ARTIFICIAL ENVIRONMENTS FOR PLANT RESEARCH

by

JONATHAN STEPHEN GIBSON

B.Sc., Washington State University, Pullman, Washington, 1967

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in the Department of

Plant Science

We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

January, 1972

Department of Plant Science

The University of British Columbia
Vancouver 8, Canada

Date April 29, 72

ABSTRACT

A review was made of environmental technology as applied to the engineering and construction of artificial environments for plant physiology research. The results of this study were utilized in the development of an artificial environment which incorporated the nutrient mist technique of growing plants.

The quality of the environment in plant growth chambers is partly dependent on the type of control instruments used. Solid state electronic control devices offer many advantages, particularly with respect to accuracy, responsiveness, reliability and remote control.

A travelling sensor was developed to detect the environmental conditions within artificial environments by remote control. This sensor greatly increased the rapidity and convenience of measurement with minimum disturbance of the environment.

The conditions of light intensity, temperature, wind speed and humidity within a commercial growth chamber, the Percival Model PGC-78, were analysed. The results indicated that the chamber's performance was quite nonuniform for all the variables tested. The manufacturer's specifications for the chamber were considered to be limited in extent and to some degree misleading.

The design of the artificial environment system constructed for this project is described. With this system, temperature control of $\pm \frac{1}{2}^{o}C$ was achieved within the plant growth area. In addition, the uniformity of light intensity and air flow in the constructed chambers was superior to the PGC-78.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figures

Figures

Figures

PREFACE

This project served as a stage in a continuing research programme aimed at developing an enclosed, accurately controlled, artificial environment for plant growth. The ultimate goal is a system which provides a wide range of uniform light intensities, air circulation velocities, temperatures and humidities, any combination of which is programmable by the operator. This work represents an attempt to reduce environmental conditions as uncontrolled variables in experiments on the physiology of plant growth.

To approach this objective, a review of the components in an artificial environment system was made and is presented in Chapter I. This review provides fundamental information concerning the design and structure of plant growth chambers. In Chapter II, some instruments for controlling, indicating and recording environmental variables in plant growth chambers are described. A special technique for measuring the physical components of the internal environment of growth chambers is also described.

A detailed study of the performance of a commercially manufactured growth chamber (Percival Model PGC-78) was carried out and is reviewed in Chapter III. The Model PGC-78 chamber approached the performance levels specified by the manufacturers. Nevertheless, several major deficiencies in environmental quality were evident, and the chambers were considered to be unsatisfactory for critical research on many aspects of the physiology of plant growth. For this reason, it was decided to design and construct a new laboratory plant growth chamber.

The design of the laboratory growth chamber is described in Chapter IV. This system was intended to provide improved uniformity and control of environmental conditions.

In developing the laboratory system, it was necessary at the outset to define the quality of environmental control which the system should possess. The requirements for environmental control and uniformity are largely dependent on the types of future research contemplated. It was expected that the system would mostly be applied to studies of the effects of environmental conditions on the growth and gas exchange of shoots and roots of small plants. Growth chamber performance criteria was therefore developed in the following way from known information on the effects of environmental conditions on the components of growth and gas exchange.

Studies with many different plant species have shown that the rates of growth and net photosynthesis can change by as much as 5% of the maximum rate if the light intensity is varied by 1000 lux or if the temperature is varied by $1^{o}C$ (Cooper and Tainton, 1968). Very little information is available on the direct effects of wind speed and humidity on growth. At low air velocities (i.e. between 10 and 80 fpm), a 10 fpm change in air velocity may cause as much as a 10% change in the rate of transpiration of sunflower (Martin and Clements, 1936). Also, psychrometric tables indicate that, for example, at initially 60% R.H., $26^{o}C$ dry bulb, a 1% change in relative humidity could change the atmospheric water vapour pressure surrounding the leaf by 10%. While these examples omit the interactions between different environmental variables, they provide an estimate of the scale of environmental change which may cause significant effects on growth.

It was therefore decided that satisfactory environmental control would be provided by a chamber with the following capabilities: temperature control to within $\pm 1^{o}C$ and a temperature range of $5^{o}C$ to $35^{o}C$; light intensity range from 0 to 40,000 lux with less than 1000 lux nonuniformity; average air velocity variable from 20 to 100 feet per minute with a uniformity of ± 10 fpm; and humidity control and stability to ± 1% relative humidity, variable from 20 to 95% relative humidity.

The system described above would permit the study of intact, whole plants where leaf chambers and excised tissue are presently utilized. The addition of the nutrient mist technique provides a system easily adapted for nutrient studies and for studies of the differences in root and shoot respiration and development. Such a system would provide environmental control adequate for a wide range of studies on the physiology of plant growth.

