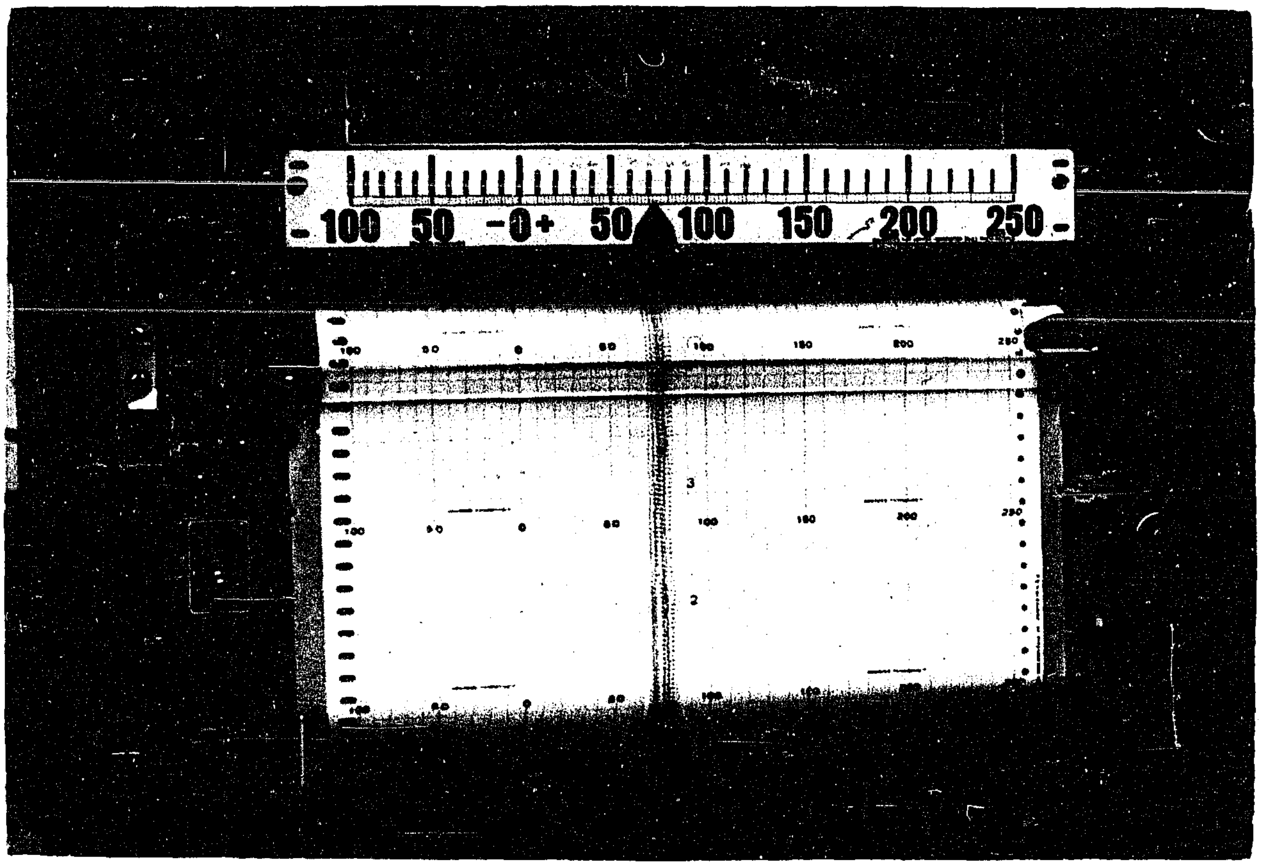

Figure 27. Twelve-step recording potentiometer.

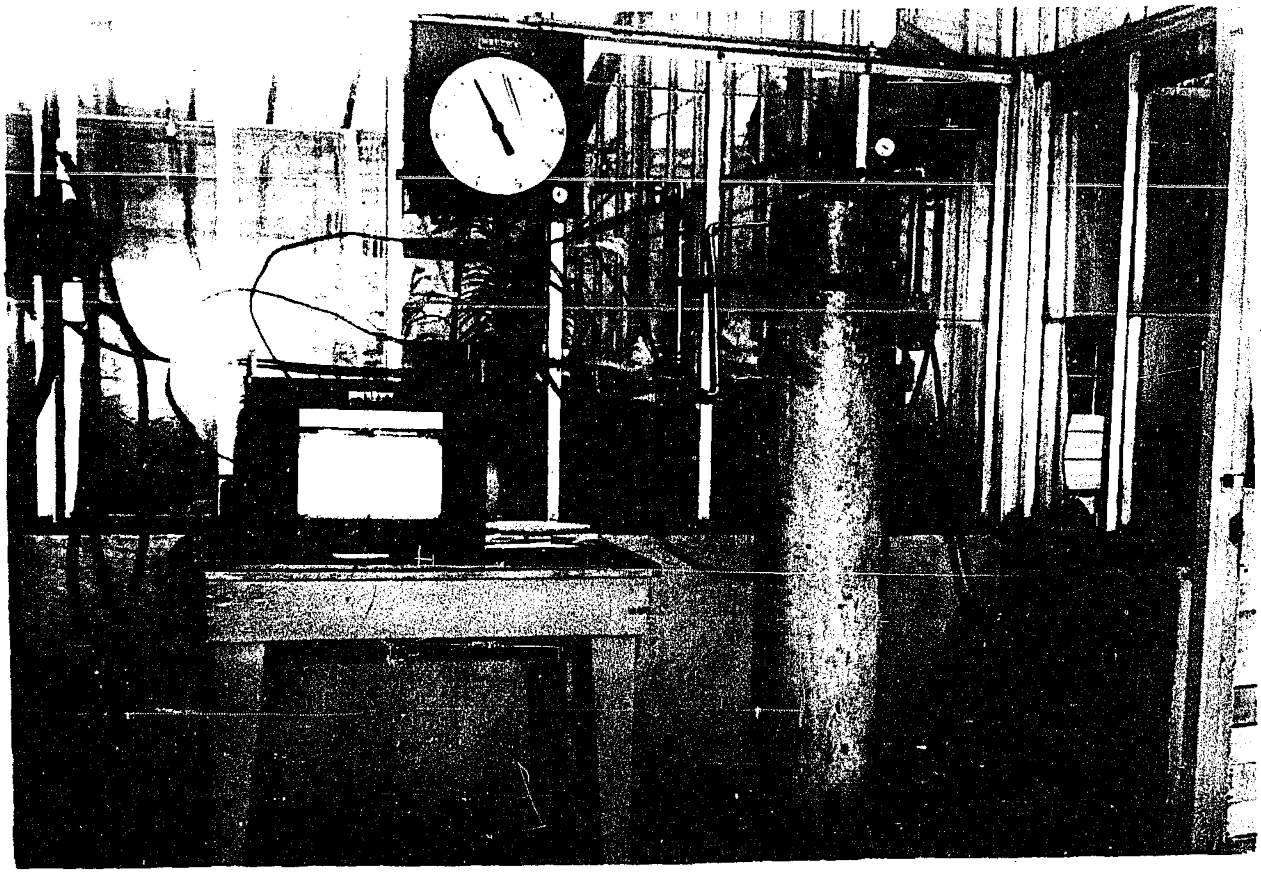

Figure 28. Recording and controlling equipment in dry greenhouse adjoining the two greenhouse rooms used for radiation studies in 1948.

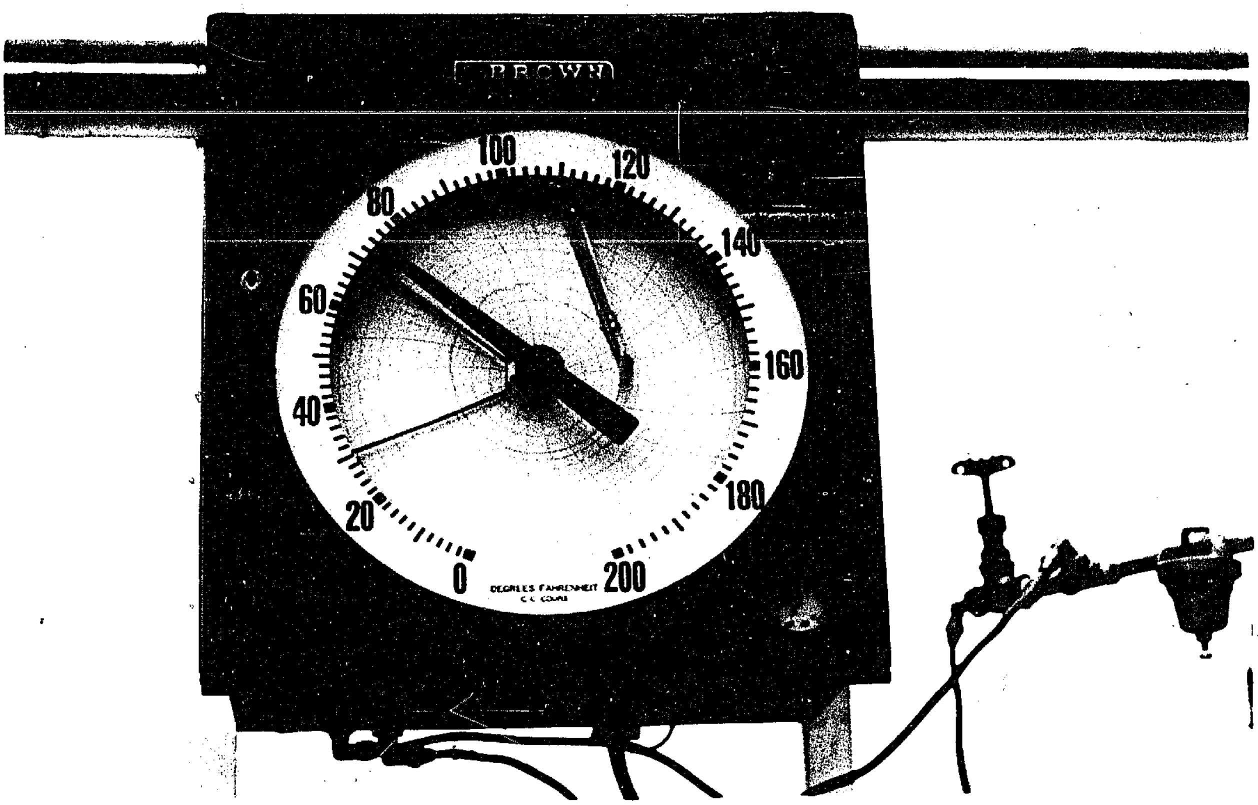

Figure 29. Brown circular-chart potentiometer controller shown mounted in the greenhouse 1948.

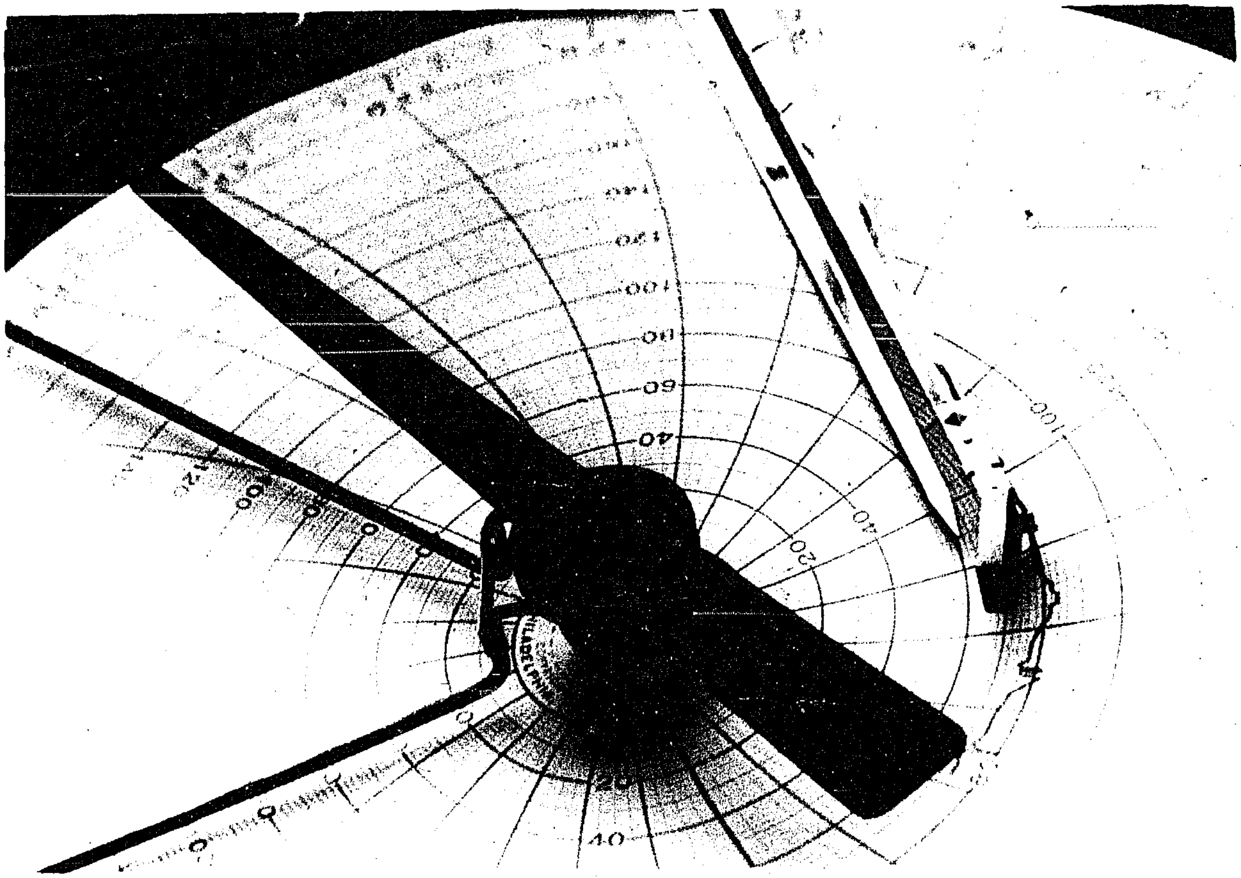

Figure 30. Close-up of circular-chart potentiometer controller showing pointer needle and recording pen.

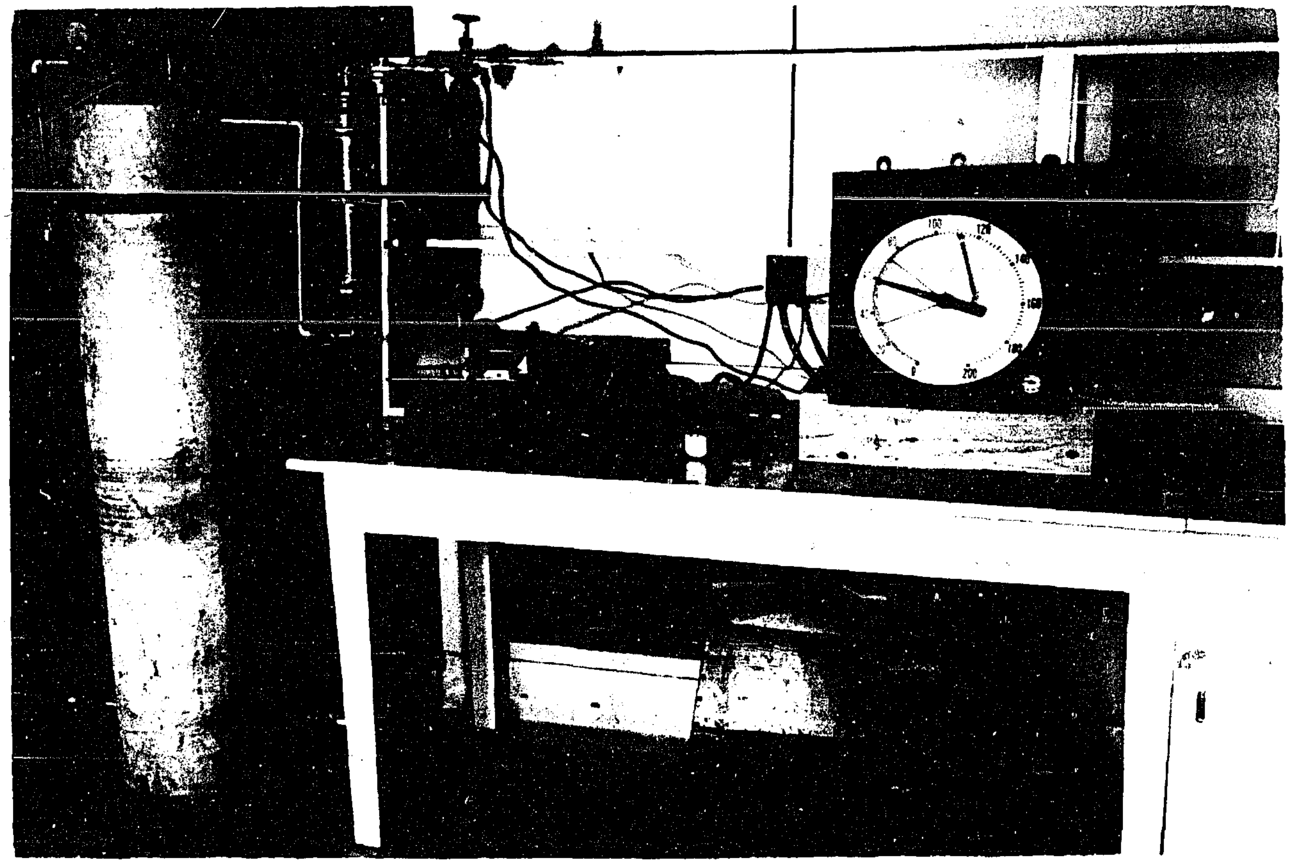

Figure 31. Controlling equipment installed in horticulture laboratory adjoining cold storage rooms used in radiation experiment during 1949 and 1950. Photographed in 1949.

(137) Gaddis of the Minneapolis Honeywell Company, (53) and by members of the agricultural engineering department. Since the only controlling potentiometer that could be acquired was air-operated, it was suggested that the Motortrol Grad-u-motor #M0900C (11) (Figure 32) could be actuated by the potentiometer controller because it was also air-operated. In order to make this instrument regulate the amount of electricity passing to the radiator, the Variac was recommended as being best adapted for the job because it could vary the amount of voltage passing through it. The instrument, Variac V-20, which was acquired for this purpose, was ingeniously connected to the Motortrol by means of a rake and pinon gear (Figure 32, 33).[1] Since no air line of sufficient pressure was available in the green-house or horticultural building to operate these instruments, a tank and compressor were installed together with the valves, pressure reducer, etc. (Figures 34 and 35) necessary to operate the circular-chart potentiometer and the Motortrol.

<u>Convected air temperature</u>

To determine the actual temperature effect of radiation, it was necessary to know precisely the true temperature of the convected air. Consequently, it was necessary to protect the thermocouple from the direct rays of a radiator and, at the

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1. Appreciation is extended to Professor A. W. Farrall, Mr. Clarence Hansen, and Mr. F. J. Hassler, who, in conjunction with other members of the agricultural engineering department of Michigan State College, helped to assemble this radiation control apparatus.

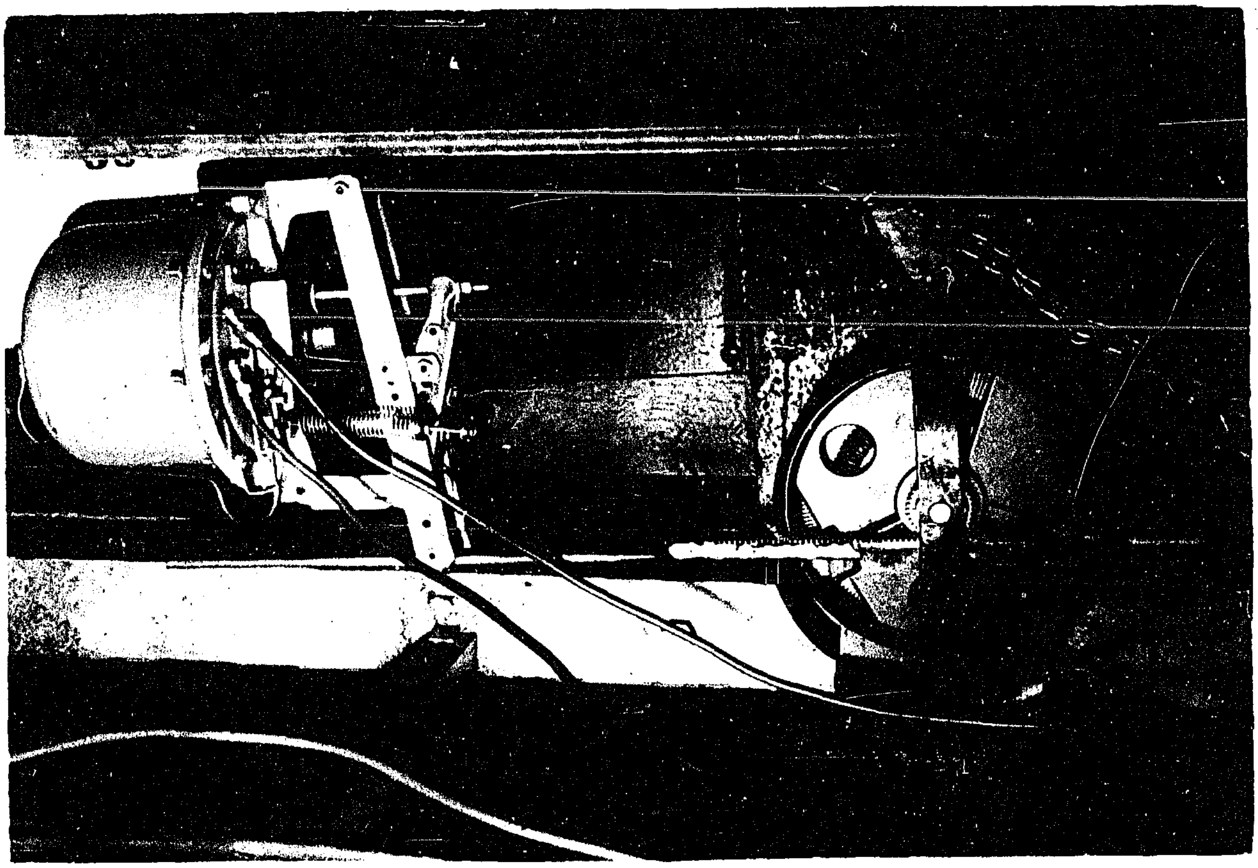

Figure 32. Top view of Variac and Motortrol with rack and pinion gear connections.