Chapter I

ARTIFICIAL ENVIRONMENT DESIGN

INTRODUCTION

The basic purpose of a plant growth chamber is to provide environmental conditions similar to natural conditions which are reproducible, and which can be varied at will. For this, a light system of adequate intensity and spectral quality, as well as mechanisms for the control of root and shoot temperature and humidity are required. The type of research contemplated, the size and number of plants involved, and the limitations of laboratory facilities must be considered in the selection of the physical components of a plant growth chamber.

The size of controlled environmental facilities built for the study of plants has ranged from multistory buildings to small desk top chambers and leaf chambers. Interest here will be centered on what are usually referred to as plant growth chambers, which have an interior usable plant platform from seven to twenty square feet, and a distance of about four feet between the plant platform and the light canopy.

The environmental conditions which can be produced by artificial systems are limited and differ from natural conditions. This difference lies in the complex interactions of natural environmental variables, and in the physical size of the natural environment relative to a closed chamber. The complexities of the natural environment are fairly well understood, but the equally complex interactions of the components of an artificial environment must be known before desirable performance can be achieved. The following discussion will consider some factors involved in incorporating mechanical and electrical devices into a plant growth chamber.

(A) Light System

A light system in a plant growth chamber must possess adequate and uniform light intensity and spectral quality on a horizontal plane, and as small an intensity gradient vertically as is possible. It must have photoperiod control, and should not emit excessive heat or harmful radiation.

The natural source of radiant energy for plant growth is the sun. However, the atmosphere filters out certain wavelengths to yield a spectrum as in Figure 1-1. Also shown for comparison are the spectra of incandescent and fluorescent lamps (Figures 1-3, 1-8) and the action spectra of photosynthesis, phototropism, and phytochrome (Figure 1-2). Usually, a combination of incandescent and fluorescent lamps are used as a source of light for plant growth. This combination most practically satisfies the light quality and intensity requirements of plants as represented by the above action spectra. The following discussion of artificial light sources will demonstrate their difference from sunlight and will indicate some of the problems of light system design in a plant growth chamber.

The spectral energy distribution of a Cool-White fluorescent tube shows a peak emission at 580 nanometers with a secondary maximum at 475 nanometers. The output is very low at 700 nm (Figure 1-3) (General Electric, 1960). As with all fluorescent lamps, intermittent operation shortens lamp life appreciably. Figure 1-4 shows percent of burnouts of fluorescent lamps plotted against percent rated lamp life (General Electric, 1960). The initial light output is variable from lamp to lamp, and this value may decrease rapidly during the first one hundred hours of operation. The lumen depreciation may amount to as much as ten percent in this period. For commercial rating purposes, the one hundred hour value is used as the initial

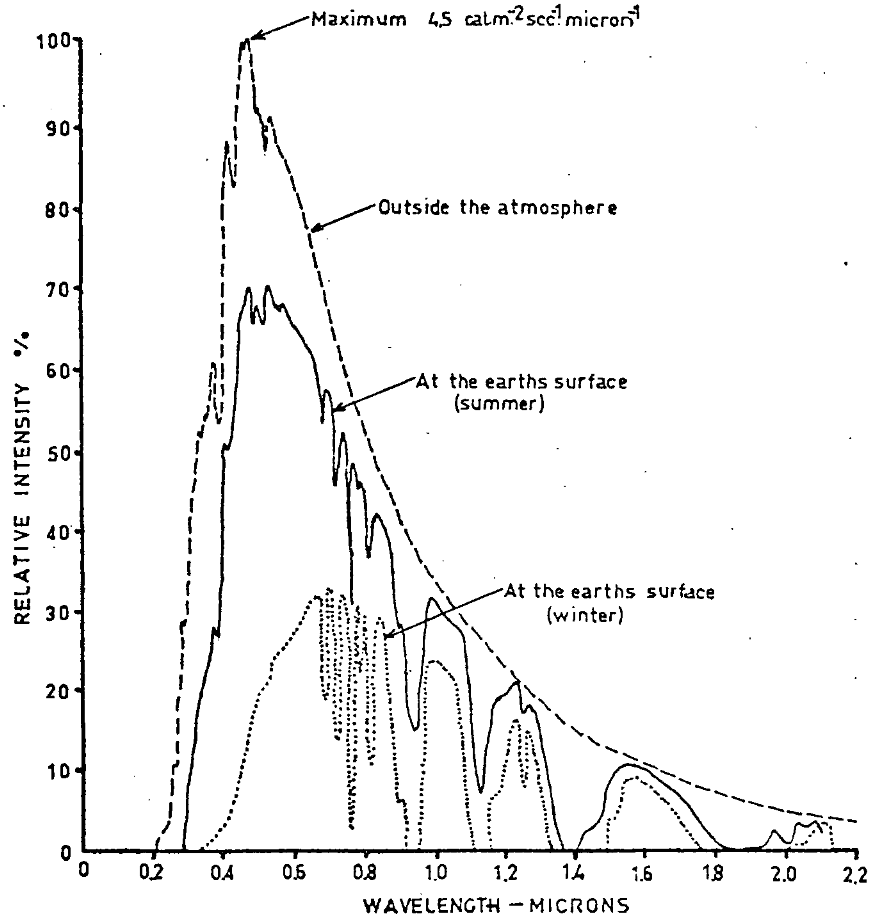


Fig. 1-1 Spectral energy of direct solar radiation intensity at normal incidence for the upper limit of the atmosphere and at the earth's surface during clear days.