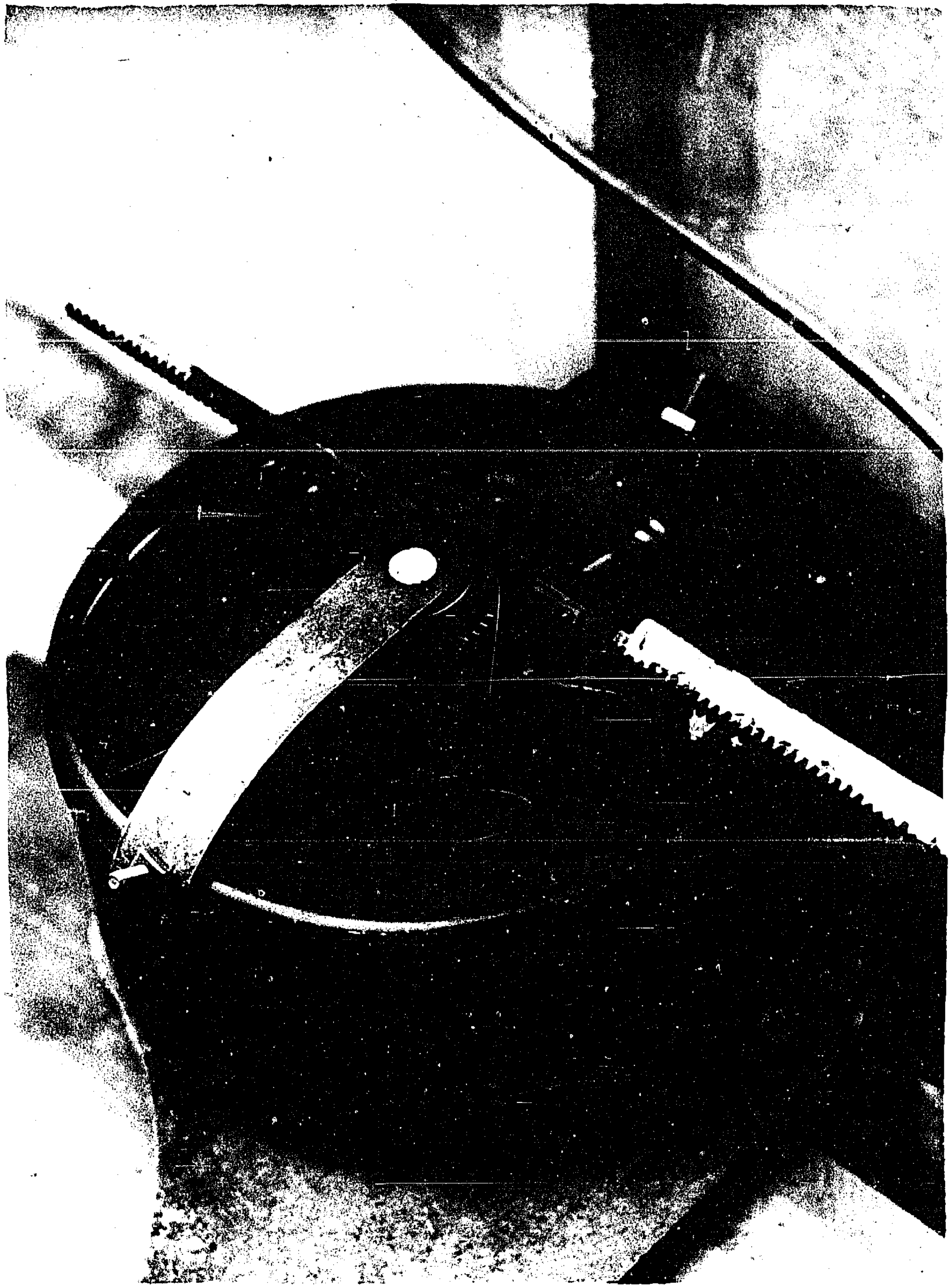

Figure 33. Side view of Variac V-20.

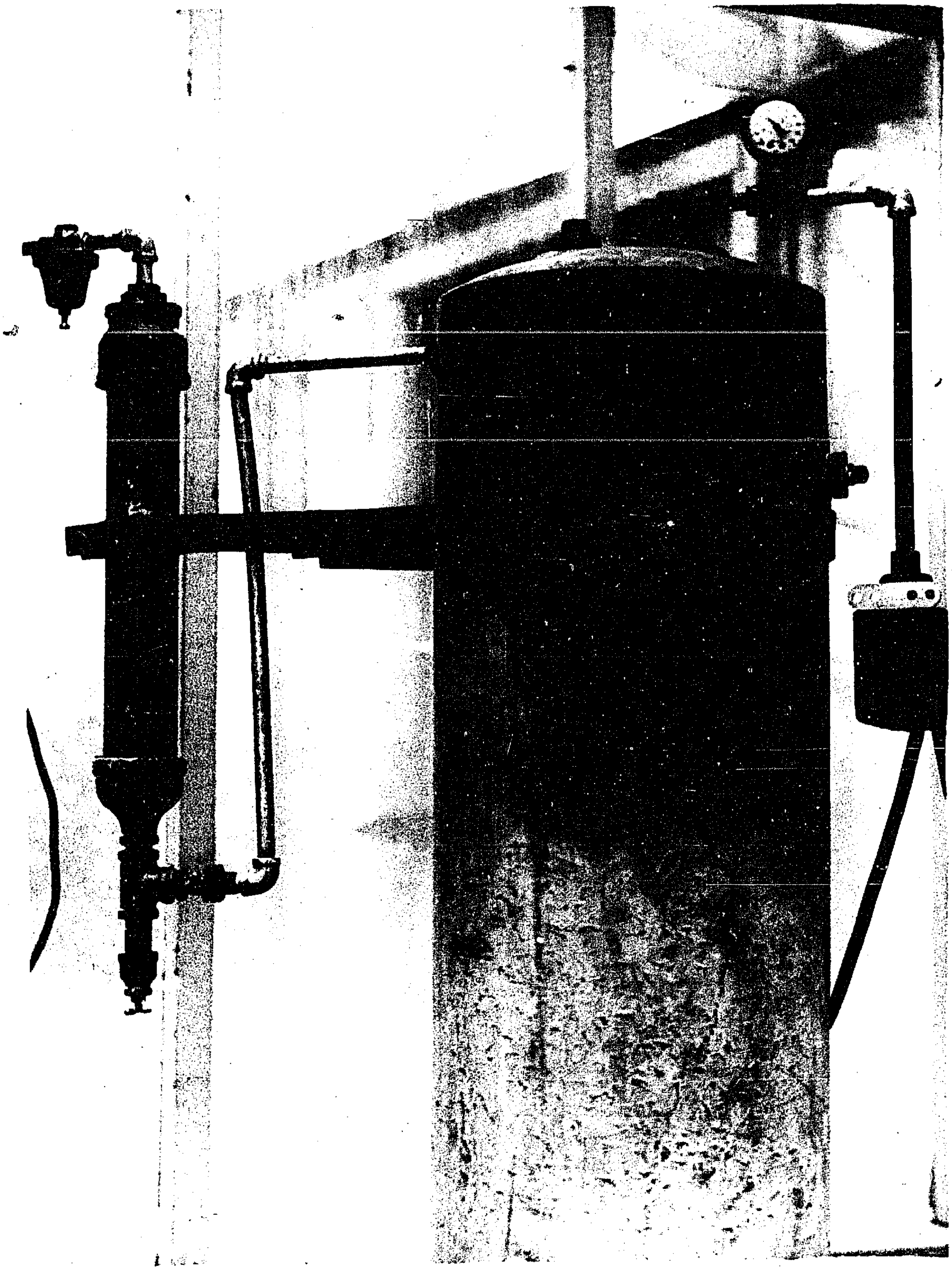

Figure 34. Air pressure tank, gauges, valves, etc. used for pneumatic operation of control equipment.

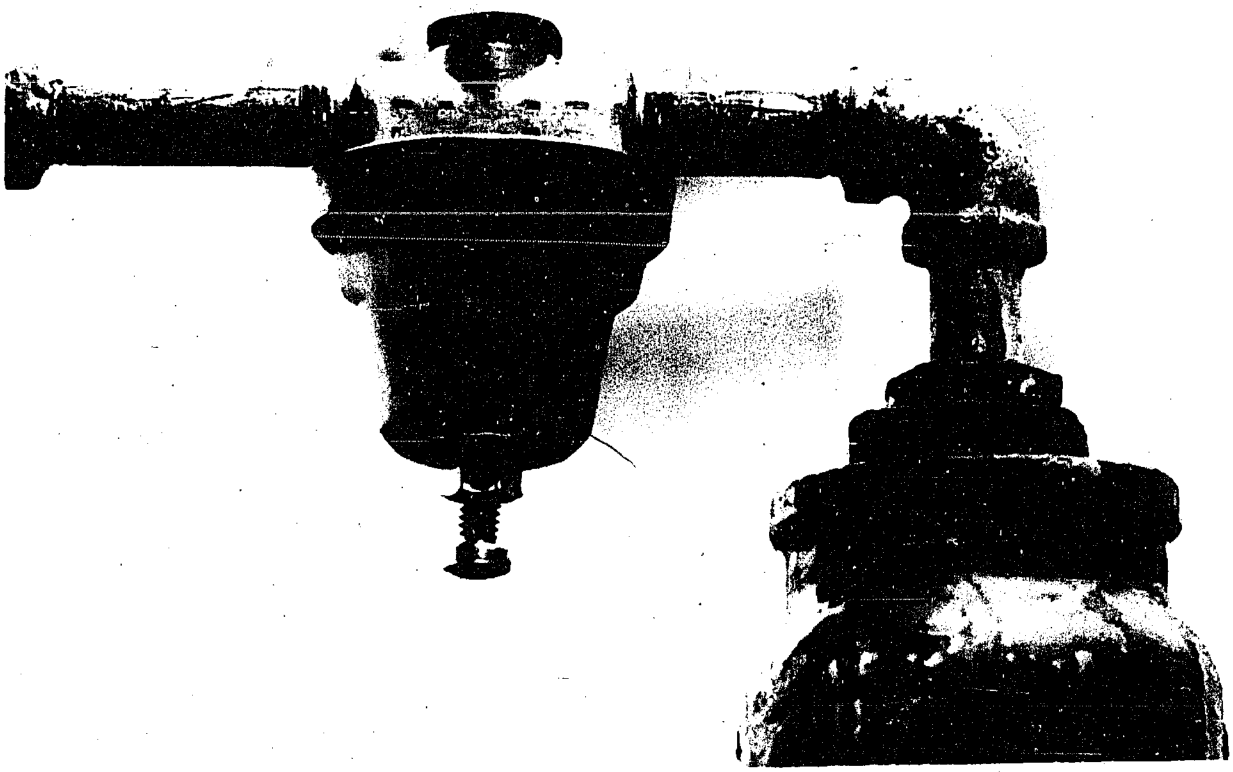

Figure 35. Pressure reducer unit used for lowering pressure to the desired 15 pounds per square inch necessary for pneumatic operation of potentiometer and Motortrol.

same time, to allow a free passage of air over the thermocouple. Several metallic contrivances were built out of sheet aluminum with an anodized surface to achieve this purpose. For the needs of this paper they shall be referred to as "convecter" or "convecters."[1] Since three designs were tried they shall be designated models "A", "B", and "C" (Figures 36, 37, 38 and 39).

Soil temperature

The mercury thermometer was used in a few cases to check the temperature of the soil (Figure 40) and air. It was far less responsive to temperature changes and was used mostly for comparison. The advantage of this measuring device was the ease by which readings could be frequently checked.

Soil temperatures were usually measured in the center of one of the pots used in the experiments. In some cases, as during the 1949 experiments, an extra pot in which the original plant had been cut off was used for this purpose. This method eliminated the danger of injuring the roots of the growing plants, especially when the mercury thermometer was used.

In the greenhouse experiments, which were carried out in the hand-made radiation and control houses (Figures 8, 41, 44) no soil heat was applied. In this case the central position

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1. The word "convecter" is used in this thesis merely for the purpose of convenience, indicating the three designs used for measuring convected air temperatures that were used in these studies. No effort is made to coin a new word. The word convector, which is listed by Webster, means an agency of convection and has a different meaning.

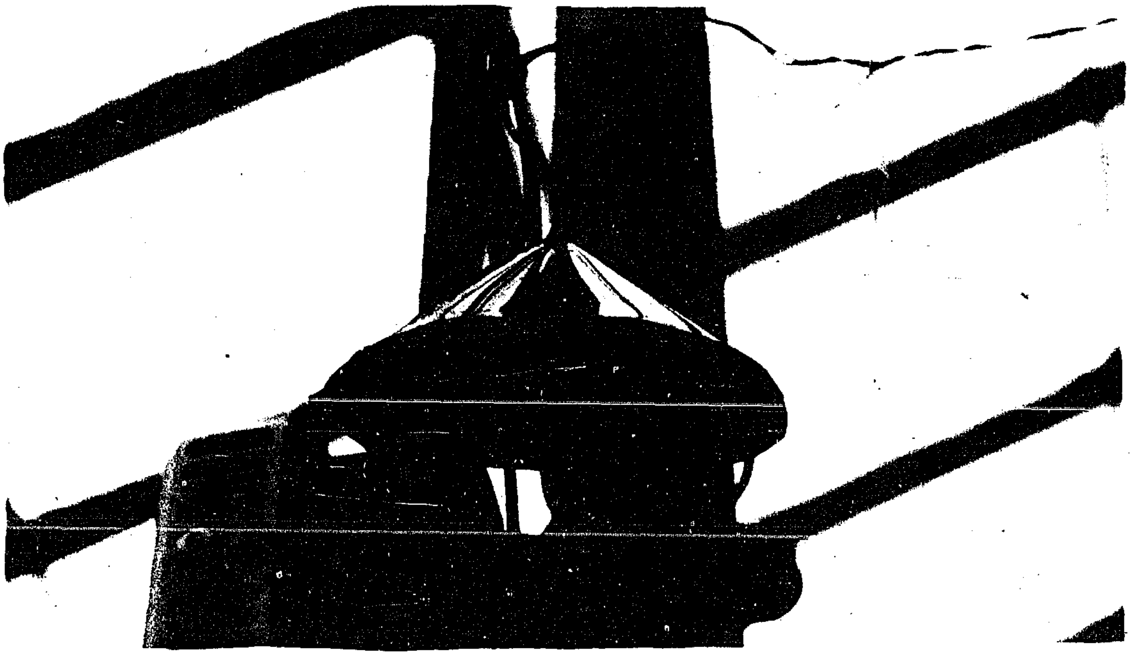


Figure 36. Lower view of model A convecter in the radiation room of the greenhouse.

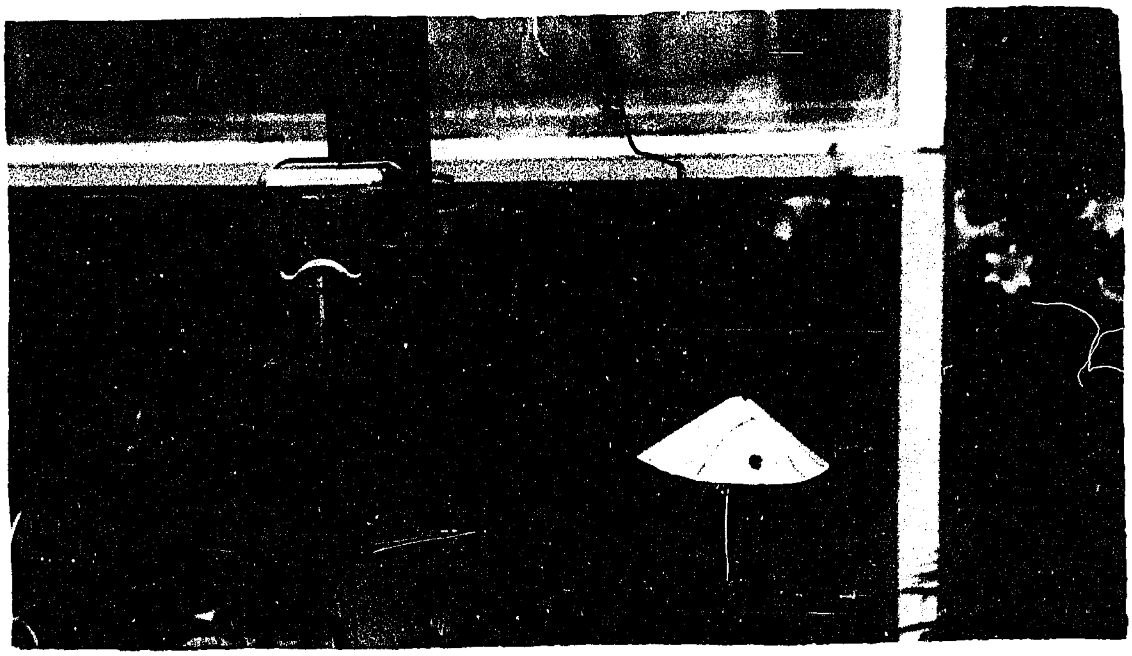


Figure 37. Upper view of model A convecter mounted near thermostat.

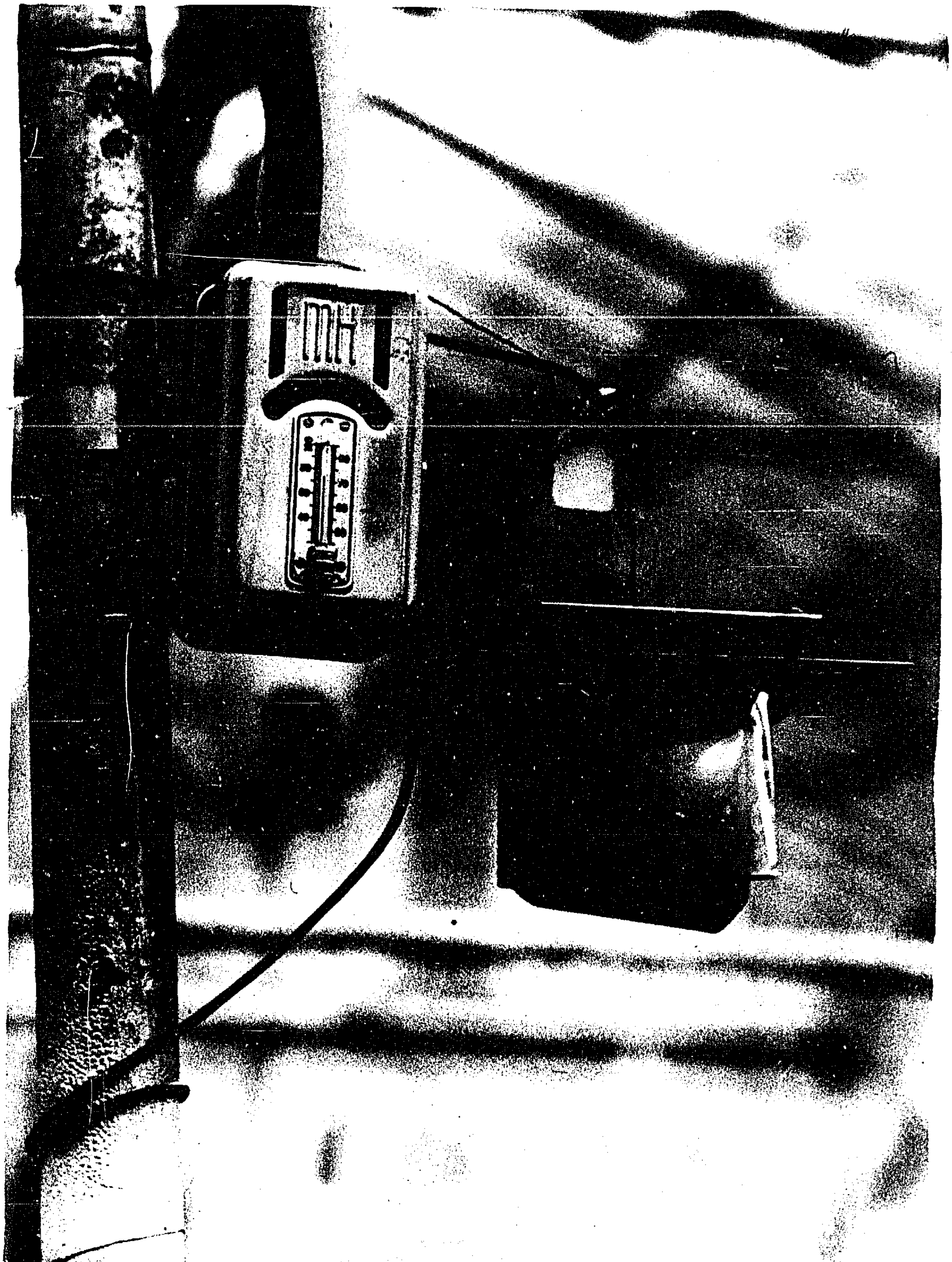


Figure 38. Model B convecter shown mounted in the greenhouse control room near the thermostat.

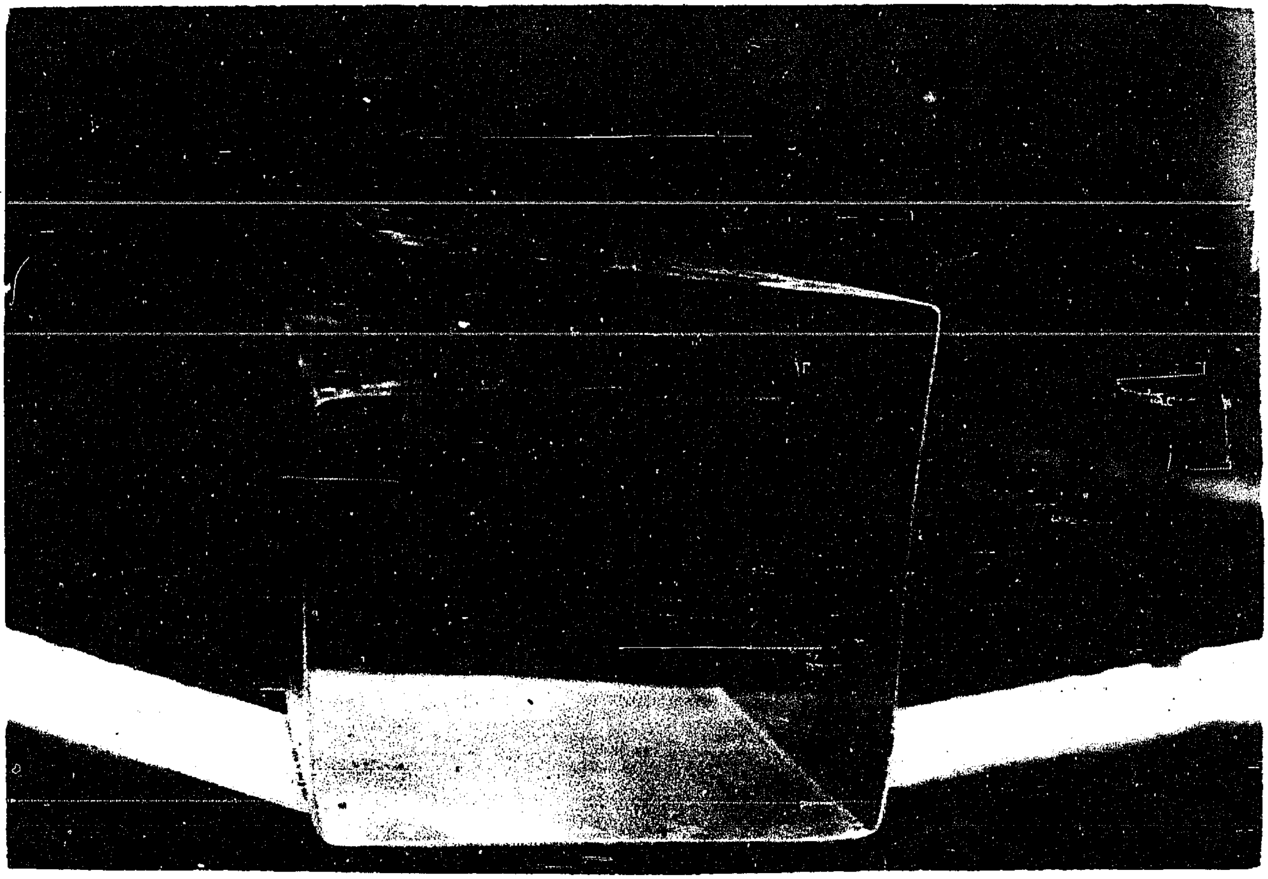


Figure 39. Model C convecter which was used for measurements of convected air temperature in the radiation and control house. (It was also used above the greenhouse for determining the outdoor temperature.)