THRELKELD, 1970.

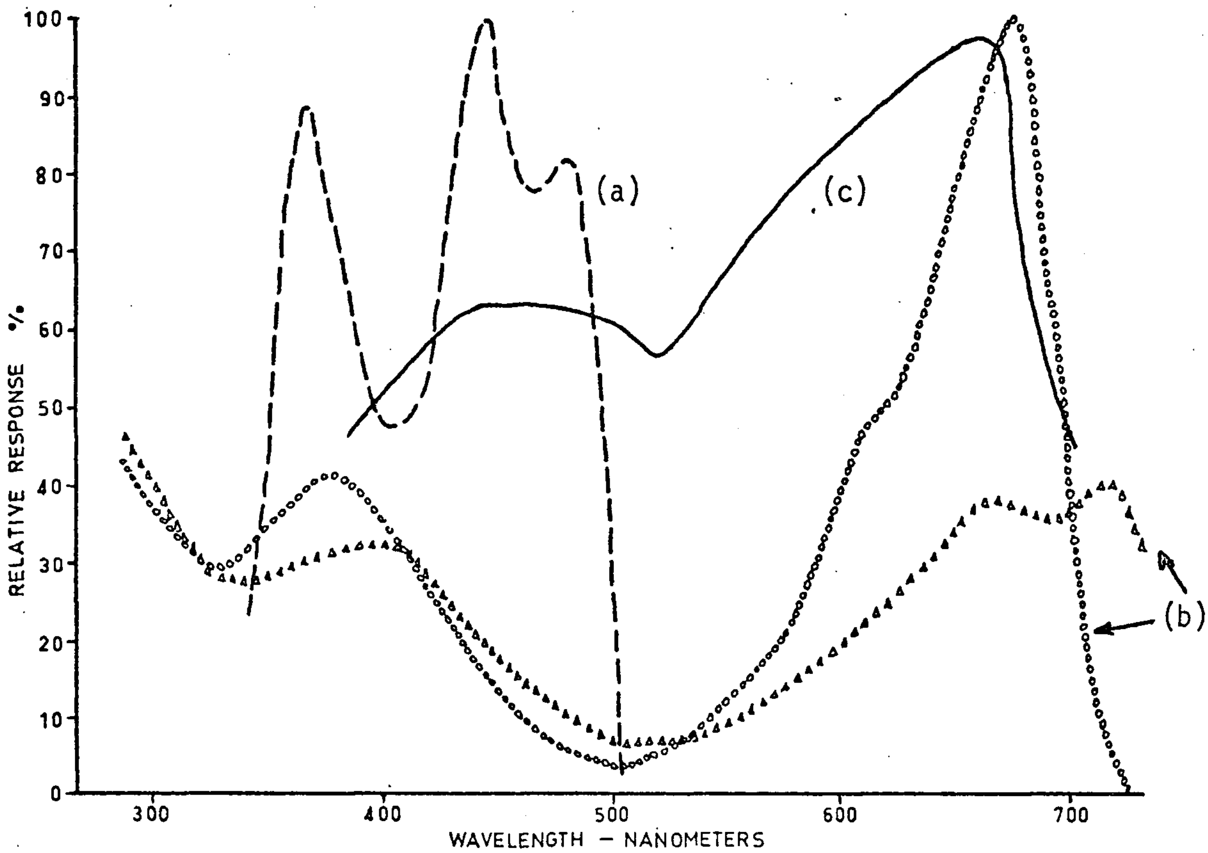


Fig. 1-2 Action spectra of phototropism (a), phytochrome (b), and photosynthesis (c).

((a), (b) Salisbury & Ross, 1969;
(c) Bulley et al, 1969).