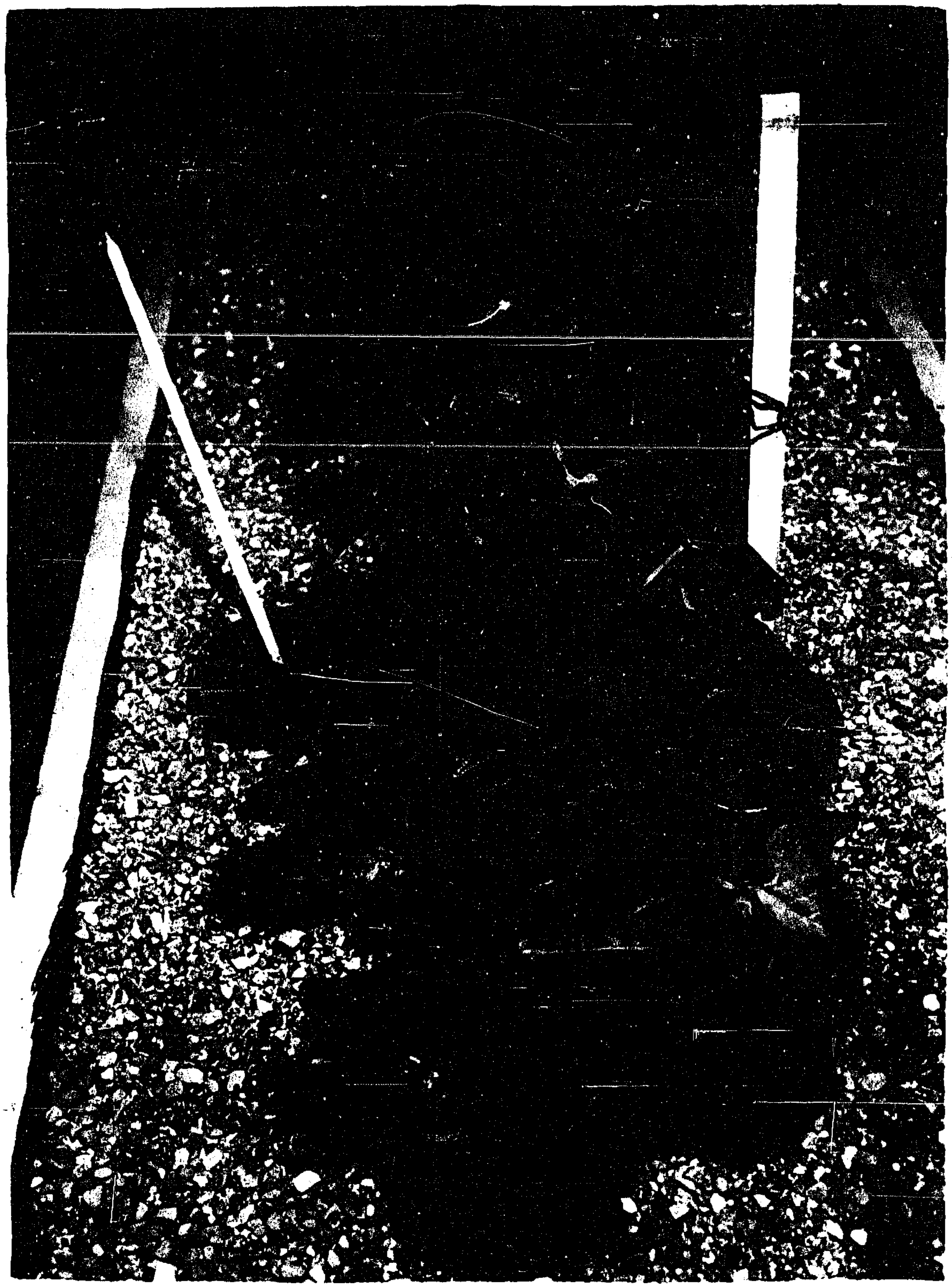


Figure 40. Double row spacing of pots containing Red Kidney beans used in 1949. (Note horizontal placement of leaves on sixth day after they were placed in radiation room. The thermometer in the extra pot was used for measurement of soil temperature.)

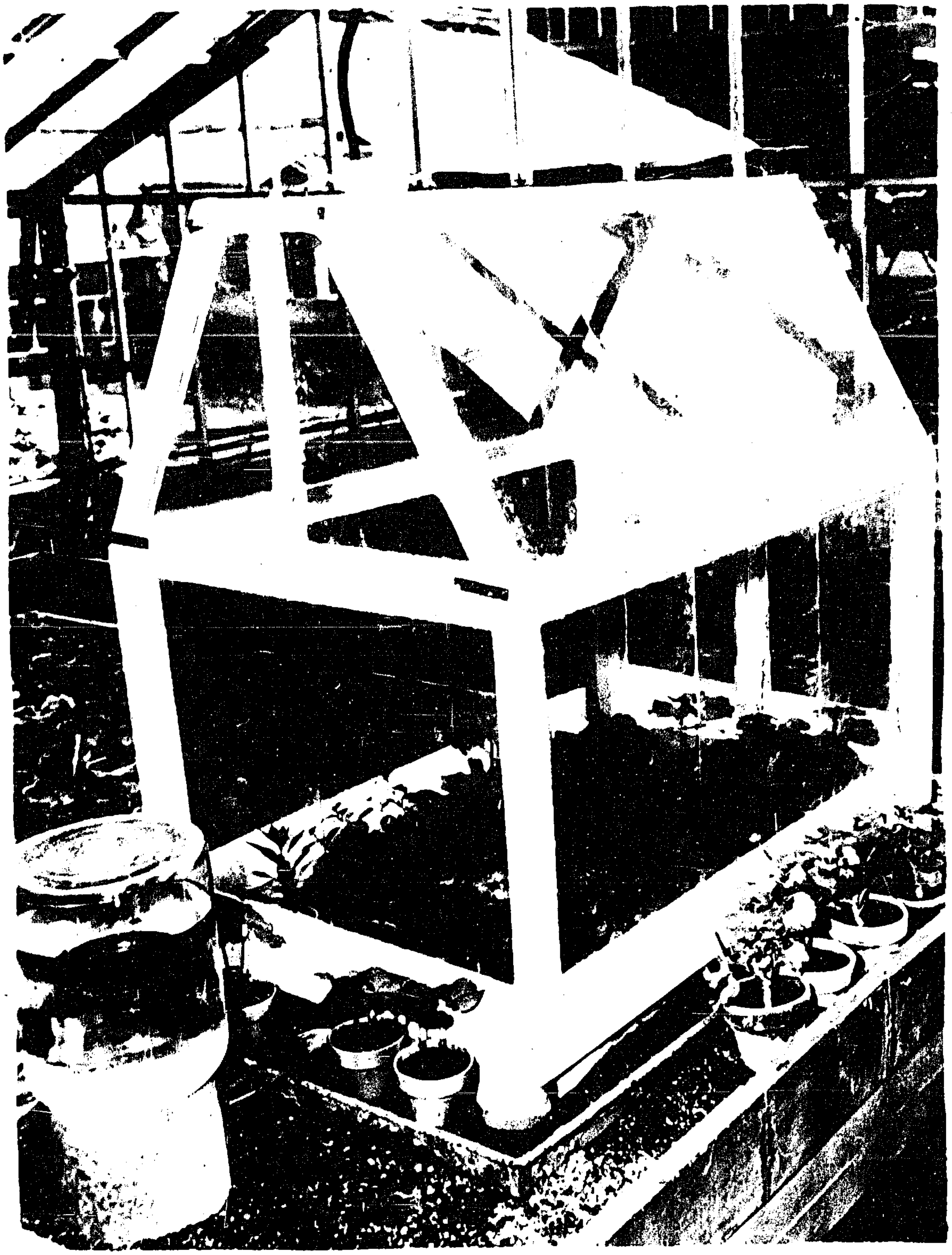


Figure 41. Radiation house used in the greenhouse during 1948.

of the four-inch pot--used at that time for the bean plants--was selected as the position for measuring the soil temperature. This position was chosen because of the temperature pattern, which was progressively colder toward the bottom of the pot and warmer toward the top where the soil surface absorbed some of the radiant energy from the radiator.

As will be mentioned subsequently, the original plan of the experiments was changed so that the soil was heated by a soil heating cable 60 feet long. In this case the temperature pattern was the reverse of the former pattern in the radiation room, with a higher soil temperature toward the bottom of the pot than at the top. This was due to the effect of the heating coil which was placed near the bottom of the tank and to the cooling effect of the 40° F. air of the room. The heating of the soil by the radiator on the soil surface was small. As in the other temperature pattern, the center of the pot was considered the most logical position to represent the average soil conditions existing around the root system. Most of these readings were made with a thermocouple.

The soil thermostat (Figure 43) was regulated by a heat sensitive bulb connected to 18 inches of flexible tubing, which was inserted in the sand and the gravel, where the greatest temperature fluctuations occurred. The setting on the soil thermostat was regulated by checking it with a 60° F. reading on the thermocouple placed in the center of one of the pots used in the experiments. The above technique was necessary in

Figure 43. Soil thermostat with electrical connections used for the soil-heating cable.

order to make the soil temperature the same in the radiation room as it was in the control room.

Thermostats

Thermostats were used throughout these experiments to control the air temperature of the rooms in which the experiments were conducted. In the greenhouse a new type of greenhouse-designed thermostat (Gaddis, 53) was installed in each of the two rooms used (Figures 37 and 38). They were manually set for a 46° F. night temperature in the radiation room and 60° F. temperature in the control room. During the day the setting was raised 8° higher. The variation in air temperature, as recorded by the sensitive response of the thermocouple suspended in the center of the model B convecter (Figure 38) when attached to the twelve-step recording potentiometer, was 2° F. (Figure 44). Temperature variation of less than one degree has been claimed for this thermostat when installed with suitable heating equipment and according to factory instructions.

The thermostats used in the cold storage rooms, combined with the cooling system installed, made close temperature control almost impossible. Each time the cooling system was set into operation by the thermostat, it brought the temperature down from five to ten degrees. These temperature dips (Figures 55, 56 and 57) were observed in both rooms although they occurred more frequently in the cold radiation room (40° F.) than in the control room (60° F.). In order to ascertain the average temperatures of these rooms it was necessary to record and

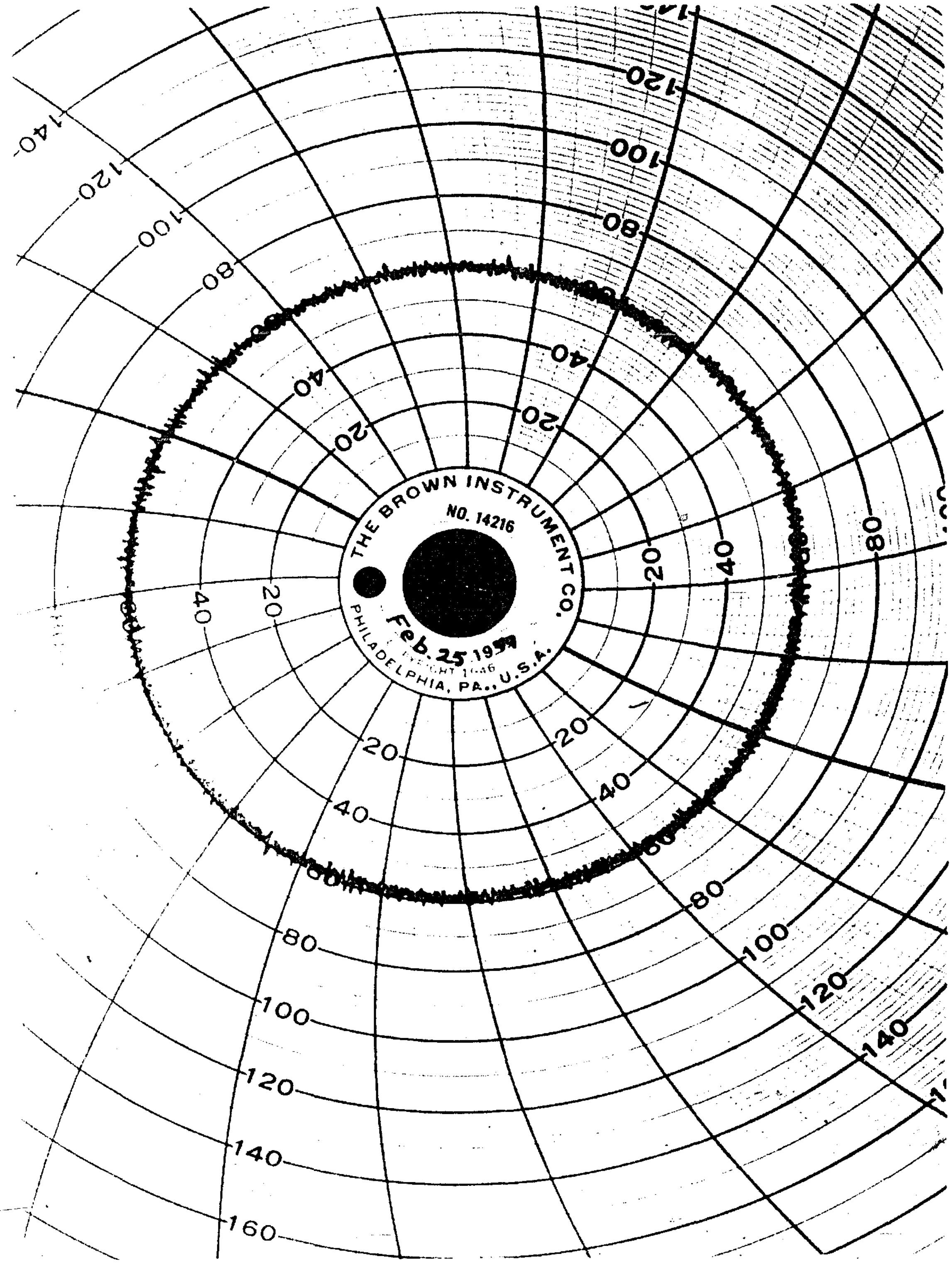


Figure 44. Temperature pattern from the circular chart potentiometer controller showing fluctuations of temperature on the control point (lower surface of a selected leaf in the radiation room).

average numerous readings on the manually operated potentiometer before the mean temperature could be found. In the control room the temperatures were nearly constant except for the cooling periods which occurred about every hour. These readings, made with the aid of thermocouples, showed a much greater variation in temperature than temperatures recorded by a thermograph placed in these same rooms; for the metallic plate on the thermograph was slow to respond to any temperature impulse.

Globe thermometers

Attempts have been made to measure the convected air temperature combined with the heating effect of radiation. An instrument supposed to make this measurement is called the globe thermometer.[1] Several adaptations of the principle upon which the globe thermometer is based have been used for making thermostats sensitive to the combined influence of these two modes of heat transfer (Adlam, 1).

The writer attempted to make a globe thermometer from a globe purchased in a plumbing shop and a mercury thermometer inserted into the center position through a cork collar. Later a thermocouple was used instead of a thermometer. Results by both measuring devices showed that the globe thermometer ab-

1. The globe thermometer was invented by Mr. H. M. Vernon, is six to eight inches in diameter, and is made of copper with a mercury thermometer inserted into it through a collar. It is painted black to simulate a perfect black body (3).

sorbed a tremendous amount of heat when subjected to radiation. When measured for several consecutive days, the twelve-step recorder indicated that the globe thermometer was a very efficient absorber of radiation. The absorption was so great that there was a definite temperature increase soon after dawn. This suggested the idea of mounting a thermostat instead of a thermocouple in the center of a globe. By this means it was hoped that the thermostat would show a nearly equal rise in temperature, one which would be great enough to be used to actuate the change-over in another thermostat from a night to a day temperature control. The usual automatic mechanisms used for actuating this change-over are a time clock or a photronic cell.

To test this theory, a thermostat was privately purchased and mounted inside a globe similar to the one previously used. Unfortunately the wrong designed thermostat was obtained which failed to make a two-way contact. The project was abandoned because it did not relate directly to this experiment. However, the idea should be fully tested to evaluate its true worth.

This theory is based on the following observations. The thermocouple inside the globe thermometer showed a quick response--a rapid rise in temperature--soon after the sun rose. The difference exceeded the average air temperature variation found under thermostatic temperature control. If the thermostat inside the globe should be set from three or four degrees above the night temperature during the night, it would remain in the off position. As soon as the dawn arrived and the sky began to lighten, the temperature would ascend to a point beyond the setting of this globe thermostat. When this happened, the impulse from this thermostat could actuate a relay, which, in turn, would close a switch operating a thermostat with a day-temperature control. If the idea is practical, it would give greenhouse growers an automatic temperature regulator cheaper than a time clock, one that would not have to be reset frequently, and one that might be almost as successful as the more costly photronic cells.

Illumination

Radiation studies were made in two different greenhouse rooms during 1947 and 1948 in which all of the luminous energy came from the sun. In the latter part of this greenhouse study, plants were grown inside of hand-made radiation and control houses (Figures 8, 41, 42) in which the light from the sun was slightly less than in the open room itself. During the next two years, 1949 and 1950, all light was provided by daylight fluorescent light tubes.

The advantages of the sun as a source of light are its higher intensity of radiation and its economy. The advantage of the artificial light source is the better control of the quantity of light (intensity) and of the duration of light (the length of time the light is on and off as regulated by a time clock). Since daylight fluorescent light was reported to

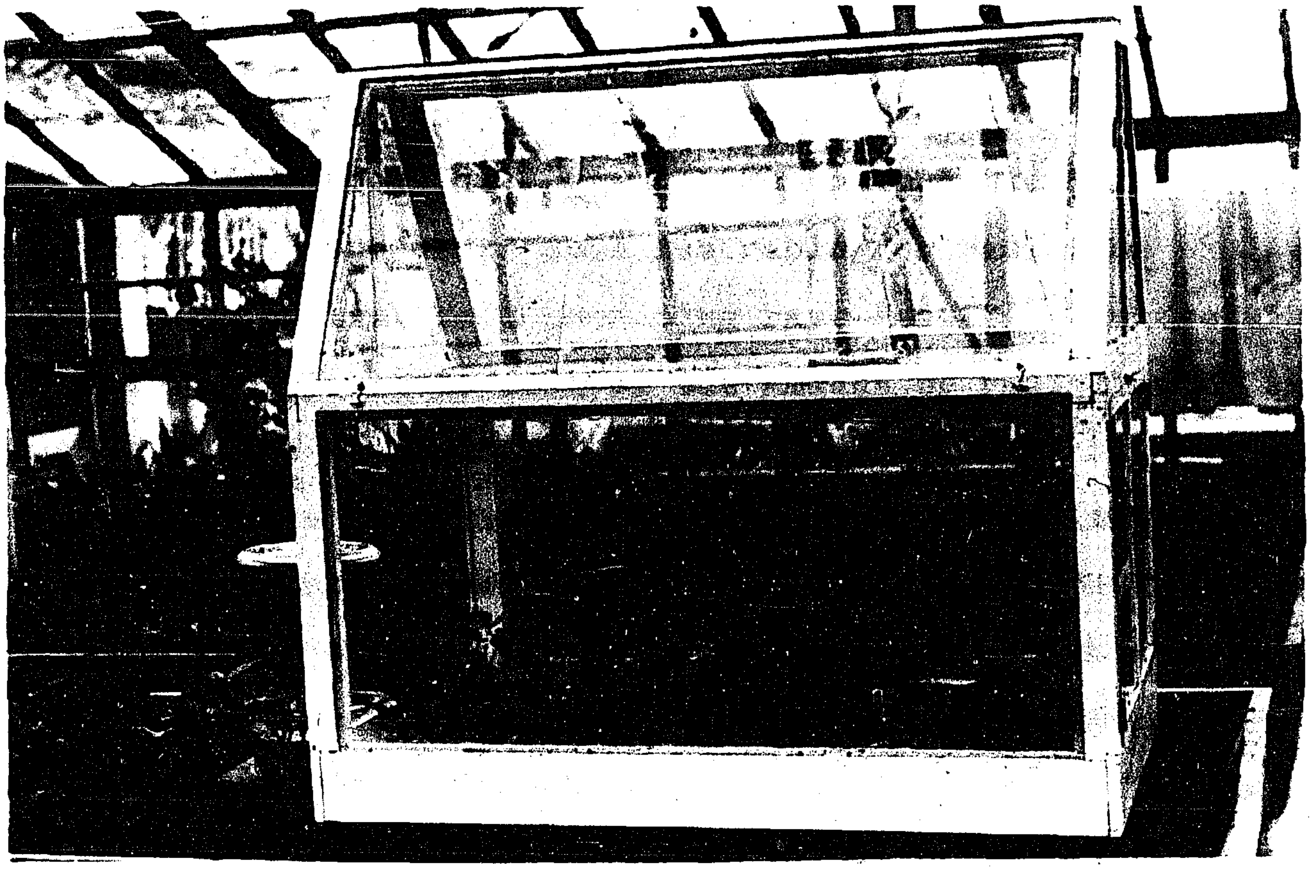


Figure 42. Control house in early morning half hour after sunrise. (Note fogging of glass which reduced the light intensity. No fogging occurred in the radiation house.)

be as good as any other artificial source of illumination for plant growth (Naylor and Gerner, 94; Withrow and Withrow, 149; Hamner, 65), it was used throughout the experiments where an artificial source of light was needed. It emits very little infra-red light and is therefore cooler than most other artificial light sources at a given light intensity. The fluorescent light is considered more desirable for radiation studies since it emits less heat-producing rays itself. Because of this it is possible to control the amount of radiation on the growing plants more accurately.

One of the disadvantages of solar radiation is the excess heating of plants, especially when it interrupts the effects of a radiation study. Sunlight is also unpredictable in nature, especially when an experiment calls for an equal supply of radiation for two different houses placed in two different greenhouses. Figure 56 shows the recorded temperature curve of two leaves on a day that was partly cloudy and partly sunny; the leaves were shaded by some greenhouse obstructions at different times of the day. This graph indicates some of the difficulties encountered when one wishes to standardize the amount of sun light. Another disadvantage associated with sunlight and the wide variation of temperatures encountered in the greenhouse under conditions of high humidity is the fogging of the glass, which reduces the light still more. (Figure 42).

The disadvantages of the fluorescent light are the low light intensity, the higher cost of operation, the breakability of the light bulbs, and the dependence upon electrical current.

The plants which were used in the experiments conducted in the converted cold storage rooms were illuminated with daylight fluorescent light tubes (Figures 15, 17, 19, 45, 46). Although most references indicate that 600 foot-candles or more light should be used for Red Kidney beans, the decision to use only 300 foot-candles was based on the following statements. First, a steady temperature of 60° F. was decided to be a satisfactory temperature range for this experiment, since that was the ordinarily accepted night temperature for Red Kidney beans and since it was impossible to have two different day and night temperature ranges in these cold storage rooms. Growing at 60° F. continuously, the plants would not require so much light as if they were growing at a higher temperature. Second, the length of day was set for eighteen hours instead of for sixteen hours as has been sometimes used for this type of study. The Red Kidney bean is a day-neutral plant and will grow satisfactorily on a longer duration than used here. A most important consideration was that all plots of beans were to receive identical hours and intensities of light. Third, the plants in this experiment were not to be grown to maturity. Fourth, by keeping the light intensity low, it was possible to eliminate the probability of CO_2 concentration as a limiting factor for plant growth. It was possible that there may have been a difference in CO_2 concentration in the two cold storage rooms used in these studies due to the poor circulation of air and the smallness of the room. Fifth, the cost of lamps and the difficulty of designing equipment for this purpose did not warrant any greater expenditure of money.