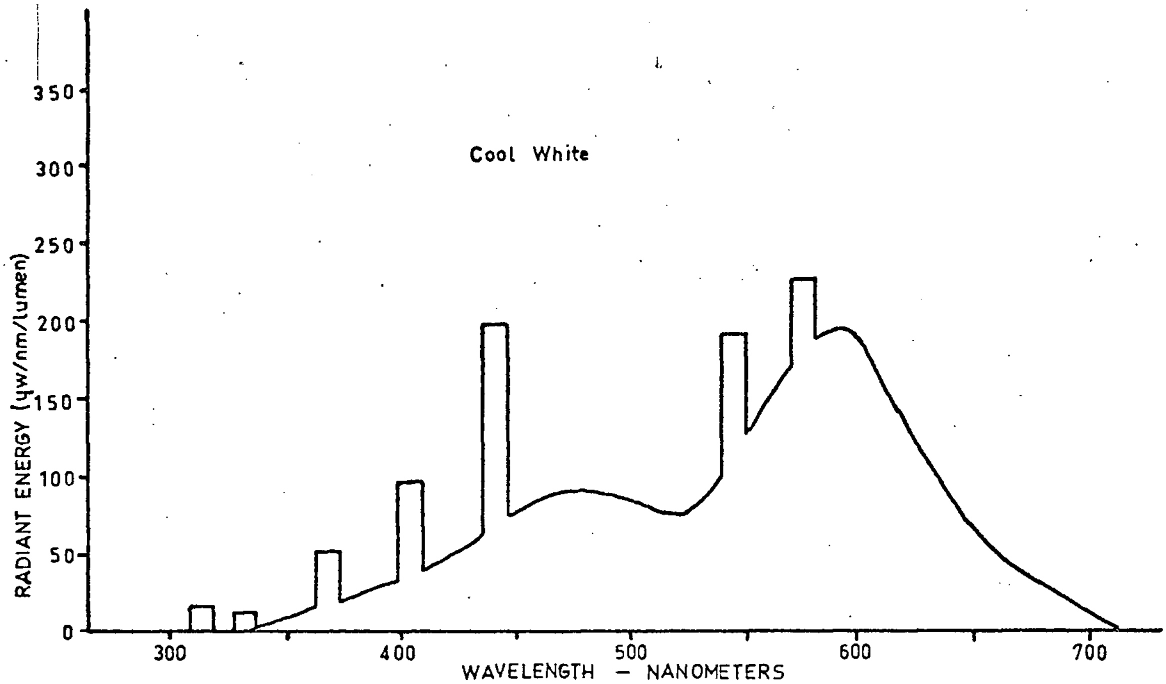


Fig. 1-3 Emission spectrum of a cool white fluorescent lamp.

(General Electric, 1960)

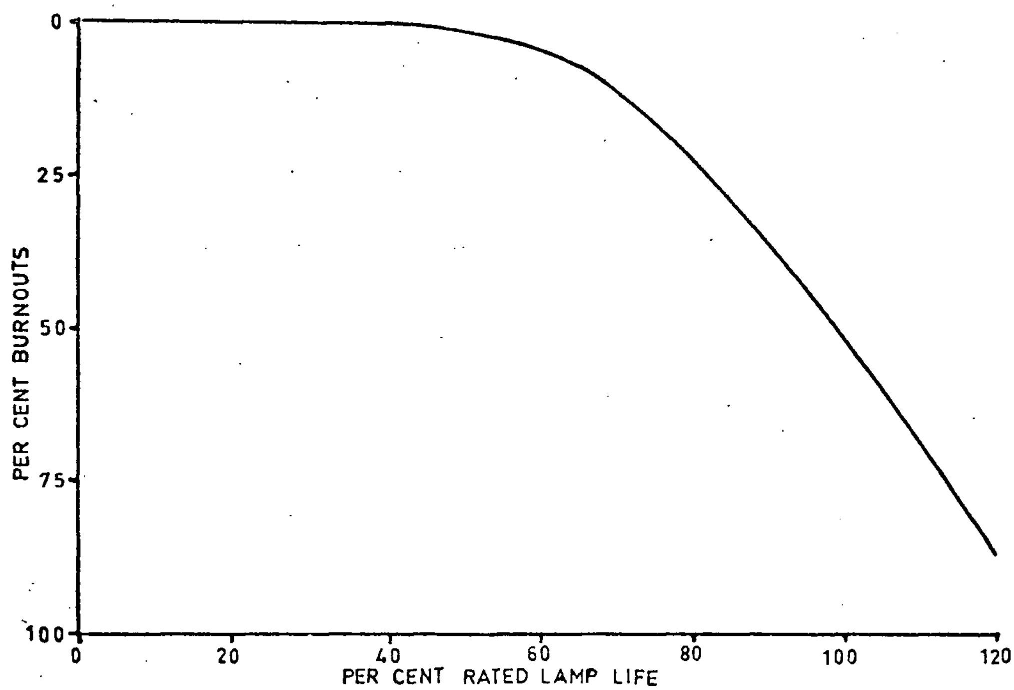


Fig. 1-4 Mortality of fluorescent lamps as a percent of rated lamp life.