To increase the luminous energy of each individual fluorescent light tube, Clarence Hansen suggested that each be mounted in an individual aluminum reflector. Since a light intensity of 300 or more foot-candles was desired, a plan was used to distribute the light of the eight fluorescent tubes where they could illuminate the bean plants evenly and be most easily handled. Since the radiator had to fit above the tank containing the experimental plants, only the space on the sides was left for the placement of lights. Therefore half of the tubes were placed on each side, four four-foot fluorescent light tubes being mounted on each panel along with their ballasts and starters (Figures 15, 16, 17, 19, 45, 46). They were swung from a framework and could be adjusted for height and angle.

GENERAL PROCEDURE

The following items are the most significant steps taken in this problem:

1. Testing the characteristics of the rod-shaped cromolox heating element--its distribution of energy and effect at different distances from an object to be heated (i.e. the operation of the inverse square law). (Figures 4, 5).

2. Acquaintance with the radiation meter and the thermopile as a radiometer for measuring the radiant energy intensities (Figure 14).

3. Experiments with the injection type of thermocouple.

4. Collaboration with Hassler and Gibson regarding methods of temperature measurement and operation of equipment.

5. Consultation with Gaddis of Minneapolis-Honeywell Company regarding the possibility of using its equipment for the control of radiant energy from a thermocouple mounted on a leaf (Gaddis, 53).

6. Experiment with various types of thermocouple attachments to the outside of a plant leaf. (Figures 21, 22, 23).

7. Installation and testing of cromolox unit in the greenhouse. This unit was mounted over a 7 x 11 foot tiled bed in a 17 x 21 foot greenhouse.

8. Purchase of one hundred Creole lily bulbs. They were planted and stored in a cool cellar until time of sprouting. They were then divided into two equal sections--fifty to a group--half to be used as control and half to be used for radiation studies.

9. Measuring the height of the growing point of twelve plants from each group of lilies at weekly intervals and counting the number of quarts of water used by each lot of plants. The absorption of water showed a difference of two to one with the greater water loss under the radiation unit.

10. Making the experimental design of a three-inch elliptical reflector and measuring its distribution pattern (Figure 4).

11. Testing methods of measuring convected air temperatures, which resulted in the designing of three experimental temperature measuring units, Models A, B and C, called "convecters" in this thesis.

12. Testing of globe thermometer and some of its adaptations.

13. Planning for and purchasing all control equipment used throughout the experiment.

14. Installation and testing of control equipment which was placed in an adjoining dry room (Figures 27, 30, 32, 33, 34, 35).

15. Accumulation of useful data by means of the twelve step recorder (Figure 27).

16. Designing parabolic reflector with the help of Hassler. This design was found to be suitable for not more than two rows of plants.

17. Construction of two houses for radiation study, one of which was to be used as a radiation house and the other as a control house (Figures 8, 41, 42, 47, 48, 49, 50, 51). They were designed for equal ventilation at their tops (Figures 48 and 49), reduced ventilation at their bases (Figure 51), and were mounted to face the same direction in the two adjoining greenhouse rooms.

18. Installation of automatic watering in both houses (Fig.

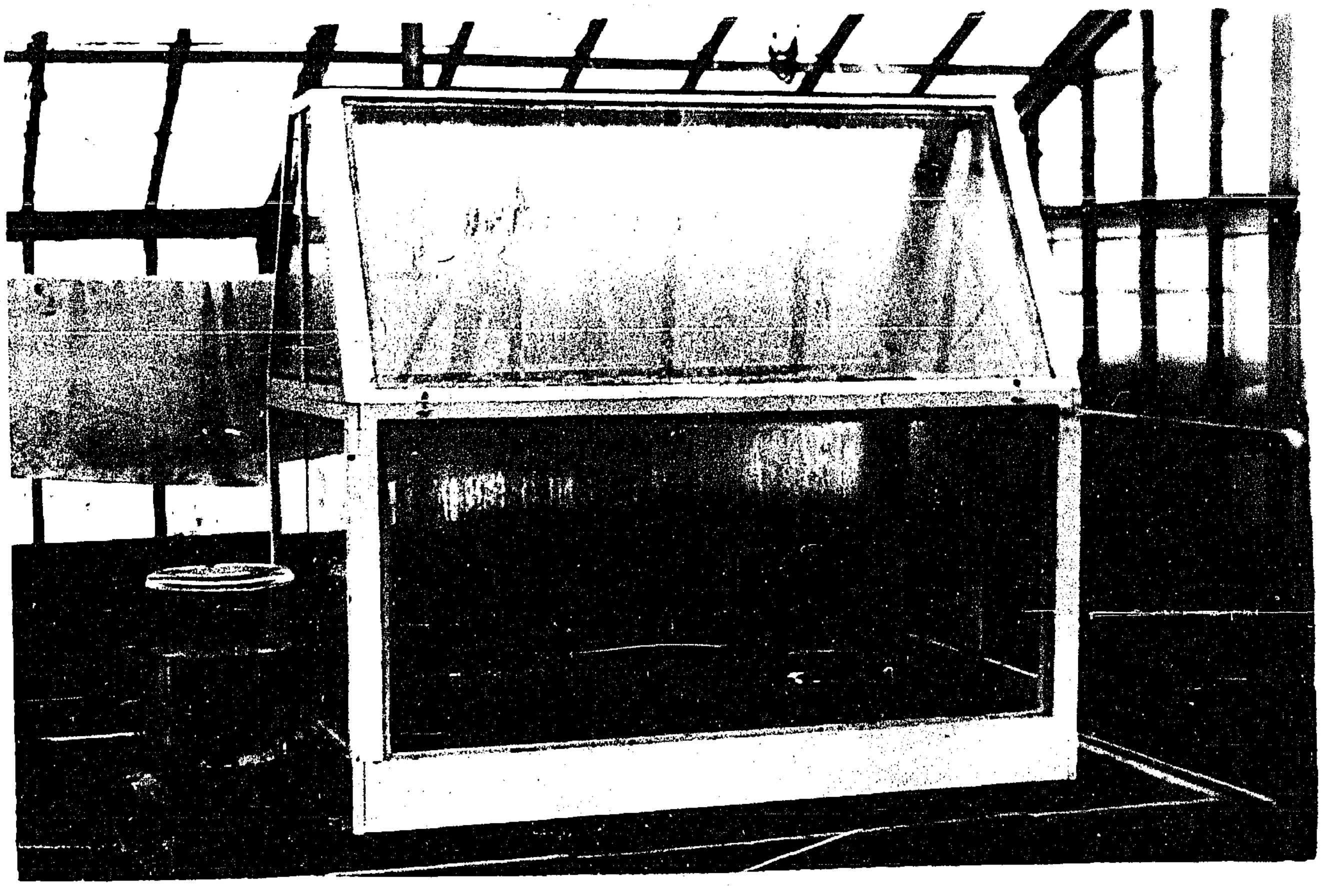


Figure 47. Control house mounted in control room 1948.

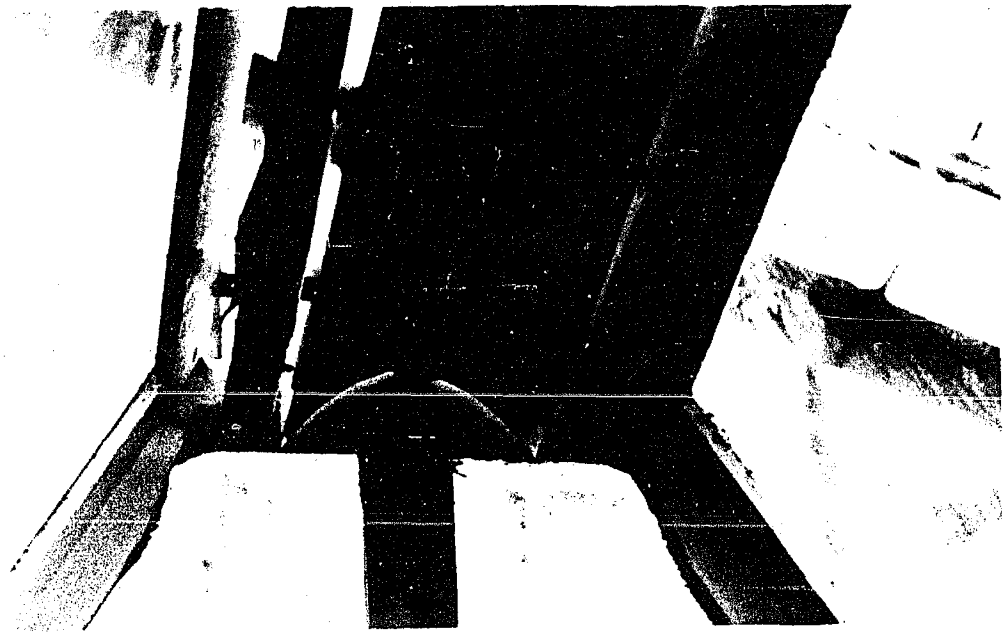


Figure 48. Lower view of parabolic reflecter mounted in top of radiation house.

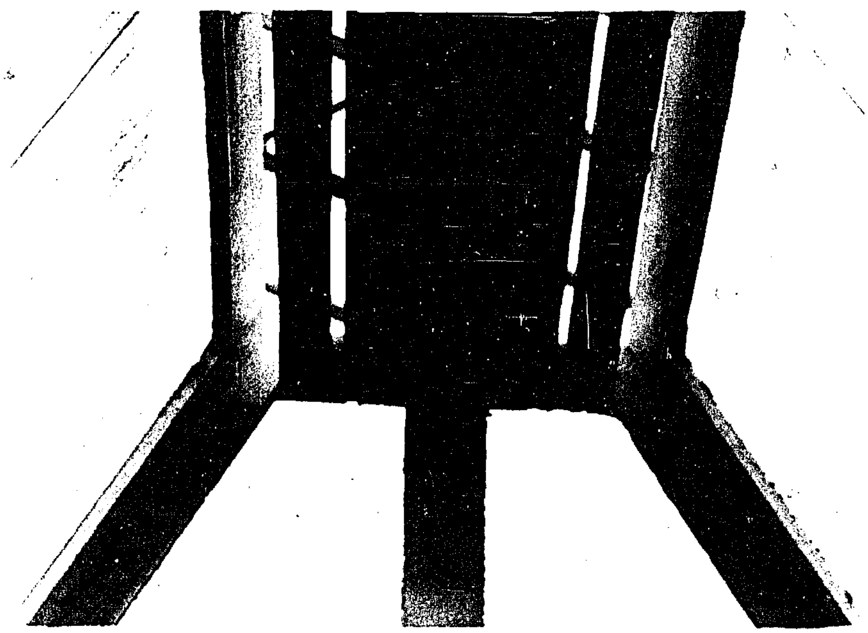


Figure 49. Lower view of top of control house showing board placed to permit the same amount of ventilation.

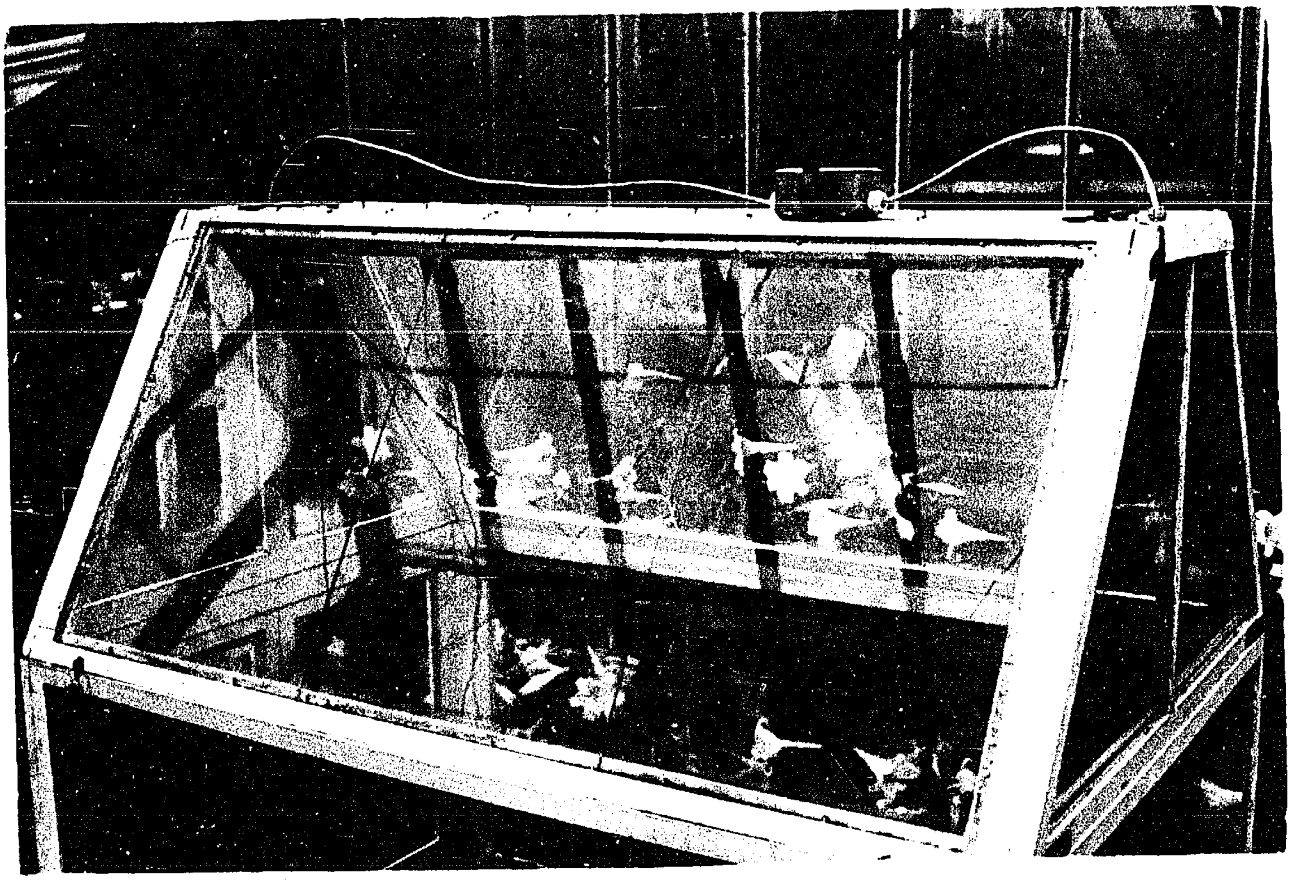


Figure 50. Side view of upper half of radiation house showing the wiring of the radiator. Note also the thermocouple wires coming into house.

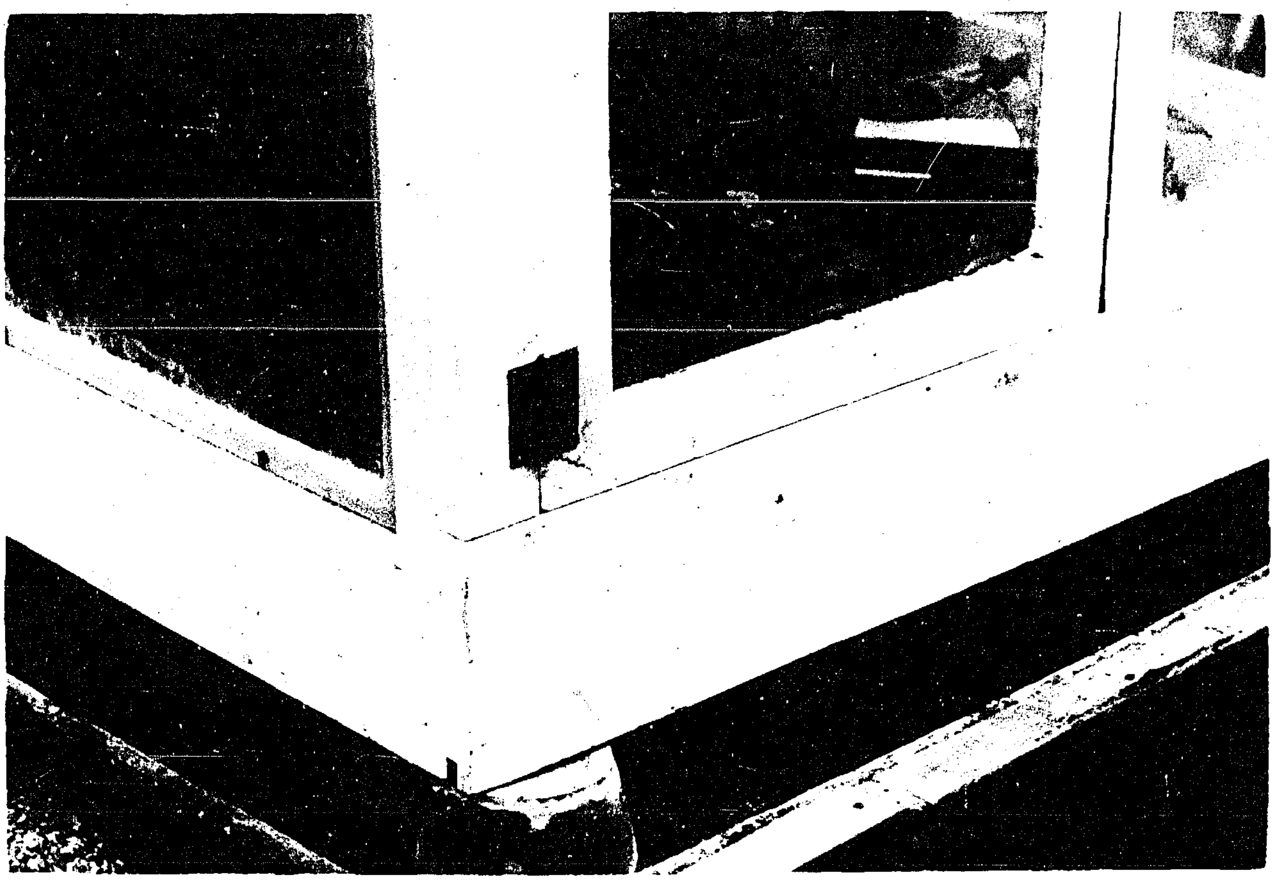


Figure 51. Front corner of control house showing how the desired amount of ventilation was obtained.

19. Installing and adjusting thermostats in two greenhouse rooms to operate at 60° F. (control room) and 46° F. (radiation room) night temperatures with a rise of 8° F. for the day temperatures (Figures 37, 38).

20. Planting of certified seeds of Red Kidney beans (Phaseolus vulgaris), four seeds to each four-inch pot. These pots were placed in the main greenhouse and watered from a sprinkling can.

21. Leaving the two most uniform plants in each pot when the seedlings arrived at the proper age for selection. Ten of these pots were placed in a single row in the radiation house and a like number in the control house.

22. Using miscellaneous greenhouse potted plants on each side of the bean plants as a filler to observe how they would respond to different temperature influences (Figure 63).

23. Setting the pointer needle on controller for operation at 60° F. plant temperature (Figures 29, 30).

24. Plotting of temperature curves on graph paper from data accumulated on the twelve-step recording potentiometer. Examples are shown in thesis (Figures 52 - 57).

25. Analysis of all individual bean plants: measuring height of plant; weighing individual green leaves and stems and calculating the ratio of both weights to each other; estimating the leaf areas in square inches with the use of graph paper; analyzing for ascorbic acid in the horticulture laboratory (Lucus, 83).

Figure 63. Potted plants used in radiation house in 1948. Red Kidney beans, geraniums, fuchsias, iresines, coleus and a tomato are represented.

26. Moving of equipment to cold storage rooms in the horticultural building to better control all environmental factors, with controlling equipment mounted in dry laboratory room adjoining storage rooms (Figure 31).

27. Purchase of electrical lead-heating cable to control soil temperature.

28. Designing and use of fluorescent lamps for illumination of experimental plants.

29. Construction of framework to hold the radiator and panels of fluorescent lamps (Figures 15, 17, 45).

30. Construction of a galvanized tin tank four and one half feet long, eighteen inches wide, and six inches deep, later coated with asphalt inside to prevent any zinc toxicity to the plants (Figures 15, 17, 45, 64, 65).

31. Installation and setting of time clock to regulate the illumination for an eighteen-hour day.

32. Planting of certified seeds of Red Kidney beans, one seed to each three-inch pot. This was the system used for all subsequent plantings.

33. Filling the tanks with a one-inch layer of gravel, laying lead-heating cables above this layer and filling the tank to within one inch of the top with sand.

34. Installation of automatic watering in both units (Figures 15, 19, 45).

35. Wiring of electrical cromolox heating unit in the elliptical reflector to the automatic controller set at 60° F.

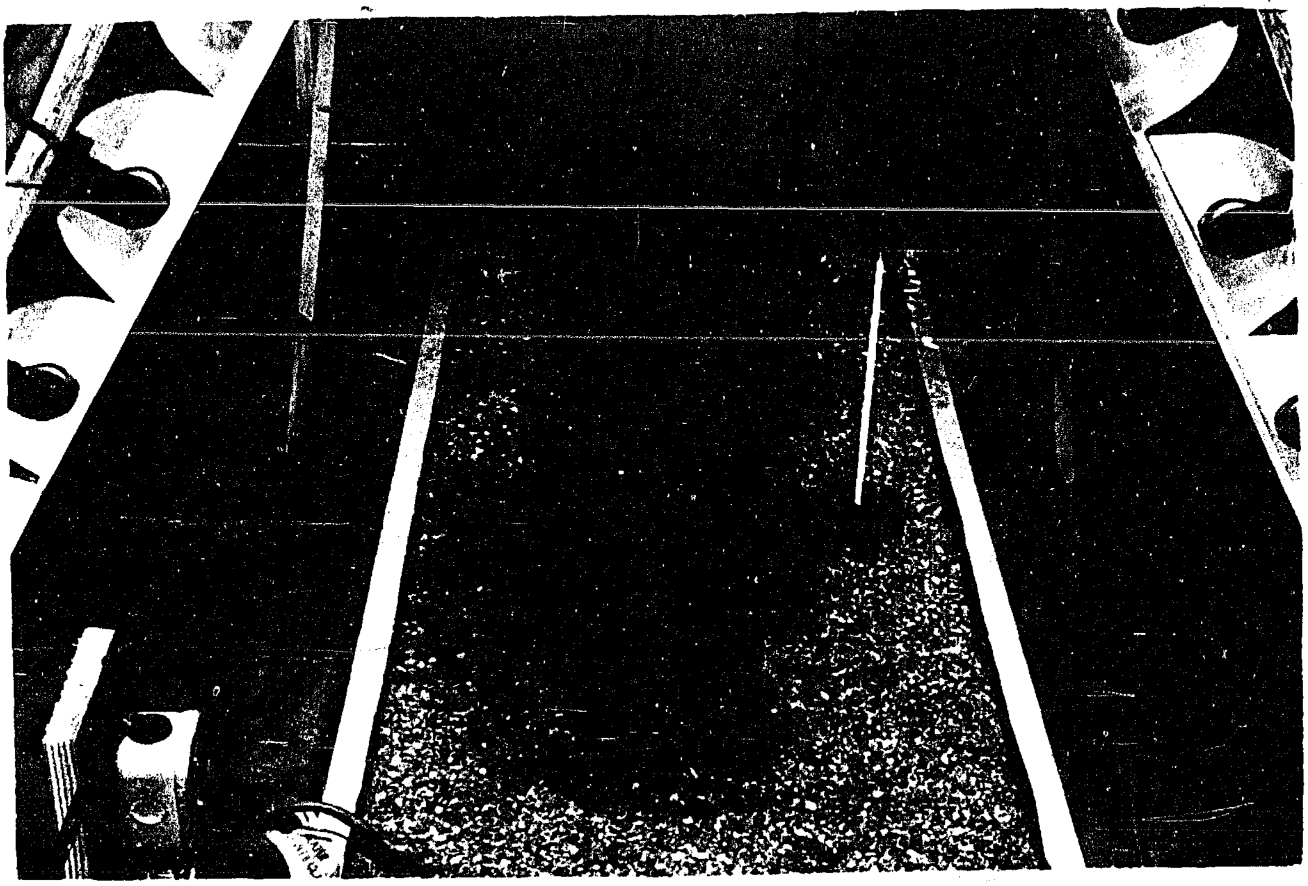


Figure 64. Top view of Red Kidney bean plants in control room. (Note use of thermometer in an extra pot to measure soil temperature and angle of the panels of light to give an even distribution of light).

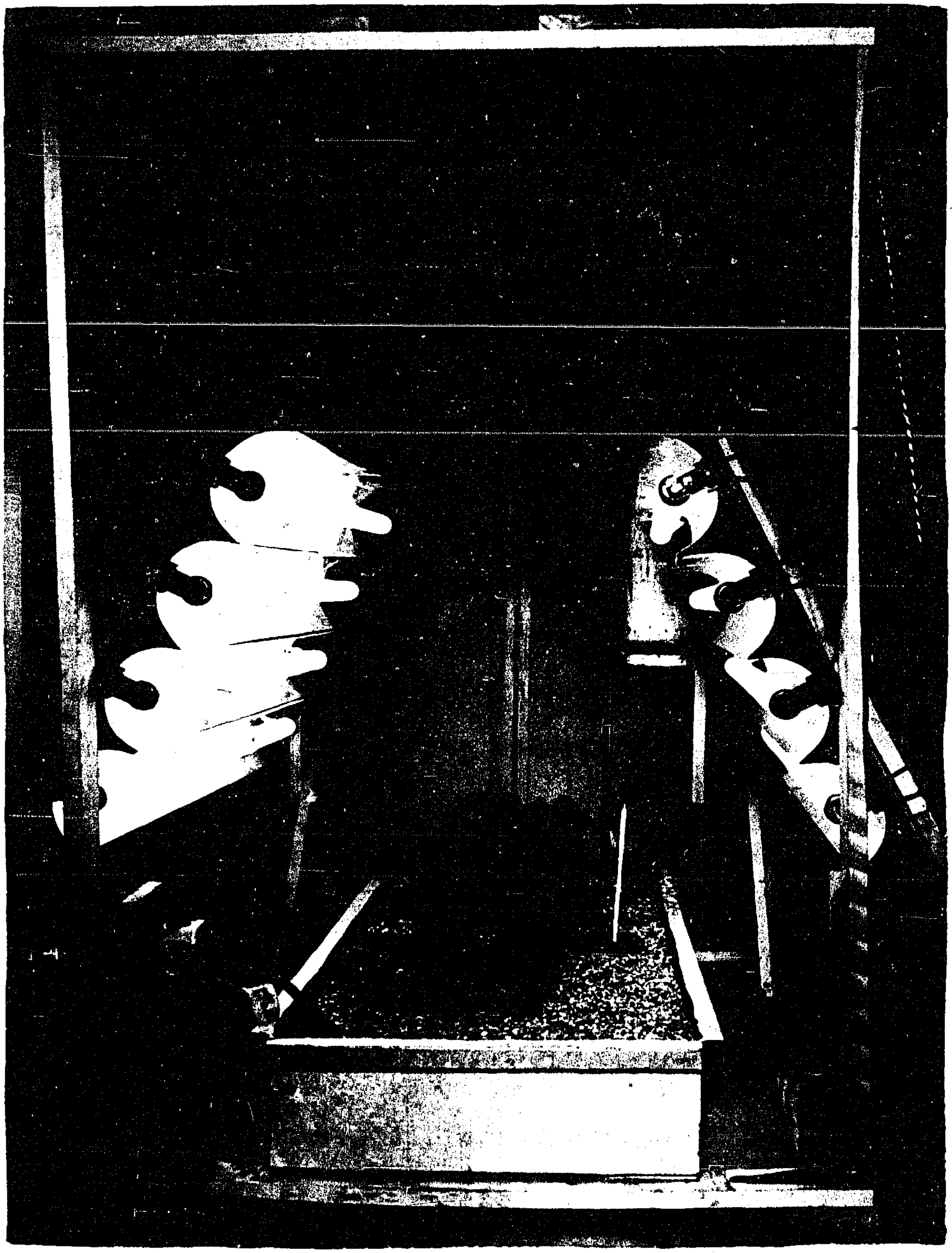


Figure 65. Complete assembly of frame, lights and tank with Red Kidney beans as they appeared the sixth day after setting in this control room (converted cold storage room). This room was set for operation at 60° F. room temperature. 1949.

This controller moved a variac which determined the voltage going to the radiator.

36. Adjusting room temperature in radiation room to 40° F. and in control room to 60° F.

37. Adjusting soil thermostat to lead heating cable to operate at 60° F. average soil temperature (Figure 43).

38. Selecting bean seedlings at the right stage of growth. From this selected group twenty pots were chosen at random for each of the two experimental rooms. These were brought into the converted cold storage rooms and arranged in two rows of ten pots each. They were pressed into the sand, watered, and a thermocouple attached to a control leaf (See Figures 64 and 65 for arrangement in control room). An extra pot was used in some cases for soil temperature measurement.

39. Wiring ten thermocouples to selector switch and extending them into the radiation and control rooms for temperature measurements (Figure 26).

40. Changing of charts daily on the controlling potentiometer.

41. Growing three different groups of Red Kidney beans for approximately four weeks each in the cold storage room during 1949. The second of these groups was divided into two sections.

42. Measuring individual plants for height in centimeters at each internode. The average of these measurements

was used for comparison (Figure 59).

43. Weighing plants when fresh and later when dried.

44. Analysis for percent of ash content in each group based on dry weight (Figure 61).

45. Analysis for percent of total nitrogen in each group based on dry weight (Figure 60).

46. Growing another group in 1950, using four rows with forty pots (Figure 17).

47. Control of temperature in the radiation room during the 1950 experiments by the raising and lowering of the parabolic-shaped reflector.

48. Analysis for chlorophyll made on a green-weight basis from plants of each group. Analysis of both groups was compared on a dry-weight basis (Figure 62).

49. Analysis for vitamin C in the horticultural research laboratory.

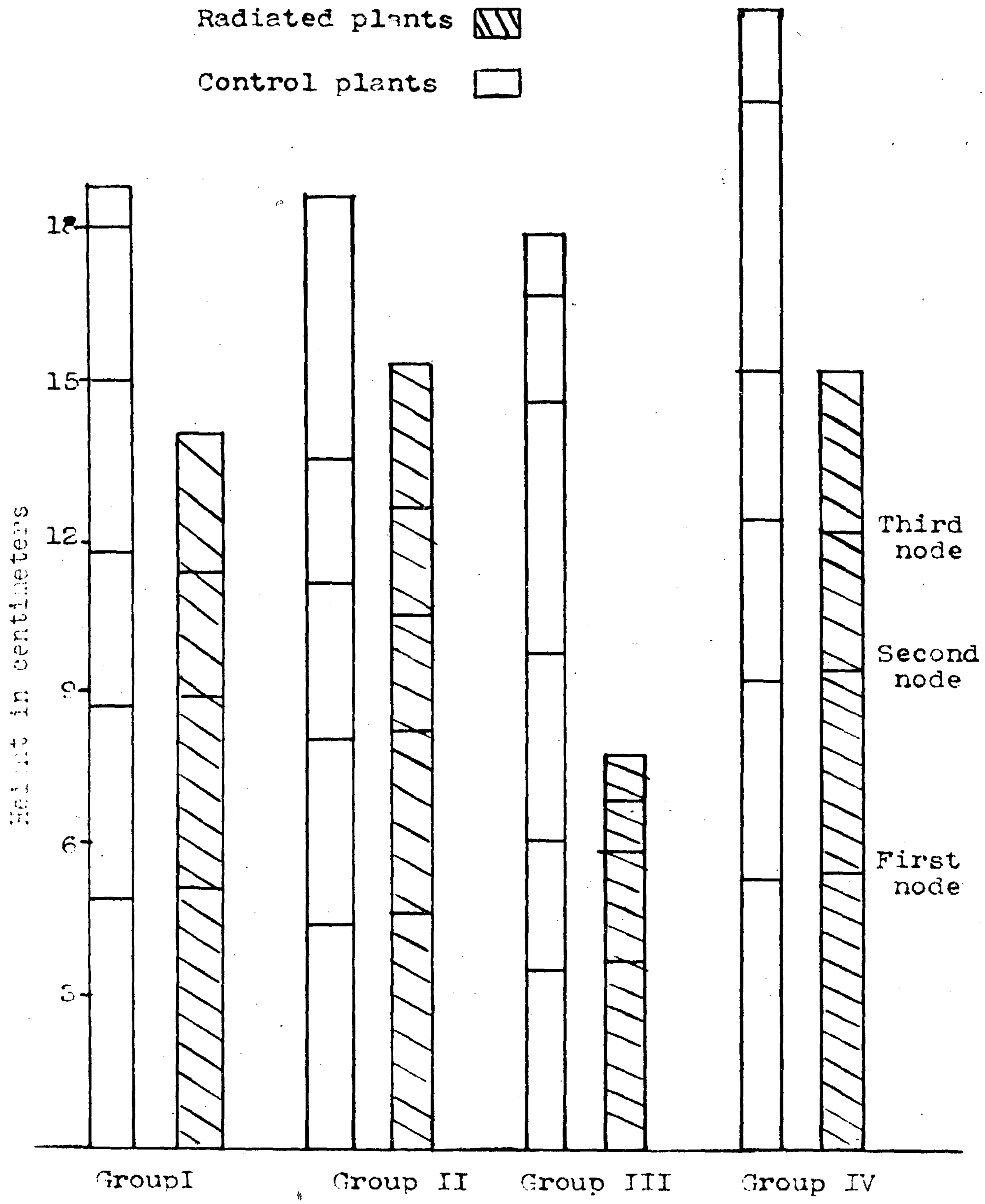


Figure 59. Relative height of Red Kidney beans grown in radiation and control rooms (converted cold storage compartments) at the end of each experiment.

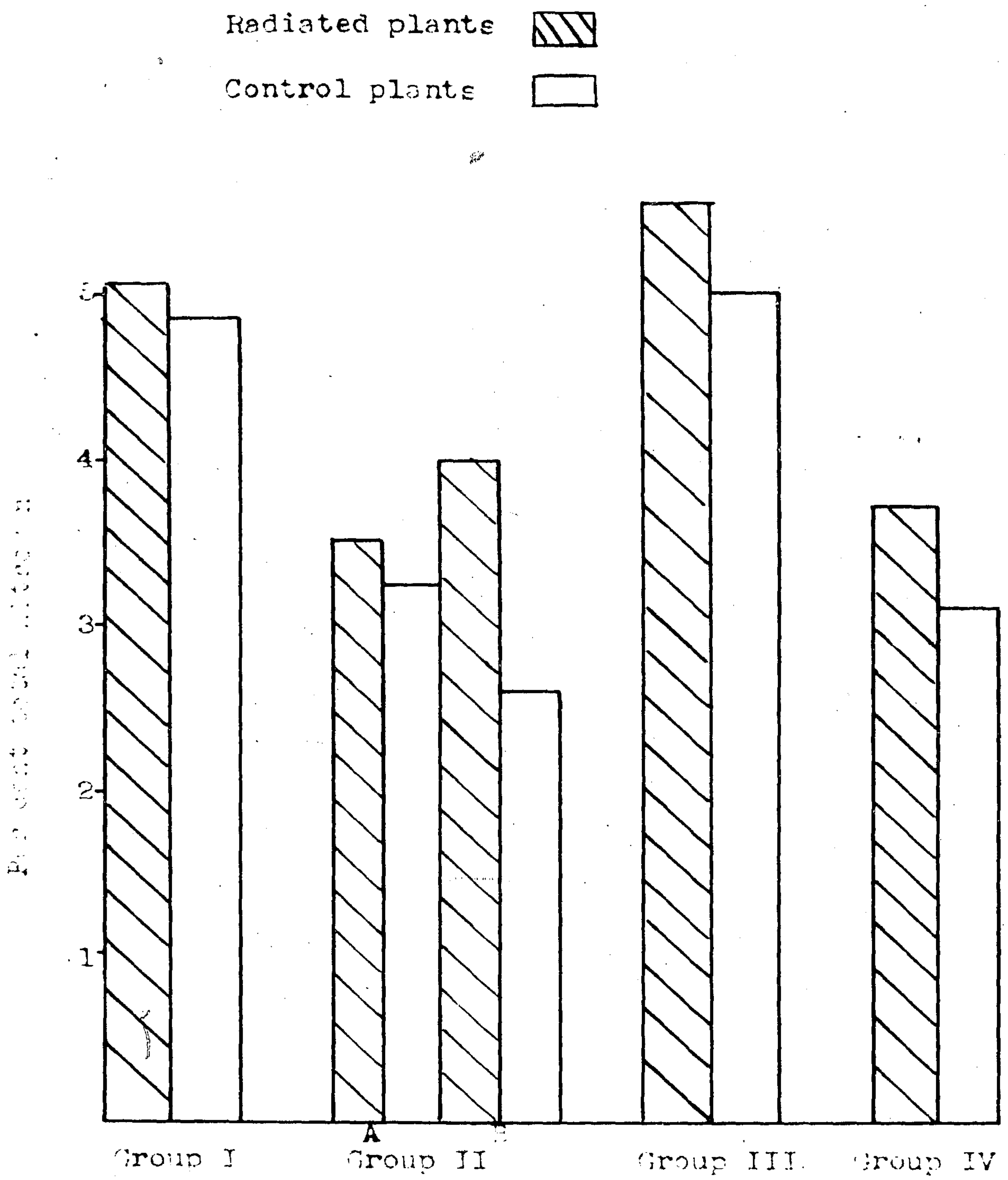


Figure 60. Per cent total nitrogen of Red Kidney Beans (above hypocotyl) on dry weight basis.

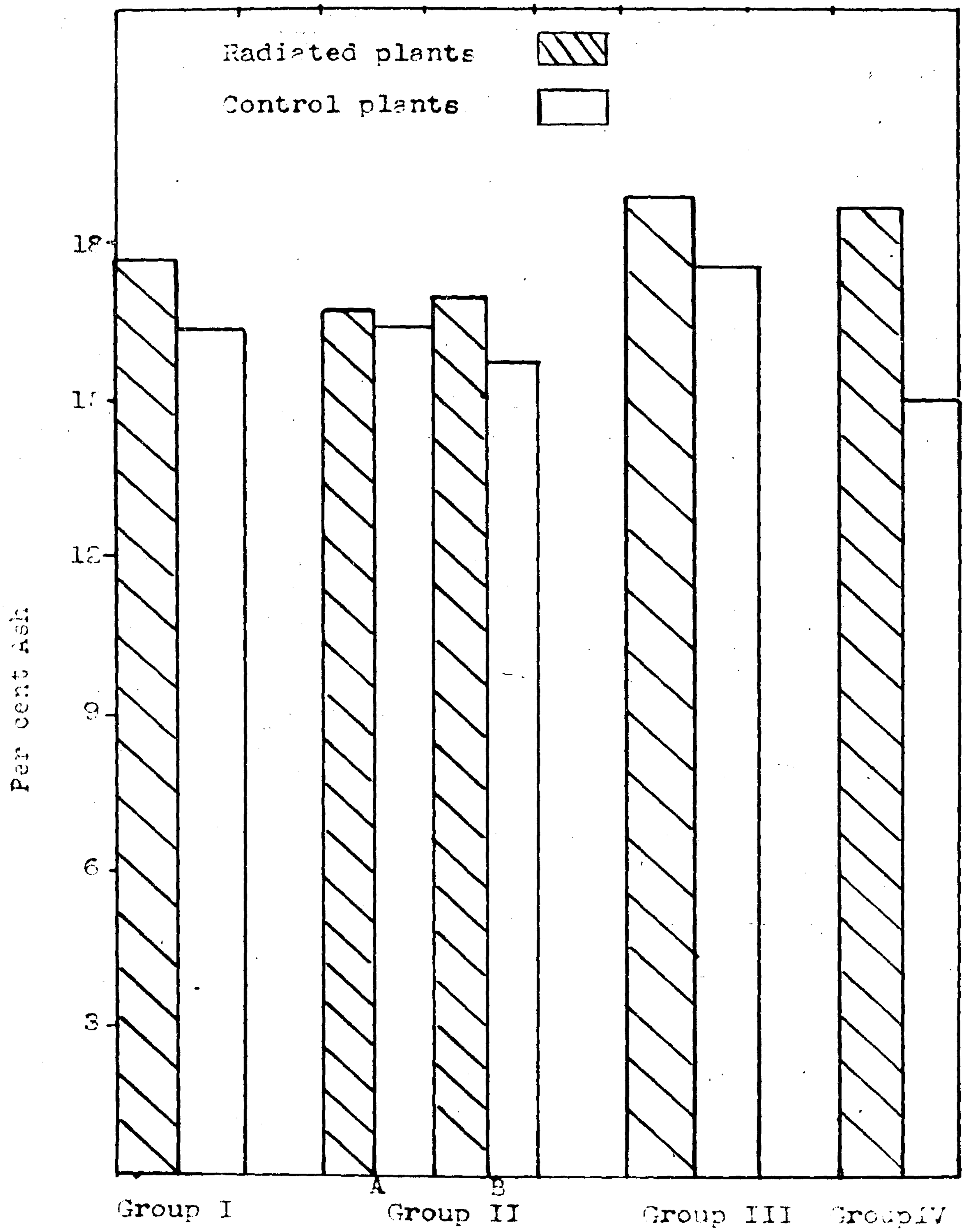


Figure 61. Per cent ash of Red Kidney bean tops (all parts above hypocotyl) on dry weight basis.

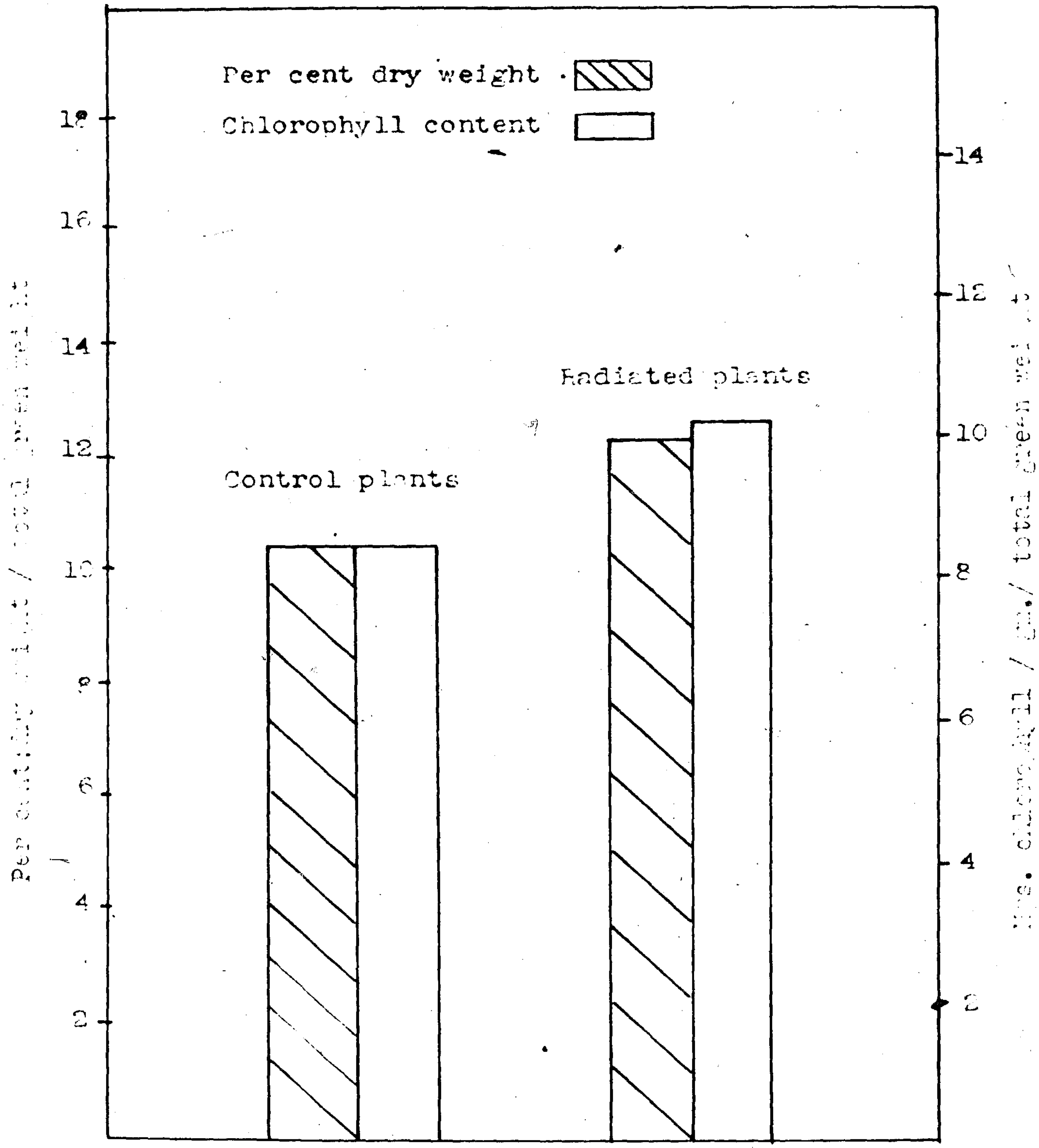


Figure 62. Analysis of Red Kidney beans (above hypocotyl) after eight days growth in the radiation and control rooms showing chlorophyll content on green weight basis compared with the per cent dry weight.

RESULTS

A. Test on lilies

Weekly measurements in inches of terminal growth to measure the effect of radiant energy on lilies in the greenhouse (1947). Linear measurements of Creole lilies in inches.

TABLE I

	May 14 - 19	May 14 - 27	May 14 - June 2
Radiated	2.14"	6.91"	8.95"
Control	2.35"	7.01"	9.63"

B. Analysis of individual bean plants grown in radiation and control house in the greenhouse (1948). (See TABLE II on next page).

C. Measurement of temperature fluctuations in the green house (Figure 58) indicates the wiring diagram used in these equipment controlling the leaf temperature.

(1) Testing maximum heating capacity of the radiator in the parabolic reflector by setting the controller for full capacity operation (Figure 52). Note the 88° F. leaf temperature while the air temperature in radiation house was 72° F.--a difference of more than 16° F.--and the air temperature in the unheated greenhouse room, 40° F., in which the radiation house was placed--a difference in temperature of 32° F. from the air in the radiation room.