(General Electric, 1960)

value. Figure 1-5 shows typical ranges of fluorescent lamp depreciation in light output with respect to time (General Electric, 1960). A typical Cool-White fluorescent lamp will emit twenty-one percent of the input electrical energy as visible light, thirty-four percent as infrared radiation, and forty-five percent of the input as dissipated heat (Figure 1-6) (General Electric, 1961). The luminous efficiency of a Cool-White fluorescent lamp ranges from seventy-five to eighty lumens per watt. By comparison, general service incandescent lamps may range from twelve to twenty-two lumens per watt (Sylvania, 1962). The optimum pressure for maximum light output for most fluorescent lamps occurs when the coolest spot on the bulb surface is about forty-five degrees Centigrade. The bulb wall temperature is affected by lamp wattage and bulb diameter, by the design of the bulb itself, and by the ambient temperature and draft ventilation conditions (General Electric, 1960).

A forty watt incandescent lamp requires about .34 amperes, gives an initial lumen output of approximately 460, and has a rated average life of 1000 hours. For such a forty watt incandescent bulb, 7.4 percent of the input energy is radiated as visible light, 63.9 percent as infrared, giving a total of 71.3 percent. A twenty percent loss of input energy is caused by convectional flow of the filling gas in a stream past the filament (Figure 1-7) (General Electric, 1960). Conduction of heat through the bulb and base of a forty watt bulb represents an 8.7 percent loss of input energy. Of all standard incandescent lamps, the forty watt bulb is the least efficient emitter of visible energy, but also emits the least amount of infrared radiation. The spectral distribution of a typical incandescent bulb is given in Figure 1-8 (General Electric, 1961). Reflector

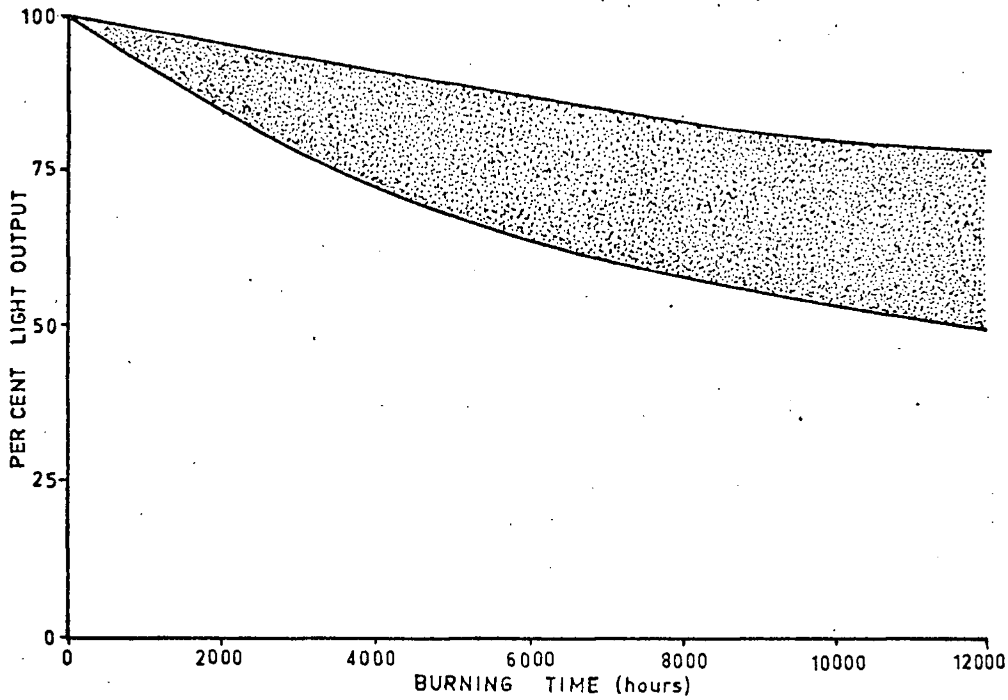


Fig. 1-5 Typical range of fluorescent lamp depreciation with time. (General Electric, 1960)