TABLE II

	Pot Number 1	2	3	4	Average
Radiant Treated Exterior					
Leaf Weight (Gms.)	8.0	8.0	9.0	10.0	8.8
Stem Weight (Gms.)	4.0	4.5	4.5	5.5	4.6
Ratio Leaf/Stem Wt.	2.0	1.8	2.0	1.8	1.9
Leaf Area - $Inch^2$	87	80	84	75	80
Height of Two Plants (Inches)	9.0 8.5	8.2 8.5	8.5 9.0	9.8 9.0	8.7
Ascorbic Acid Mg./100 Gr.			88.2	89.2	88.7

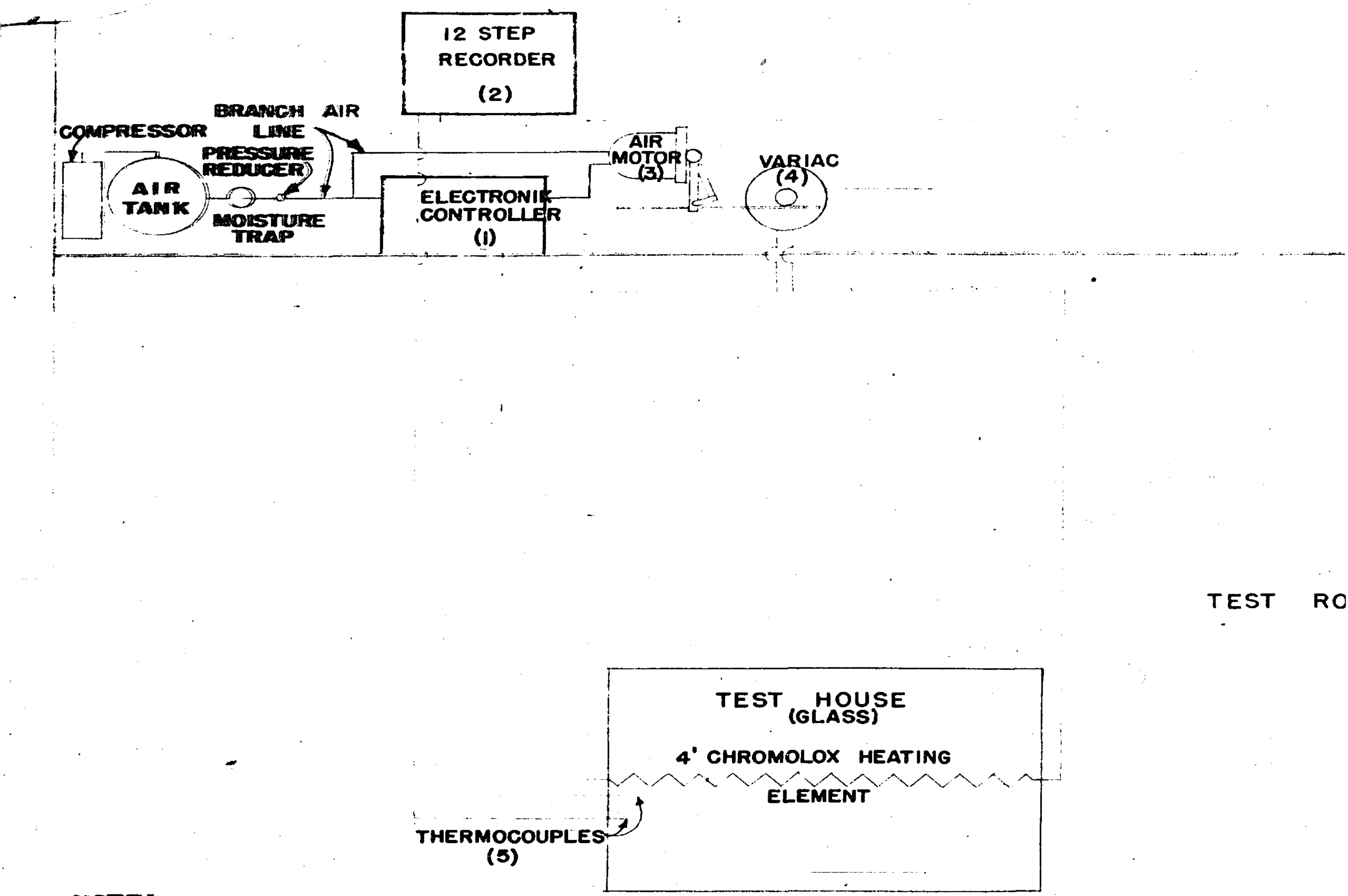
	Pot Number 11	12	13	14	Average
Check Plants Exterior					
Leaf Weight (Gms.)	11.0	7.5	12.0	11.0	10.4
Stem Weight (Gms.)	6.0	4.5	6.0	5.5	5.5
Ratio Leaf/Stem Wt.	1.8	1.7	2.0	2.0	1.9
Leaf Area - $Inch^2$	73	65	83	71	73
Height of Two Plants (Inches)	10.0 10.1	7.5 7.7	11.5 11.0	10.5 9.5	9.7
Ascorbic Acid Mg./100Gr.			98.6	79.8	89.2

(Table Continued on Next Page)

TABLE II (Continued)

	Pot Number						
	5	6	7	8	9	10	Average
Radiant Treated Interior of Glass House							
Leaf Weight (Gms.)	12.5	10.0	8.0	13.5	11.0	12.0	11.1
Stem Weight (Gms.)	5.5	6.5	4.5	7.5	5.0	7.0	6.0
Ratio Leaf/Stem Wt.	2.0	2.3	1.8	1.8	2.2	1.7	2.0
Leaf Area - Inch^2	105	95	83	120	100	94	100
Height of Two Plants (Inches)	12.0 10.5	12.5 12.0	9.5 9.8	13.0 13.0	11.5 11.0	12.9 12.0	11.5
Ascorbic Acid Mg./100 Gr.					92.4	84.7	88.5

	Pot Number						
	15	16	17	18	19	20	Average
Check Plants Interior of Glass House							
Leaf Weight (Gms.)	8.0	12.5	8.5	17.5	12.0	12.0	11.7
Stem Weight (Gms.)	5.0	8.0	5.5	10.0	9.0	7.0	7.4
Ratio Leaf/Stem Wt.	1.6	1.6	1.55	1.75	1.3	1.7	1.6
Leaf Area - Inch^2	75	105	81	130	90	115	99
Height of Two Plants (Inches)	11.2 12.0	11.5 14.5	10.1 12.5	15.3 15.0	11.5 13.0	12.0 12.5	12.6
Ascorbic Acid Mg./100 Gr.					78.3	70.2	74.2



NOTE:

(1) BROWN ELETRONIK CIRCULAR CHART AIR-OPERATED, AIR-O-LINE CONTROLLER 152 P13 P-63-11

(2) 12 STEP BROWN ELECTRONIK RECORDER 153 X65 P12-X-2F

(3) MINNEAPOLIS-HONEYWELL GRAD-U-MOTOR MO900C

(4) GENERAL RADIO CO. V-20 VARIAC

(5) THERMOCOUPLES ON UNDERSIDE OF PLANT LEAF

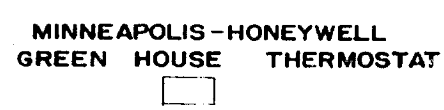
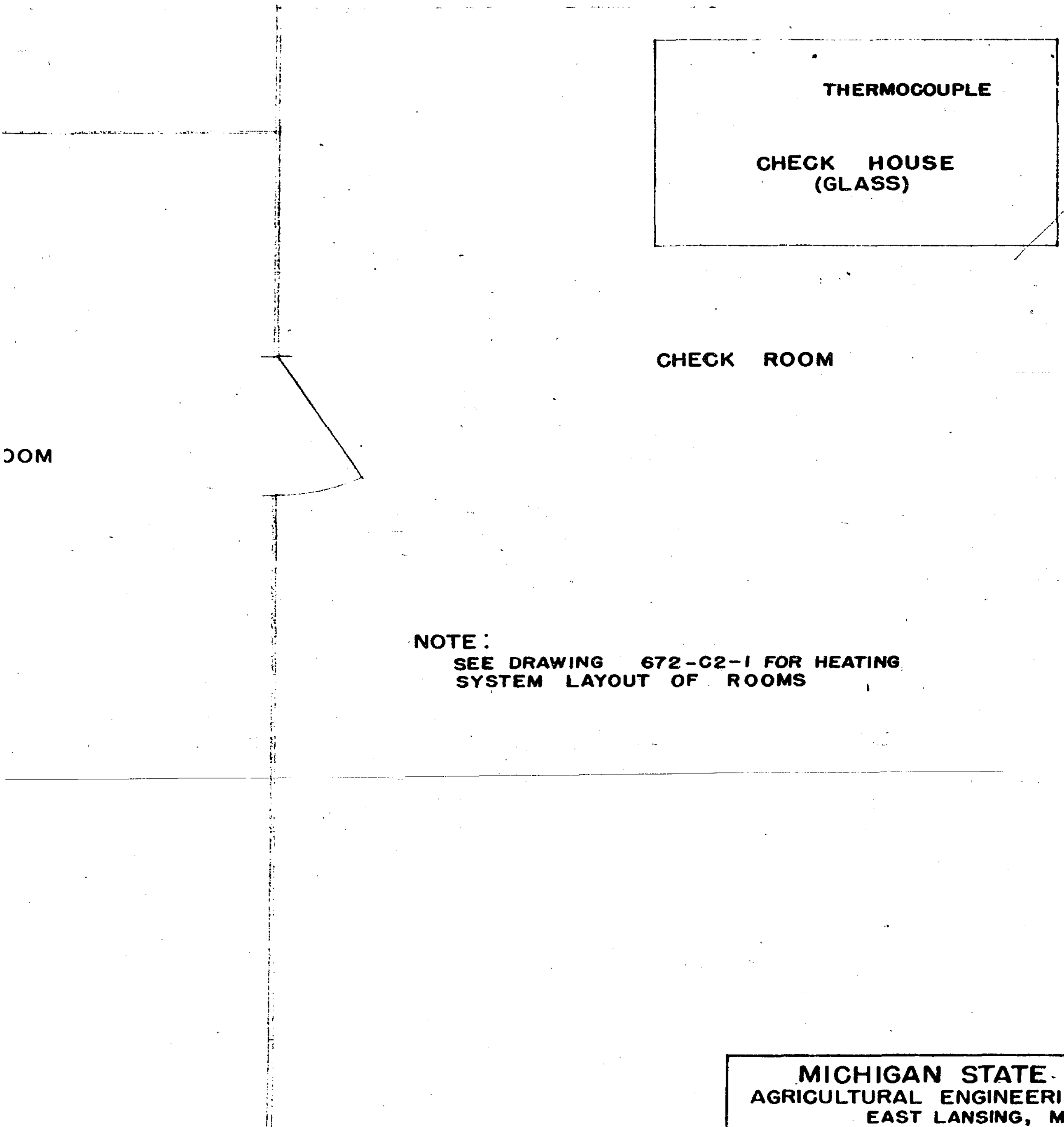


Figure 58. Wiring Diagram.



NOTE:
SEE DRAWING 672-C2-1 FOR HEATING SYSTEM LAYOUT OF ROOMS

MICHIGAN STATE COLLEGE AGRICULTURAL ENGINEERING DEPT. EAST LANSING, MICH.		
RADIANT HEAT TEST SET-UP HORTICULTURE GREENHOUSE		
PLANNED F.J.H. DRAWN SAIA TRACED CHECKED	APP. BY [illegible]	
	DATE 3-24-48	SHEET
	SCALE $\frac{3}{4}$" = 1'-0"	NO. 672-C2-2

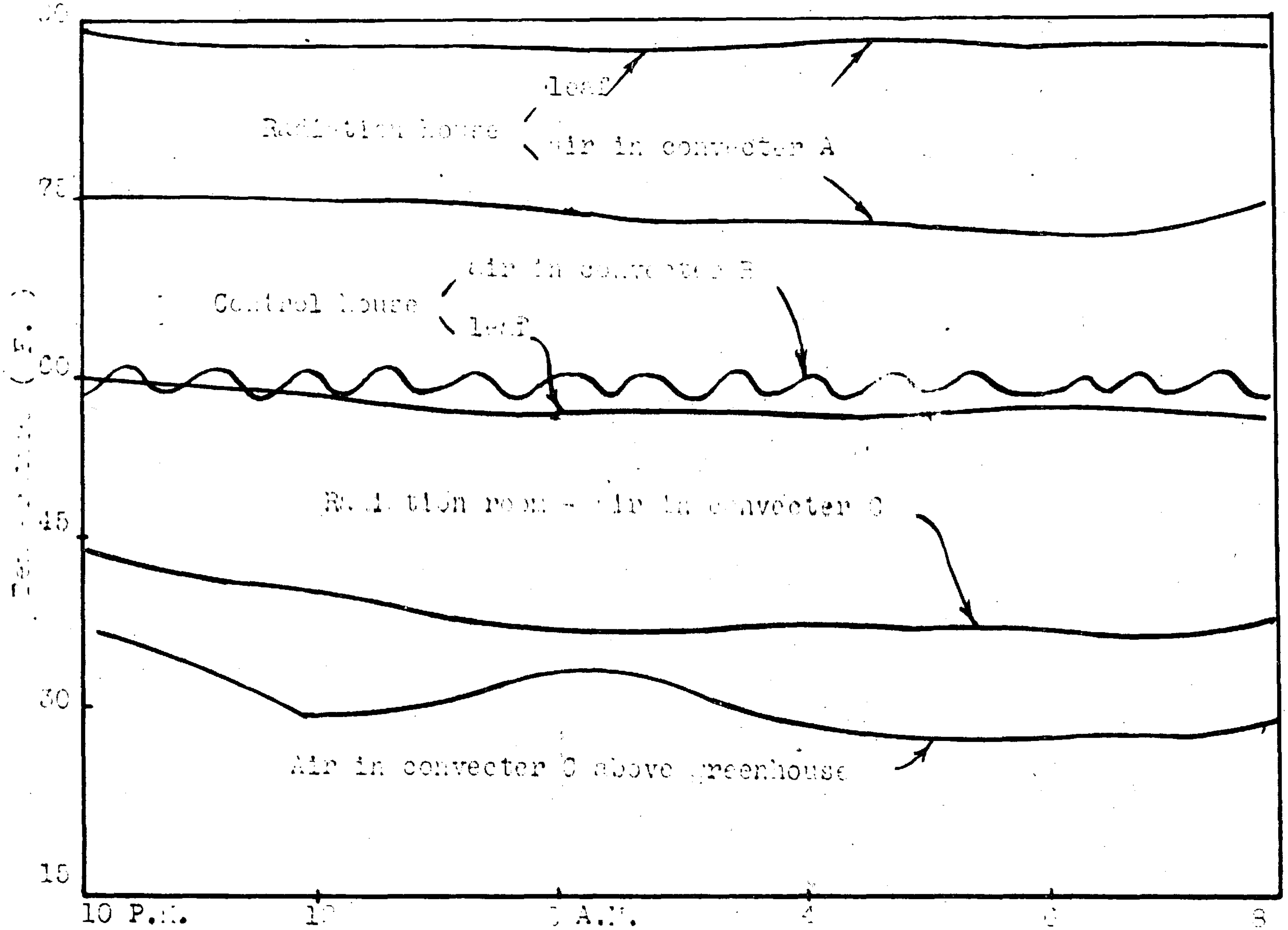
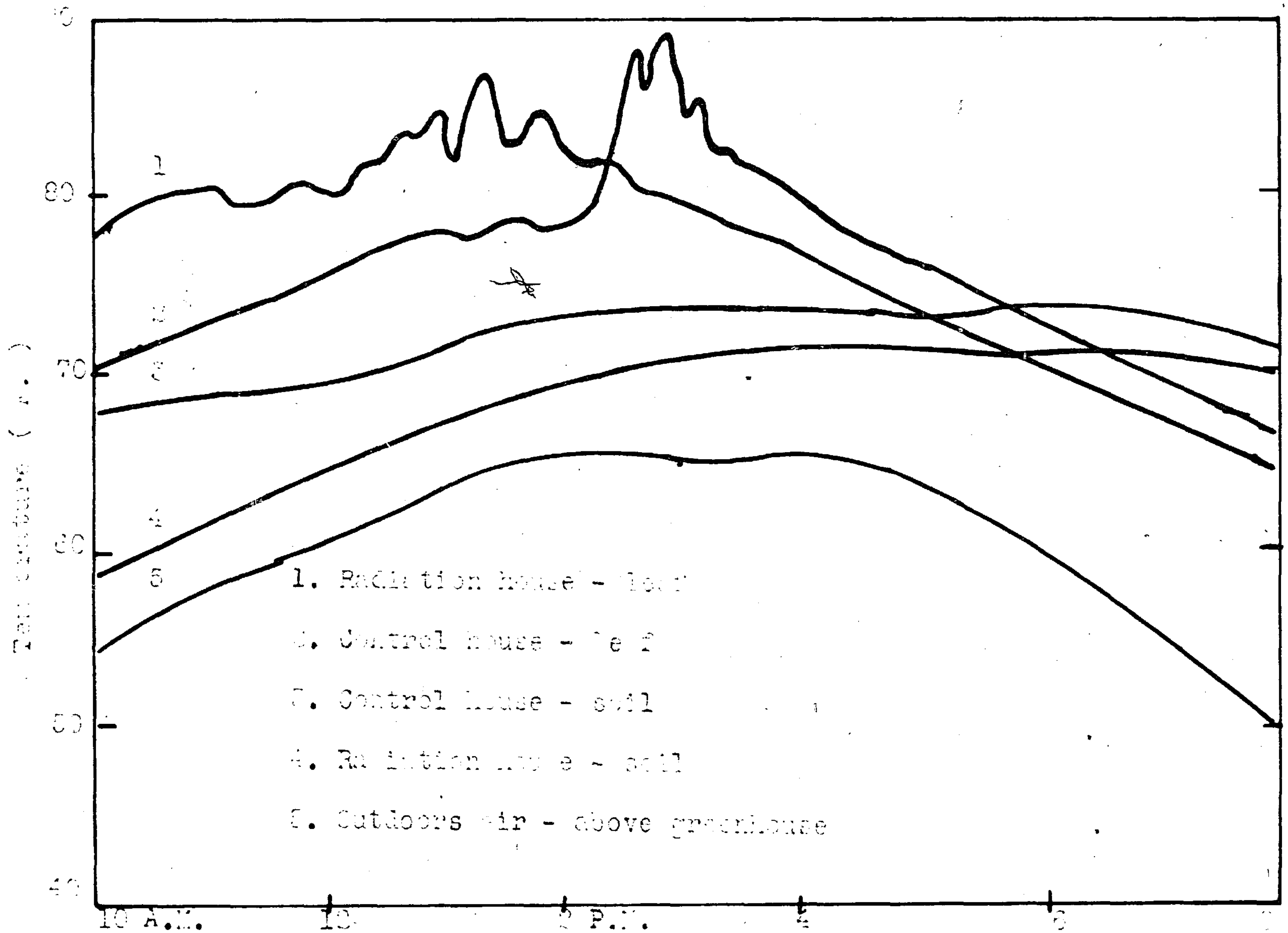


Figure 8[illegible]. Temperature curves in the radiation room of the [illegible] at night when the radiator was set for full-capacity operation. Test made in 19[illegible].

This shows that reradiation from plants can heat the air within a small enclosure and retain most of this heat due to the "heat trap" effect illustrated in Figure 2.

(2) Testing normal operation of radiation unit at night with the controller hand set at 60° F. (Figure 54). In this case the only leaf whose temperature was recorded on the twelve-step recording potentiometer registered a temperature slightly higher than that of the control plant. Note also that there was some accumulation of heat within the radiation house (Figure 8, 41) shown graphically in Figure 53.

The soil temperature consistently measured lower than the leaf temperature but was higher than the air temperature in the same house for the following reasons: (a) the soil temperature tends to become warmer in the daytime due to the higher air temperature and the radiation effects from the sun, part of which it retains throughout the night due to the capacity of soil water to hold heat; (b) the soil absorbs some heat from the radiator, the amount depending upon the degree of direct exposure (no obstructions by leaves, etc.), the distance from the radiator, and the absorption factor (varying with the color, nature and texture of the soil); (c) the soil tends to be cooler because of the colder water, not exposed to artificial radiation brought in by the automatic water system (Figure 18), and because of the loss of heat by conduction and convection and by the evaporation of water.



Time of day Apr. 30, 194

Figure 5 . Temperature curves showing the effect of solar radiation on the leaf temperature in both the radiation and control houses.

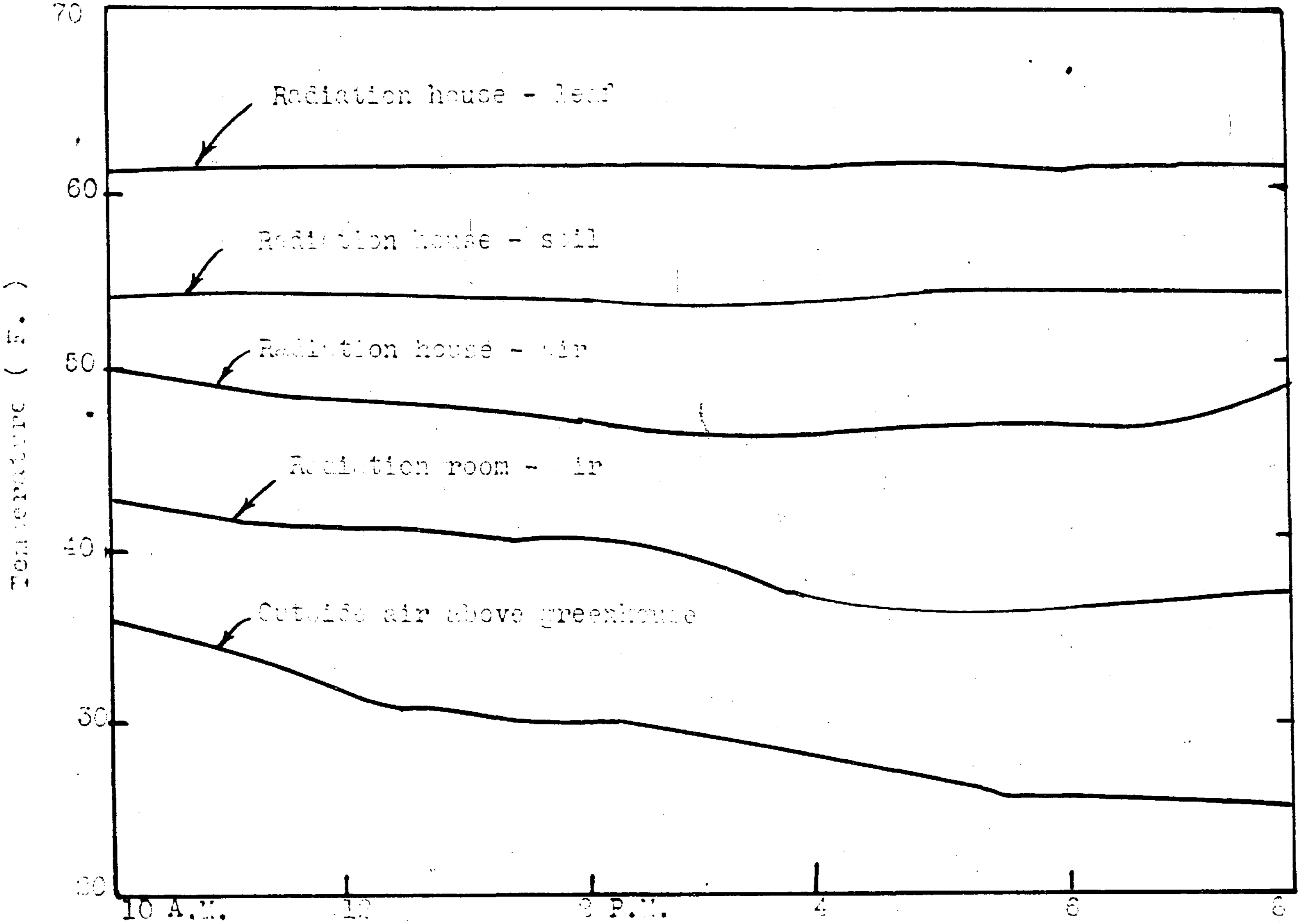


Figure 54. Normal night temperature curves in the greenhouse when the controller was set for [illegible]° F. operation and the greenhouse left turned off. (At other times the radiation room was set for [illegible]° F. in temperature).

(3) Testing the normal operation of the radiator during the day (Figure 53). As mentioned previously, great fluctuations may occur in leaf temperature when the leaf is alternately exposed to and shaded from the sun. A tremendous increase of temperature was often observed under intense solar illumination. Note the smoother curve for both soil temperatures.

(4) Testing convecters. Temperature readings from thermocouples placed in the central position of all three models of convecters checked fairly close to air temperatures at night and in heavily shaded spots during the day but varied a little under radiant conditions. It is sometimes believed that thermocouples give the true convected air temperature. This is not always true, especially when radiation is exposed directly upon the thermal junction, since a small amount of heat is absorbed by radiation. When the thermocouple is protected from the direct rays of the sun or an artificial radiator, the temperature it records approaches very closely the exact air temperature. However, in making a protecting device for a thermocouple, care must be exercised to maintain free circulation of air.

In developing these convecters, these two factors were considered--protection from all objects of unlike temperatures and free circulation of the air.

The model B convecter (Figure 38) seemed to meet these conditions most precisely because it was larger and most protected from radiation. Model A protected radiation from the above only (Figures 36, 37). The model C convecter (Figures 36, 45) was the simplest to make and to use. One of the model C convecters which was mounted above the greenhouse, protected the thermocouple adequately enough to make reliable temperature readings of the outside air possible. Care was taken to insure that no light would fall on the thermocouple from the open sides of this design.

Although all convecters were made from highly polished surfaced aluminum, which reflected about 95 percent of all radiation falling on it, the less as it became weathered, the convecters did absorb a small amount of radiation when subjected to long periods of intense radiation. This condition was minimized by building a larger convecter and by protecting the thermocouple with more layers of polished metal. Those were two reasons why the model B convecter proved the most satisfactory.

D. Measurement of temperature fluctuations in the converted cold storage rooms (1949-1950).

(1) Normal operation in the control room. As noted in Figure 57, leaves in a similar position often registered slightly different temperatures. Some of the factors affecting this variation were angle of incident exposure, height,

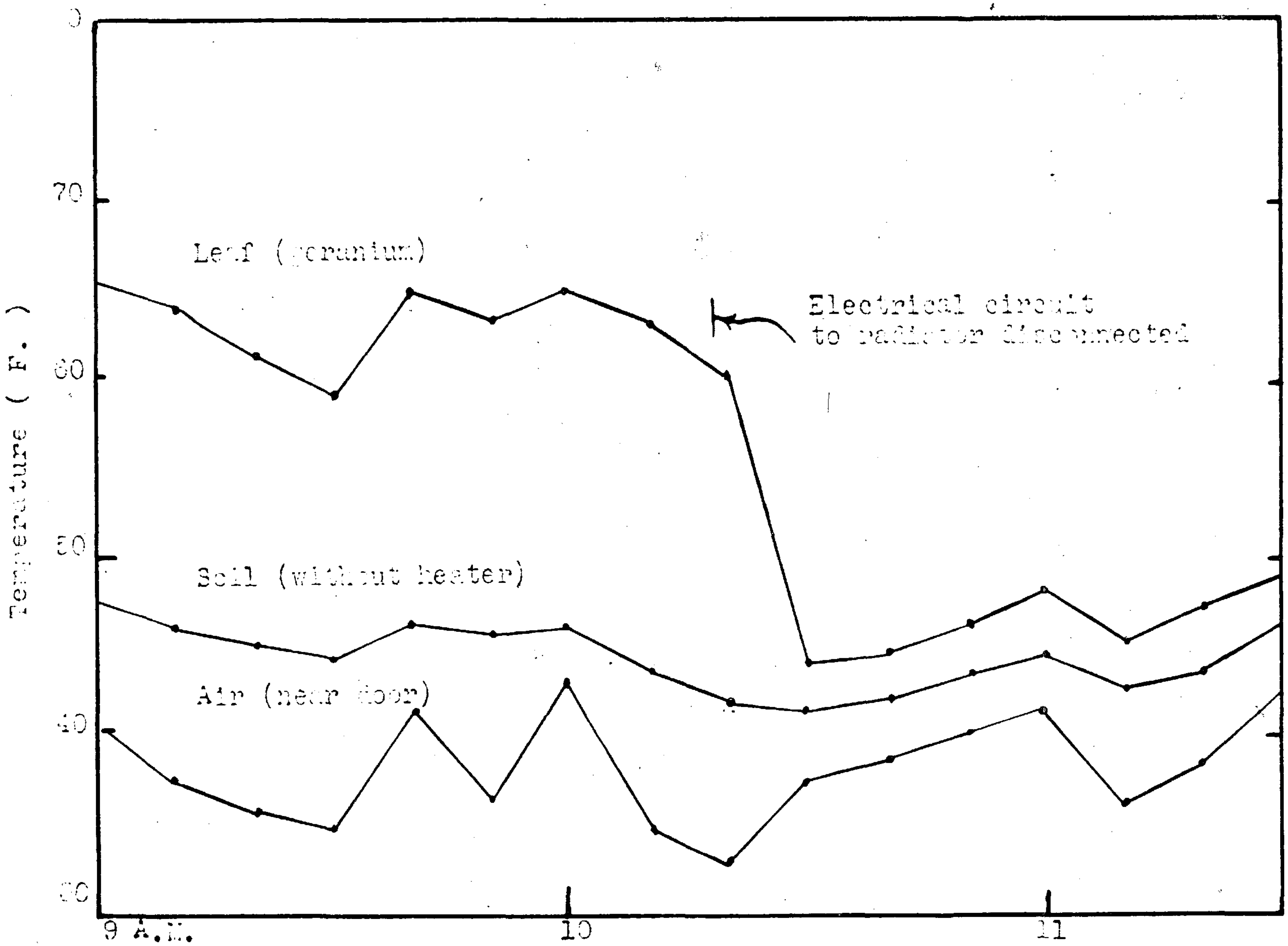


Figure [illegible]. Temperature curves in the radiation room showing the changes in temperature before and after the radiator was disconnected.

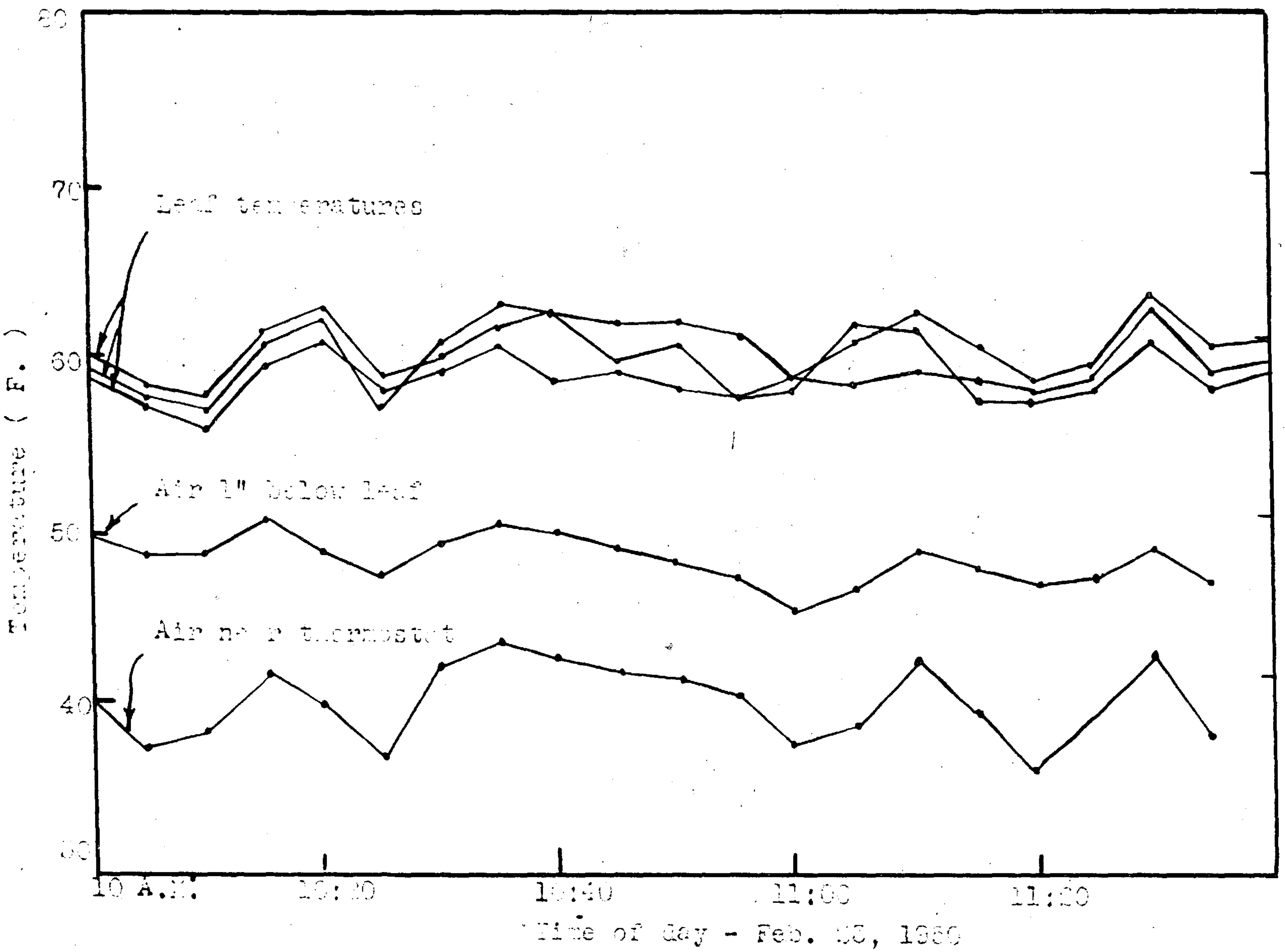


Figure [illegible]. Temperature fluctuations in radiation room on average day.

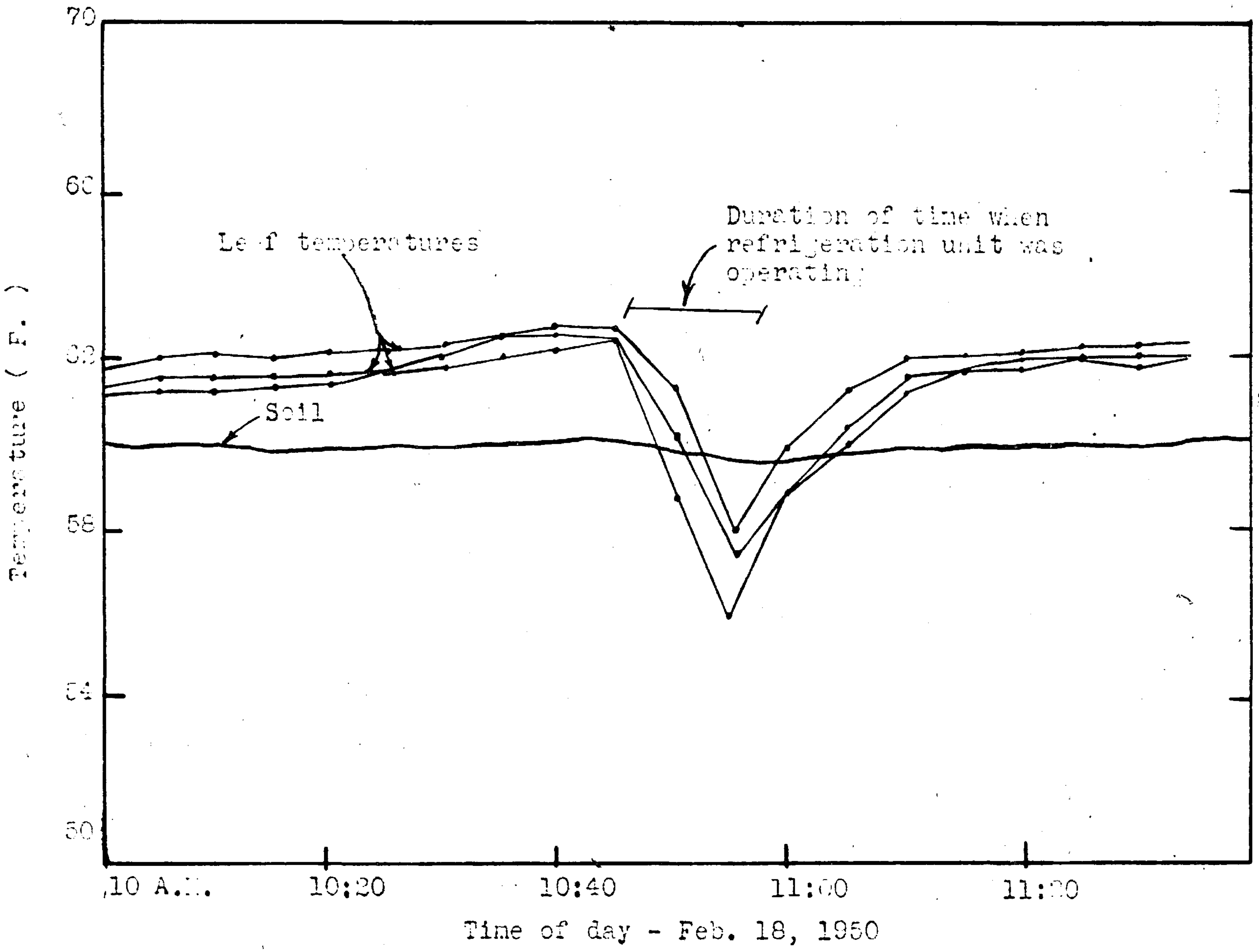


Figure 57. Normal temperature fluctuations in control room(converted cold storage compartment).

and absorptive properties. This curve graphically illustrates how leaf temperatures were affected by the on and off action of the refrigerating unit. Note particularly the constant temperature of the soil. Not shown here, however, 1° F. drop in temperature when the fluorescent lights were turned off by the time clock.

(2) Normal operation in radiation room. As indicated on the curves, at different locations in the radiation room (Figure 56), the air temperature fluctuated greatly due to the irregular cooling action of the refrigerator, the thermostat, and the fan. The differences in absorptive properties of leaves in a similar position are again portrayed in these curves. The air beneath the leaf was partially heated by the leaf, as shown here and in numerous other readings which are not included in this thesis. When a thermocouple was located between 1/2 to 1 inch below the leaf, it registered a temperature about mid-way between that of the leaf temperature and that of the air temperature.

E. Results of the 1949 and 1950 seasons. During the 1949 season a series of mechanical disturbances varied the results to some extent. For example, the heating load of electricity--1600 or more watts when operating at optimum capacity--overloaded the circuit and burned out the fuse on a few occasions. Little damage was done to Group I, but the experiment was terminated a few days early when some of the equipment needed to be altered.

With Group II, the variac burned out on the second day of the experiment. All of the plants in the radiation room were, as a consequence, thrown out. When the equipment was repaired the following day, it was considered desirable to follow the plan described below with the remaining good plants. The control plants in Group II were divided into two sub-groups, one-half being used in the radiation room and the other half left in the control room. Then an equal number of bean plants were brought in from the greenhouse from the same original lot as the rest of the plants. These were slightly larger, and again were selected for uniformity and divided by random choice for the two divisions of the experiment. They were designated as Group A (divided plants from the control room) and Group B (plants brought in later from the greenhouse). The plants from the greenhouse never adjusted themselves so satisfactorily to the change as did those which started in the control room. Evidently plants can adjust themselves better to their environment when they are younger in age, and have a less elaborate root system.

Group III was also exposed to one short period of intense heat when the variac burned out, and to a period of cold temperature when the variac was disconnected. These two exposures did not last more than ten hours and the results from the plants of this group should not be given too much consideration. They are included here for completion of the record.

Because of the unsatisfactory operation of the equipment during 1949, it was necessary to duplicate another run in 1950. This time the experiment was conducted without mishap, and the results may here be considered the most significant of all groups.

The manner of heating was changed in 1950, as previously stated, by using the elliptical reflector instead of the parabolic, which made it possible to double the number of plants used (Figure 41). To test the temperature pattern of a leaf under radiant energy and later after it was disconnected, a test was run after the Group I was completed in 1949. This figure shows how the temperature might have fluctuated on occasions when the electrical current was disconnected.

All plants were individually measured for height at each internode (Figure 59). This demonstrated that the average height of the control plants was, in each case, significantly higher.

Each group was analyzed for total nitrogen. The amount of nitrogen originally used in each group varied. The significant feature here (Figure 60) is the higher percentage of total nitrogen found in all of the radiated plants on a dry-weight basis within a given group. These increases, however, were associated with a reduced growth in each case. The maladjusted plants brought in later from the greenhouse (group 2-B) showed a higher total nitrogen percentage even though the plants did not appear so healthy as in group 2-A.

A higher ash content was also shown for all radiated plants with a maximum difference shown in 1950 (Figure 61).

Throughout these experiments the deeper green color of the radiated plants seemed to indicate that they contained more chlorophyll. To test this, an analysis for chlorophyll was made on five plants from each group fourteen days after the plants were set into the control and radiation rooms. The results are plotted on a bar graph against the percentage of dry weight/green weight (Figure 62). Besides showing the increase in chlorophyll content, the bar graph also shows that radiated plants had a higher percentage of dry weight. When compared together, the increase in chlorophyll is not considered significant.

Some of the plants were analyzed for ascorbic acid content a few days before the end of the experiment. No significant difference was detected on the basis of dry weight. The method followed (Lucus, 83) consisted of macerating the stem and leaf tissue for three minutes in a Waring blender with a two percent solution of metaphosphoric acid. The macerated material was filtered through a fluted filter paper. From the clear filtrate a two ml. aliquot was transferred to a porcelain dish, where it was titrated against a .02 percent solution of sodium 2, 6-dichlorobenzenoneindophenol to a faint pink end point.

F. Plant growth behavior. Although all plants were similar after moving (Figure 15; radiation room) and (Figures 40, 45, 46; control room), they soon developed individual characteristics. The following differences in leaf shape were observed. Those in the control room curved inwardly and became bumpy in appearance (Figures 13, 24; 1950 plants). Leaves that developed later showed less of this tendency; however, they still faced toward the sides, in the direction of the fluorescent lights. The lower leaves died and the older remaining ones dropped (Figure 11). The higher humidity in the control room kept the dead leaves from drying up as fast as they would have done in the greenhouse.

Those plants in the radiation room were smooth and dark green in appearance (Figures 12, 17, 25) in the early stage of their growth. At the same time the growing point of the plant was yellowish and chlorotic in appearance. The terminal growth was much slower than was that of the control plants at the same time. The first pair of leaves grew in a more or less horizontal position; this appearance was more pronounced at times other than those when the photographs were taken. Later leaves that developed showed a similar but less pronounced horizontal placement, while the older leaves at that time tended to bend downward and to look more as those of the control leaves had previously looked. (Figure 10).

Mildew infected the second group of plants in 1949, probably while they were still growing in the greenhouse before they were transferred to the converted cold storage rooms. The infected plants became noticeable when they were in the storage room about two weeks. The infection grew fastest on the radiated plants. They were sprayed and no further infection appeared.

DISCUSSION

The results obtained in this thesis require an explanation of the operation of some of the principles, underlying the experiments.

Temperature Relationships

All discussions of radiant energy tend to center around the topic of temperatures and their relationships to other environmental factors. First, let us consider the temperature of the radiator or source of radiant energy, second, the temperature of the air, and finally, the temperature of the plant itself.

As previously stated, the efficiency of the radiator increases with the temperature in a nearly direct proportion to the fourth power of the Absolute temperature (Stefan-Bolzman law; Figure 3; Koller, 76). Furthermore the higher the temperature of a radiator, the less the intervening air is heated. A radiator at a high temperature--especially above 200° C.--is more effective in heating a distant object by radiation than it is at a lower temperature. For example, the electrical heating unit used by Farrall et al. (48) heated the air only .5° F., while at the same time it heated the ground from 6 to 8° F. above the surrounding air. In the present experiments, as substantiated by numerous temperature readings made with several thermocouples, the air was usually heated only to a negligible extent. Areas near the leaves where the air was warmed more than elsewhere, were heated largely through the effects of conduction and, to some extent, convection.

When a leaf is heated to a temperature above the surrounding air temperature, it returns a portion of this energy to its immediate vicinity in several ways. First, heat is lost by radiation--the phenomenon by which heat is emitted from the leaf, in the infra-red portion of the spectrum, to distant objects. Second, heat is lost from the leaf by conduction. The following illustration will serve to show how heat is lost by conduction in still air. Air molecules surrounding a heated leaf receive a part of the kinetic energy from that leaf and, in turn, release a part of their absorbed energy to the row of molecules lying adjacent to them. Carleton (31) stated that heat can best be defined as the total kinetic energy possessed by the molecules of a substance. Thus it becomes apparent that this kinetic energy and heat can be considered identical as far as these discussions are concerned.

The net result of the transferring of energy from one layer of molecules to the next, and so on ad infinitum, is to give a pattern with concentric layers of molecules whose energy decreases as the distance increases from the leaf blade. This pattern seldom remains intact without being disrupted by other influences. Third, heat is lost by convection. When air is heated and gains more kinetic energy, it becomes lighter or less dense than cooler air. Wherever air thus becomes heated it will tend to migrate to areas of less density and thereby create a condition known as convection currents.

When the air is in motion--as in breezes or wind, and through the action of a fan--both conduction and convection patterns become modified or partly disintegrated. In other words, air movement increases the relative amount of heat lost by conduction and convection by increasing the temperature differential between the layers of molecules lying close to the leaf. At the same time, however, the air movement will decrease the temperature differential between the leaf and the average air temperature. Radiation loss from a leaf depends more upon the lower temperature of distant non-adjacent surroundings than upon the temperature of the air which immediately envelops it. The heat absorption of the atmosphere that is absorbed by the atmosphere is largely due to water vapor and, to a lesser extent, carbon dioxide. Nitrogen and oxygen, themselves, absorb an infinitesimal amount of energy.

Radiation studies on growing plants are altered by these temperature patterns. Air movement is not wanted because it disrupts the conduction-temperature pattern. Additional calories of radiant energy are required when breezes remove these heated molecules lying adjacent to the leaf; therefore, when these particles remain undisturbed, it is possible to heat the plants by radiant means using less energy, for wherever the air-heated-by-conduction molecules can be held intact, the heat lost by conduction and convection is greatly reduced. Even when all air movements are eliminated, if that were possible, convection currents will modify this conduction pattern, the extent of the modification varying with the temperature differential which the experimenter maintains between the leaf and the average air temperature.

Although it is next to impossible to eliminate the heat lost by convection, it is possible to prevent unnecessary air movements. These controlled conditions are, however, not found in many plant-growing chambers because the need is seldom specified to the designers who draw up the plans for the construction for such rooms. Few experimenters have ever asked for still air because still air does not give them the even distribution of temperature which they require in most of their experimental work.