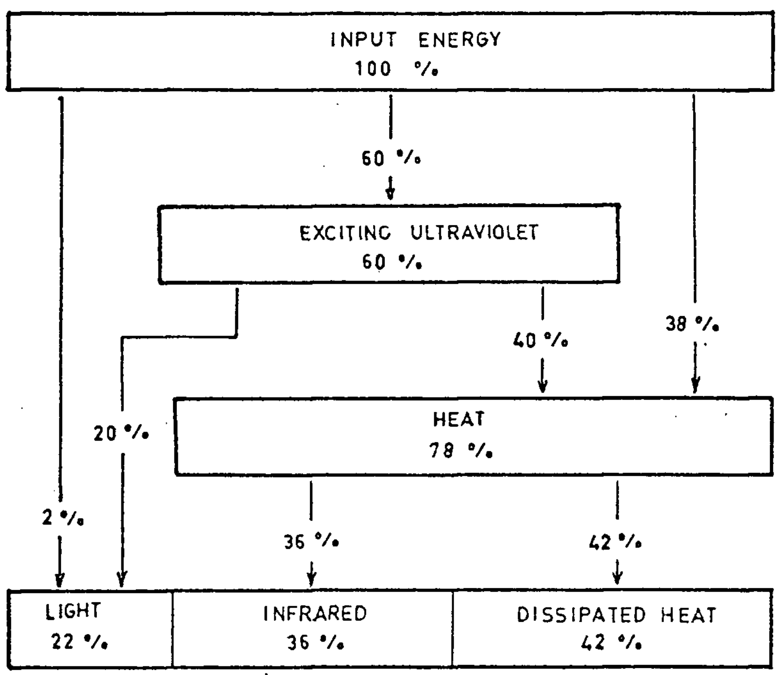


Fig. 1-6 Energy distribution of a typical cool-white fluorescent lamp. (General Electric, 1960)

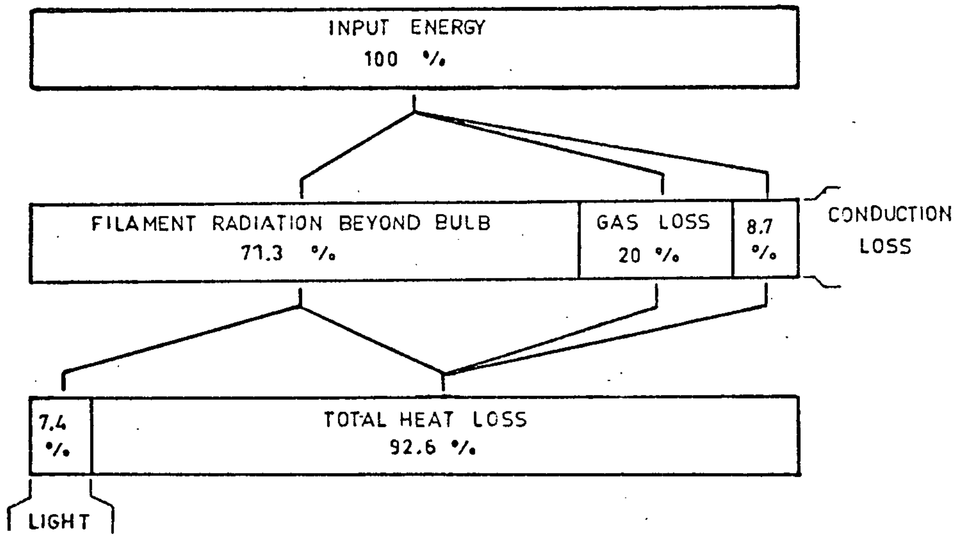


Fig. 1-7 Energy distribution of a typical 40 watt incandescent lamp. (General Electric, 1960)

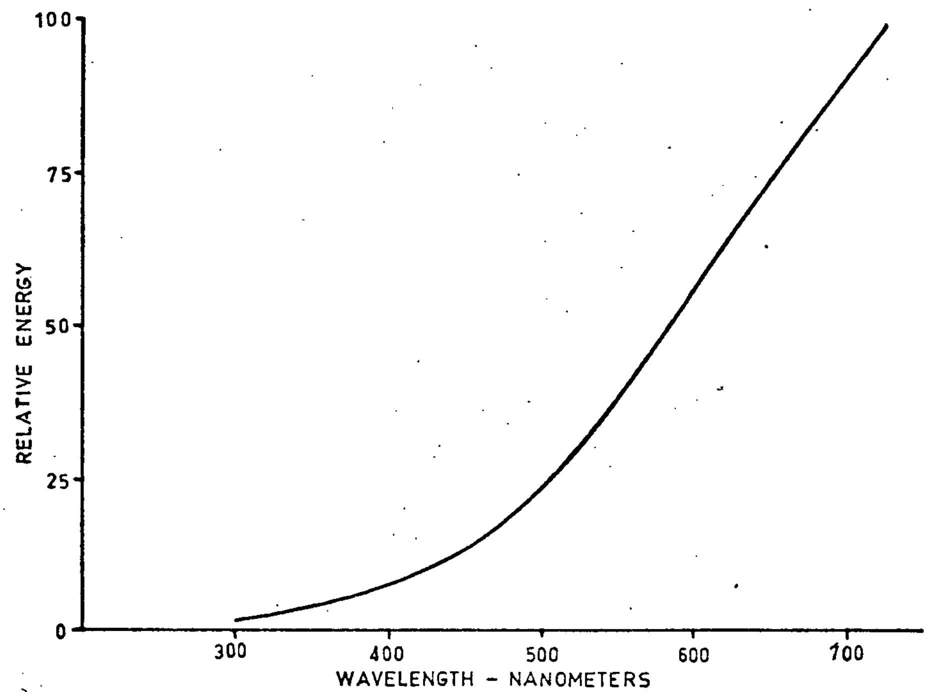


Fig. 1-8 Spectral energy distribution of a typical incandescent lamp. (General Electric, 1960)

bulbs which tend to focus the light and create uneven intensity are not as suitable for plant growth chamber applications as non-reflector bulbs.