In the radiant heat experiments carried on in the cold storage rooms, a differential of 20° F. was maintained between the leaf and the average air temperature at a distance from the plant. In spite of the unwanted air circulation in these rooms, there was a slight temperature pattern extending from each of these plants into the adjacent air. A difference of 10° F. was found between one-half and one inch from the lower and protected surface of the leaf. A temperature differential of 20° F. is seldom encountered in nature under solar radiation. Perhaps some of the alpine plants on the southern exposures may be heated that much or even more, but such examples are infrequent. A temperature differential of 10° F. is often found, and a 5° F. increase is commonly observed where plants are exposed to solar radiation. In any practical application of radiant heating, it is much better to think in terms of a small differential than in terms of a large differential, such as was attempted in this experiment. However, it was important to test the effects of radiation under as severe a test as possible in order to learn its potentialities. The present type of radiant heating is impractical, not only because of the high temperature differential maintained, but because of the use of electricity, which will never be practical unless it becomes much cheaper than it is at present.

The cold storage rooms which were used in these studies were not adequately adapted to radiation studies because of the irregular air circulation caused by the fans in the room. The fans were necessary in order to circulate the cooled air from the refrigerating units.

Many attempts were made to minimize the irregular flow of air. During 1949 the entire framework with all the equipment was moved from one part of the room to the other. An endwise position, as viewed from the door, at the farthest end of the room from the door proved the most successful of all positions tried. During 1950, wrapping paper was draped around the framework in various ways, and eventually a system was provided which proved partially successful.

In designing a room for the purposes of radiation studies, one of several different ideas might prove practical. First, air could be conditioned to the proper temperature before it is introduced into the room. Ducts used for this purpose could be so located and baffled that little draft would reach the plants. Second, a system of radiant cooling could be used whereby pipes of a refrigerant could be imbedded behind some highly emissive material in the wall and ceiling. The ceiling should prove most practical because the warmer air moves to the top of a room. The cost of construction would be high because of the need for extra thick insulating material behind such a panel, if an efficient cooling system is wanted.

If these systems are impractical the present rooms could be converted into more desirable cold rooms by increasing the cooling area, using a lower temperature refrigerant and adjusting the cooling system for continual operation.

The inverse square law of radiation distribution, which applies to perfect black bodies (Figure 5) does not apply absolutely to plant leaves which cannot absorb 100 percent of the radiation as does the theoretical black body. Leaves permit a part of the waves which fall upon them to pass through. The transmission is small, but it allows the shaded leaves or the shaded portions of leaves to receive some heat. Other waves of light are reflected. The amount of radiation reflected depends upon the angle of incidence and the surface characteristics of the leaf. In radiation experiments the experimenter wants to minimize the amount of reflection and increase the degree of absorption. This is best accomplished when the leaf is horizontal, i.e., at right angles to the direction of radiation.

The principle of the inverse square law answered the question why the leaves closest to the radiator were the hottest. The difference is theoretically quadrupled for every doubling of the distance between the radiator and the plant. This indicated that the lower leaves of the radiated plants did not receive as much energy as those higher up. It also meant that the stems did not receive very much direct radiation because of their position. The relatively small exposed area per volume of both the petioles and the stem showed that these areas were locally cooler than the leaves, which had a relatively larger exposed surface for their volume of tissue. Borthwick (17) showed that localized cooling of plant tissue can and does greatly slow up the metabolic rate of growth. Although the growing point is closer to the radiator than other parts of the stem and some leaves of the plant, it probably is not heated as much as the leaves are. This lower temperature may help to explain the chlorotic condition seen at the growing point of the radiated seedlings. Meyer and Anderson (89) say that the dividing cells in the top of the growing point is a region of intensive respiratory and assimilatory activity. Thus any decrease in temperature at this region may well account for any tardiness in the rate of growth.

When it was necessary to operate at such close distances as was necessary in 1950, 14 to 16 inches from the radiator, it was difficult to estimate the average amount of radiant energy received per plant. If any error was made, it was on the side of underheating due to underestimating the volume of colder tissue in the stem and petioles. Air currents which tended to cool some plants more than others and the unevenness of radiation distribution produced errors which were partially counteracted by moving the plants from time to time. The narrow distribution of radiant energy for the two different reflectors meant using two rows of plants with the parabolic reflector and four rows with the elliptical reflector. A space had to be vacated at both ends and at the sides because of the insufficient amount of radiant energy. The position of the leaves brought in an uncertain variable, but fortunately the strong tendency for the leaves of the radiated plants to face in one direction simplified calculations.

All light intensities were balanced with a Weston light meter (photometer), but it appeared that there may have been a variation in the amount of luminous energy received by the different plants because of their placement and the curling of some of the leaves. Since there was no simple way to ascertain this difference, it was assumed that all variations tended to cancel each other and that whatever variation occurred was not significant.

The leaf position constantly altered due to nutation. This alteration could have been photographed with a time-lapse camera. The thermocouple connection with the leaf was sufficiently strong in almost all cases to counteract any tendency of plant movements to loosen these junctions. When it was necessary to use thermocouples for thermostatic control of radiant energy, extreme care was taken in attaching them; none of these attachments loosened.

Soil Temperature Relationships

Soil temperature greatly affects the absorption of water by growing plants in general and more so by certain high temperature crops. Arndt (7) found that cotton wilts when the temperature of the soil falls to a region between 17 and 20° C., while Doring (43) found that, when several plants were transferred from a soil temperature of 20° C. to one of 0° C., the absorption of some plants was greatly retarded and others were scarcely affected. Kramer (77) also found species differences with respect to water absorption at low soil temperatures. Meyer and Anderson (89) state that the principal factors affecting the rate of absorption by growing plants are: (1) available soil water, (2) soil temperature, (3) aeration of the soil, and (4) concentration of solutes in the soil solution. All these factors likewise influence the rate of transpiration.

In the experiments conducted in the cold storage room, these above-mentioned factors were controlled in the following ways. The necessary water was made available by the use of automatic watering; the soil temperature was kept constant by the soil-heating cable regulated by the soil thermostat; the soil aeration was adequate under automatic watering conditions, as stated by Post (106) under this subject; and the soil solutes were probably nearly equal because each group of experimental plants was potted from an evenly mixed pile of soil, and because the seedlings were never fertilized from that date until the end of the experiment. Quick tests by the Spurway system of soil analysis checked perfectly each time an analysis was made. From the foregoing considerations it is seen that the variability of the plants in the experiments was little affected by soil conditions.

Since an increase in total nitrogen and ash was found in the radiated plants, the following references regarding the intake of nutrients at different soil temperatures are included. Kramer (77) showed that salt intake is reduced at low-temperature levels. Allen (3) described how calendulas and snapdragons showed marked symptoms of nitrogen deficiency at the slightly low soil temperature of 52° F.

Regarding the relationship between light intensity and soil temperature Steinbauer (123) showed that the greatest response to an increase in concentration of the nutrient solutions occurred at the higher light intensities, indicating that a greater need for nutrients occurred under these conditions.

If differences in soil temperature caused any of the differences noted in the radiated plants, they were probably due to the variation in the different parts of the pots which were warmer at the bottom and colder at the top while they were in the 40° F. room. It is not known what effect this localized heating may have had on the soil roots. The roots and root hairs appeared normal and equally distributed with the largest quantity toward the bottom. Nodule development appeared equally abundant in both group of plants.

Stoutemeyer and Close (127) and Stout et al. (126) mention that the localized heating of a heating cable laid on the surface of the soil gave the most growth to plants growing nearest the heating coil. When the heating coil was placed beneath the rows of gladioli, Emswoller and Barthwick (47) found that these plants were forced greatly ahead of unheated corms. Zerfoss and Strand (152) and Porter and Ditchman (105) mention that heating the plants with electric bulbs in the hotbeds gave a good growth even when the soil was not heated.

Hayward and Spur (69) relate the intake of ions to the osmotic pressure differences existing between the soil solution and cell sap and to the metabolic status of the roots in respect to the carbohydrate reserves. Substrates of high osmatic concentration tend to inhibit the meristematic activity and elongation of the root.

Vapor Pressure Deficit

The relative dryness of the air determines, in part, the amount of water that is lost through the plant by either cuticular or stomatal transpiration. It also determines the amount of water lost from the soil by evaporation. At a given temperature of the air the relative humidity can be used for comparing differences in the humidity, but it fails to indicate the drying power of the atmosphere when the temperature of the air varies. In discussing the transpiration of plants under different temperature conditions, a more reliable guide is the use of the vapor-pressure deficit. This deficit is an index of the relative water-absorbing capacity of the atmosphere--the true criterion which determines the rapidity by which this air changes liquid water into water vapor. The higher the vapor pressure deficit, the greater the capacity the air will have to evaporate water from a leaf or atmometer into vapor. According to Anderson (4) the vapor-pressure deficit is the difference between the actual vapor pressure of the atmosphere and the vapor pressure of a saturated atmosphere at the same temperature. The vapor pressure can be calculated from tables when the relative humidity and temperature are known (Oosting, 98). The vapor pressure deficit increases with the rise in temperature and will vary from place to place in a more or less direct relationship to fluctuations in temperature when transpiration is not considered. Air molecules adjacent to a heated leaf, therefore, have a greater energy factor which aids the transformation of liquid water into vapor. This energy tends to hasten the transpiratory rate of the leaves under radiation conditions, and the vapor thus formed, in turn, lowers the vapor-pressure deficit in that vicinity.

Localized areas of varying degrees of moisture, especially around the leaf and the stomatal or transpiring areas, are known as microclimates (Ramsey et al., 113). These are characterized by a humidity gradient, the vapor pressure deficit at the evaporating area of the inter-stomatal spongy cells in the leaf differing from that of the dryer air at a greater distance from the leaf.

Meyer and Anderson (89) stated that most transpiration occurs through the stomatas but that in some cases some water is lost through the cuticle; the amount lost by both methods depends upon leaf characteristics. Miller (91) stated that the amount of transpiration depends upon the intercellular spaces, which may form between 3 to 70 percent of the total volume of the leaf.

The leaves on plants growing under intense radiation probably have fewer intercellular spaces because of the difference in texture that is seen when intensely radiated leaves are compared to leaves growing under less intense radiation. Oosting (98) stated that plants growing under intense solar radiation have a thicker palisade layer and less sponge tissue, while those growing under conditions of less radiation have fewer palisade cells and more sponge tissue. These statements indicate that radiated leaves have less evaporating area within their leaves, and since water is lost in such large amounts under radiant conditions, the water loss per intercellular transpiring area must be relatively large. The probable reduced evaporating area and the high water loss would indicate, besides, that the inter-stomatal cavity is a region of higher humidity than might otherwise be anticipated.

The experience with mildew infection in the second group of plants during the 1949 season, in which the mildew flourished more in the radiated plants than in the control plants, seemed to verify the idea of a higher moisture condition in the intercellular cavity. Mildew usually develops on the surface of the leaf, and casual observation has often given the impression that it could not grow if all water were kept off the surface. Under radiant energy exposure leaves are usually quite dry on the surface due to the increase vapor pressure deficit resulting from a higher leaf temperature. Actually, however, the mildew grew a great deal. It becomes apparent that the spores must have germinated within the intercellular areas of the leaf, and that sufficient water must have been present to make germination possible. To enable the mycelium to furnish enough water must have been available to maintain a lush growth. Further research with mildew under radiation conditions should be made to find out the true relationships existing under such growing conditions.

The use of radiant energy for the prevention of purely surface-borne organisms, such as damping-off organisms are supposed to be, should prove a fruitful field for future research since it offers one of the most practical applications for the future use of radiant energy.

The higher vapor-pressure deficit on radiated plants caused considerably more water to transpire from the leaves. This increased loss of water is frequently observed by horticulturists who note that plants require more water when the solar radiation is most intense. Under the combined influence of both sunshine and artificial radiation, the lily plants grown in these experiments showed a water consumption twice as high as those same plants growing under solar radiation only. Red Kidney beans growing under artificial radiation showed only a 4:1 difference at the start and a 6:1 difference toward the end of experiment. This difference was partly due to the higher humidity which developed in the control room, since no effort was made to control the moisture content of the air. No effort was made to control the humidity because of the difficulty of maintaining temperature control and because of the poor adaptation of the available humifiers to the purpose.

All beans growing under control conditions showed a higher water content in their leaves as revealed in the difference between the green and dry weight of the plant tissue. This is graphically shown in Figure 65 in relation to the chlorophyll analysis. The differences, although not shown in this thesis, were not as high when the comparisons were made after the plants were four weeks in the radiation and control room. The radiated plants were usually dried to about 11 percent dry weight, while the control plants weighed to about 10 percent dry weight. It appears that the most succulent plants are those growing under the control conditions. Could this be due to the influence that radiation has in influencing the intercellular structure of the leaves? Future investigation using cross-sections of the leaves would indicate the differences in cellular structure.

Vapor-pressure variation affects the radiation loss from the soil (Puckett, 112), and the thermal conductivity is higher on wet soils than it is on dry soils (Nicholas, 97).

Most references in the literature regarding the relationship of intake of salts vs. water intake indicate that no apparent relationship exists between these two phenomena; however, since more ash and total nitrogen were measured in the radiated plants over the control plants in these experiments, two references in partial support of the theory that the higher water intake influences the increased intake of solutes are offered. Sorauer (121) found that the pea plants growing in a dry chamber had a slightly greater dry weight and ash content than similar plants growing in humid chambers. Muenscher (93) obtained 5 percent less ash in plants growing in rooms where the transpiration was reduced one-half. This, he remarks, still is not significant. However, it seems, there might be some slight effect on the ion intake from an increased absorption of water which is not normally present under the usual type of experimental designs.

Plant Movements

The Red Kidney bean showed some diaphototropism; i.e., the plants bent their leaves in the direction of light. This was evident in the early hours of the day when the leaves were facing the eastern sky. The effect was most pronounced when the light was in the most unilateral direction--i.e., when the light on one side was more intense than in any other direction.

The experimental bean plants used in the cold storage rooms also responded in a different way. The lights used, 300 candle-power in the 1949 season and 240 candle-power during 1950, seemed to cause the plants in the control room to face toward the two sides on which these lights were placed. In the radiation room the leaves were more or less at right angles to the direction of the radiation source. It appeared that the radiant heat source might have had a tropic stimulus on these leaves in much the same way that the lights have in phototropism.

Boysen-Jensen (18) showed that phototropism was the result of the unequal stimulus of auxins, or plant hormones, which tend to migrate to the shady side of the stem. These hormones cause a more rapid growth on the side away from the light and thus cause the stem to bend in the direction of the light. Auxins in plant tissues can be inactivated by light of high intensity (Burkholder and Johnson, 29). The shorter waves are the most efficient in causing this inactivation.

The horizontal placement of the Red Kidney bean leaves in the radiation room probably indicates that the radiation from the heater causes some destruction of these hormones.

It appears that there might be a two-fold reaction to radiant energy. First, it seems to stimulate the leaves already formed and give them a very healthy and vigorous green appearance; and, second, it inhibits the terminal growing point which at certain times, especially when the plants are young, become chlorotic in appearance (Figure 50). This may indicate the reaction of two different types of growth substances. This inhibitory type of growth cannot be associated with any similar response typical of that produced by various colored lights. This growth looked more like the reaction to blue light, however, the internodes that developed were normal in length. The main conclusion that can be arrived at is that the plants just did not grow as fast, and that the slow growth may have been due to such reactions as the probable lower temperature of the stem, injury to the growing point, the higher osmatic pressure (which undoubtedly existed at this point) which can inhibit meristematic growth (Hayworth and Spurr, 69), or the lower carbon dioxide content which could have existed. If any injurious gases were present there was no way of detecting their presence. The leaves on the radiation plants were thicker, and the stimulus of the radiant heat probably diverted part of the nutrient of the plant to form added palisade layers rather than for use in the meristematic region of the growing point. This thicker palisade layer is described by Turrell (133), who describes how plants developed a significant degree of xeromorphy under high light intensities.

Goodwin (56) found that light inhibits the length of growth of the first internode of Avena sativa. However he found no inhibition in the infra-red wave band longer than 1.6 microns at the intensities used. Later the same investigator found that the greatest inhibition was found in the visible yellow and red light (Goodwin, 57). The wave band used in these experiments centered around the four micron wave length with a broad spread extending from at least 1 to 10 or 20 microns.

SUMMARY

1. Radiant energy was used from a cromolox heating element to heat plants above the surrounding air temperature. A plant whose temperature requirement was high, such as the Red Kidney bean, which requires a 60° F. night temperature for optimum growth, was found suitable for most of the radiation studies.

2. Radiant energy can be used to heat the leaves of Red Kidney beans to a temperature of 20° F. above the average room temperature in which they are growing when 60° F. is used as the standard leaf temperature at a distance of 14 inches with the elliptical designed reflector and 24 inches with the parabolic reflector.

3. When the analysis was made of the plants growing under radiant conditions and those used as control plants, an increase of ash and total nitrogen was indicated in each case; this increase may have been due to the greater intake of water and to the fact that some of extra nutrients in the soil may have entered the plant with the extra water absorbed.

4. No significant difference in vitamin C or chlorophyll content was found when the analyses of the radiated and control plants were compared on a dry weight basis.

5. Red Kidney beans grown under radiant energy displayed a dark green, flat, smooth leaf in a more or less horizontal position, while the control plants at the same age of growth

were curled, bumpy and tended to face sidewise in the direction of the two panels of light. Terminal growth of the plants in the radiated group was partially chlorotic and stunted in appearance and the growing point of this group did not develop as fast as those in the control room. This difference in growth may have been due to a difference in temperature existing at those points and the uninterrupted presence of radiant energy.

6. Both the 300 and 240 foot-candles of light intensity proved adequate for the needs of plant growth in these experiments, although more illumination might have proved better. The daylight fluorescent tubes gave off a negligible amount of heat--warming the plants approximately 1° F.

7. Automatic equipment for the heating of Red Kidney beans proved successful. When the circular-chart pneumatic-potentiometer controller was activated by a stimulus from a thermocouple located on the under surface of a selected leaf, it controlled the variac through a motortrol giving the required amount of voltage to the electrical heating rod. The temperature variation was about 2° F.

8. The elliptical reflector gave the best distribution of energy but could not be used at sufficient distances to eliminate the deleterious effects associated with the disproportional degree of heating occuring at close distances.

9. The total height of radiated plants was less in all lots, although the length of each internode approached a

condition approximately normal. The radiated plants developed fewer internodes than the control plants.

10. The thermocouples made from soldering the copper and constantan wires with silver end to end proved very successful, easy to use and accurate.

11. Red Kidney beans proved to be a particularly valuable plant for such radiation studies because of its sensitiveness to temperature changes and the ease of growing seedlings that are suitable for selection purposes.

FUTURE SUGGESTIONS

The use of radiant energy to heat plants to a temperature of 20° C. above air temperature does not look promising when viewed from the results of this thesis. It was justified, however, in this case, to determine what effects such a temperature differential would have on plant material.

It is suggested that a temperature differential of 10° F., such as is commonly observed in the greenhouse on most plant material, be used in future research which may have practical applications. If the plants which demand a 60° F. night temperature could be grown in a greenhouse heated to 50° F. by usual means, with an extra 10° F. supplied by radiant means, and if this job could be done more economically than heating the same greenhouse to 60° F. air temperature, it would be considered practical means of heating providing the cost of installation would not be prohibitive. The fuel bill of heating greenhouses in Michigan to 60° F. is approximately twice the cost that of heating the same greenhouse to 50° F.

Heating plants at close distances, as was necessary in the present experiments, created several undesirable features in which the temperatures varied greatly from one part of the plant to the other. Future heating from radiant sources should make use of greater distances, and ultimately the farthest distance possible in a greenhouse--under the ridge of the greenhouse. The distance of the sun, 93 million miles, is ideal because it heats all parts of the plants, equally exposed, identically.

Electricity, as a source for radiation, is still too expensive to compete on an equal basis with coal or oil. In the present studies it was the only available means of controlling radiation for experimental purposes. However, future control may be obtained by other methods. The most promising, still in the theoretical and untried stage, is radiation from the flow of a liquid[1] heated to a temperature of 500-600° C., circulated by means of a pump, and heated from a central location by whatever fuel is most economical.

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1. A "liquid-metal coolent" is referred to, as well as a sodium-potassium alloy used at Oak Ridge National Laboratory which melts at 59° F. Gallium melts at 86° F. and boils at 3600° F. If a metal is needed to resist high temperatures, molybdenum, with a melting point of 4750° F. or an alloy made from it could be used.

The conduit for such a flow would have to extend from one end of the greenhouse to the other; it would have to be heavily insulated on the top to prevent heat loss and scientifically shaped on the bottom with the proper convex curvature, to insure equal distribution of radiant energy to all parts of the greenhouse. Commercial preparations on the market--like gallium or some alloys--may be suitable to find application in such a system.

Air circulation should be studied to insure the efficiency of radiant heating. An ingenious method was used by Gray (60, 62) to detect air movement in the greenhouse. By this means it might be possible to minimize unwanted air circulation. Freeland (52) suggests one method of controlling circulation which might be modified for these experiments.

Radiant energy experiments carried on without solar radiation should be supplied with ample light. Illumination of 600-1000 foot-candles of daylight fluorescent or white fluorescent light is suggested, especially if the plants used are to be grown to maturity. It is desirable to measure and control the CO_2 concentration in order to remove it as a controlling factor in plant studies under higher intensities of illumination.

Refrigeration should be constant and controllable. Besides modification of the present system, two other methods might be used which would be suitable for radiation studies.

First, air that is conditioned to the proper temperature, humidity, and, if need be, CO_2 concentration could be introduced by means of ducts with suitably baffled outlets. Second, refrigeration could be obtained by means of a radiant cooling system mounted behind a highly emissive ceiling or wall and with ample insulation to the outside air. This system should give a theoretically even distribution of cooling, especially if placed in the ceiling, with little air movement other than the normal convection currents.

The vapor-pressure deficit should be controlled. Wallace (136) suggested a simple and effective humidity control which consisted of a radio-grid actuated by a humidistat. The most suitable humidistat available is probably the electric hygrometer. Its accuracy is much greater than that of the design based on the expansion of the human hair.

If a more highly efficient source of radiant energy is desired other than the type emitted by a heated metal (black body type), there is the possibility that future developments of suitable filtering devices may provide a higher concentration of energy to plants. With their use a higher temperature emitter could be used similar to zirconium--one of the most concentrated forms of radiant energy that is used in industry. Becker and Fan (15) have tested the optical properties of different metals and report that both germanium and especially silicon transmit a large quantity of infra-red rays in the near infra-red region of the spectrum. A filter made of

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If it is desirable to study the effects of a narrow band of any particular radiation, it now seems probable that the newly described interference filter will be suitable to studies of the effect of visible light on plants and probably could be likewise adapted to studies of the effect of infra-red radiation. Because of the narrow band of emission it would not be considered an efficient type but rather one that could be used to tag, so to speak, the effects of each distinct band in the spectrum.

If the effects of radiation are to be studied in the greenhouse, it is necessary to determine the amount of solar illumination falling on the plants being studied. To ascertain the amount of solar illumination at Ithaca, New York, Post and Nixon (106) built a graphic light meter which recorded light from ½ to 10,000 foot-candles continuously throughout the day and year. Another method of determining the accumulative effect of light over the entire day is based on the light chemical reaction of oxalic acid-uranyl sulphate by ultra-violet light (6).

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