In natural conditions, the negligible change of light intensity from the soil surface to the top of a plant (assuming no absorption by the plant) is a function of the distance from the earth to the sun, assuming clear atmospheric conditions. In an artificial environment, the light source may initially be about four feet from plants. As the plants grow towards the light system, they are exposed to gradually higher and higher light intensities. Vertical light intensity gradients can be partly reduced by making all the wall panels and light support surfaces as reflective as possible. Clear baked enamel finishes (high gloss) can approach 95 - 98% reflectivity (General Electric, 1960). With the use of such reflective materials, a more uniform vertical light intensity pattern can be obtained in the plant growth area (Kalbfleisch, 1963). It is usually expensive to design a plant growth chamber with an extremely low vertical light intensity gradient. Any objects in the chamber, including plants, shelves, pots, and instruments, disturb the uniformity of light intensity. Special designs are available if uniform vertical light intensity is important (Controlled Environments, 1970).

The uniformity of light intensity on any horizontal plane between the plant platform and the light canopy is determined largely by the position, dimensions and wattage of the lamps used. Reflective walls may influence horizontal uniformity, depending on how the chamber is constructed. Kalbfleish (1963) has published extensive measurements on a variety of lamp canopy arrangements using various lengths of fluorescent lamps spaced from 1/8 inch to several inches apart. A typical chart (Figure 1-9) indicates that the center of the horizontal plane 24 inches below the light canopy had the highest light intensity which decreased in light intensity towards the sides of the canopy. Figure 1-10 demonstrates the influence of a 24 inch long highly reflective curtain mounted around the perimeter of the same lamp canopy used in Figure 1-9. Measurement distance from the canopy was again 24 inches. It is clearly evident that the reflective curtain produces more uniform intensity.

The light intensity to which a plant is exposed in a small plant growth chamber can be varied by moving the plant closer to the lamp canopy by means of movable shelves. Alternatively the lamp canopy may be mounted on a pulley system, allowing the light intensity to be adjusted without moving the plants. Moving the lamp canopy or plants may change the air circulation and heat transfer in the chamber and thus may require a change in temperature and humidity control settings. Moving the lamps or plants are the most commonly used techniques for varying light intensity in commercial plant growth chambers.

Another method is to vary the intensity of the lamps themselves. A special ballast is required to vary the intensity of fluorescent lamps. This ballast is expensive and limited to lower wattage lamps seldom used in plant growth chambers. The intensity of incandescent lamps can be varied by a series potentiometer. This method is less satisfactory since several additional electrical components are required and uniform spectral quality cannot be maintained.

Photoperiod control is generally provided by on/off switches driven by 24-hour clocks. To simulate natural conditions, several clock-switches may be used to switch on and off both the incandescent and fluorescent lamps.

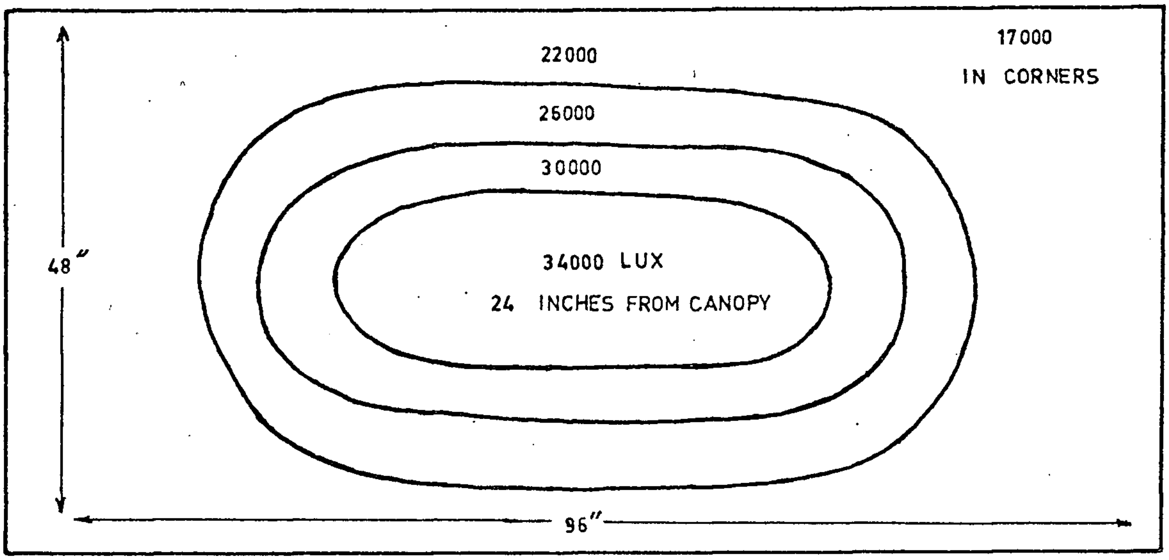


Fig. 1-9 Horizontal light intensity distribution 24" below an uncurtained light canopy of fluorescent lamps.
(Kalbfleisch, 1963.)

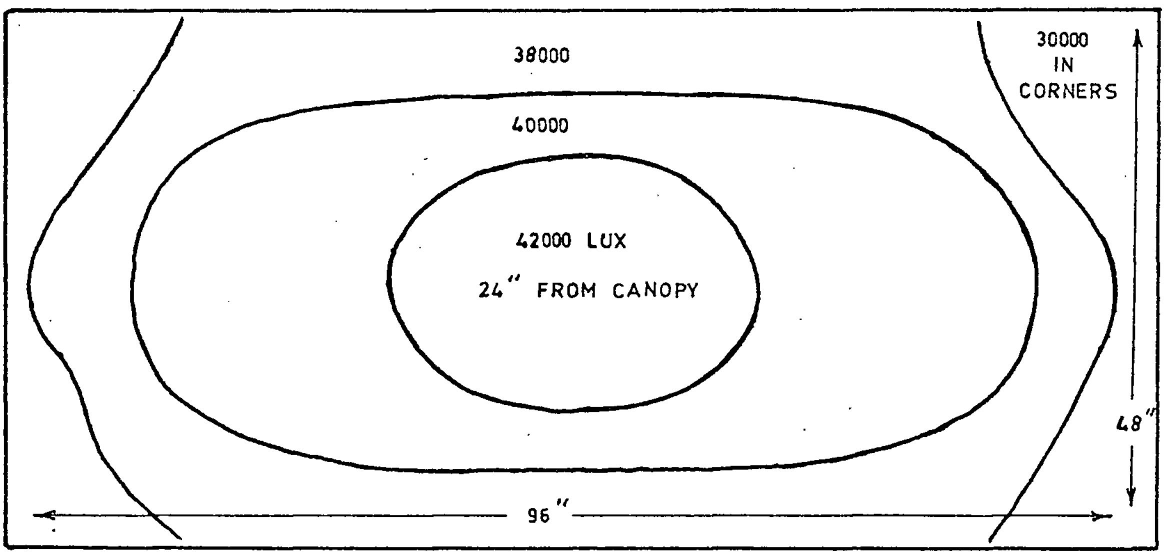


Fig. 1-10 Horizontal light intensity distribution 24" below a curtained light canopy of fluorescent lamps.
(Kalbfleisch, 1963.)

Lamp canopies for plant growth chambers can consume several thousand watts of power. The influence of the heat input from the lamp canopy on other environmental variables in a chamber is important and will be discussed later.

New lighting systems and lamps now being developed may greatly improve lamp canopy performance for plant growth chambers. Newly developed high intensity lamps using mixtures of sodium, mercury and other gases produce sun-like emission spectra (Phillips, 1969). Any lamp of suitable intensity and spectrum for plant growth that reduces infrared output would considerably simplify plant growth chamber design.

(B) Temperature Control

The temperature control equipment of a plant growth chamber must provide reproducible control, and must not cause erratic changes in the other environmental variables. The temperature range of general purpose plant growth chambers usually extends well below and above the optimum growth temperatures for plants, typically -10^{o} to $50^{o}C$. The precision and reproducibility of temperature control in the chamber depends on the sensitivity and location of the control device, the selection of heating and cooling elements, the rate of flow and volume of air circulation, and the variations of the heat load within the chamber. The uniformity of air temperature depends on the air circulation patterns within the plant growth area and the effects of the light canopy.

Three types of temperature control are commonly encountered. The simplest is the constant temperature type, which maintains temperature close to a single control point. Second is the diurnal type, in which the day temperature is different from the night temperature. Thirdly, a temperature programmer may be utilized to simulate natural temperature cycles. A discussion of instruments to implement the three types of temperature control is contained in Chapter II.

In order to control temperature in a plant growth chamber, moist air must be heated or cooled to a predetermined control point. Some aspects of these processes can be visualized with the aid of a diagram such as Figure 1-11 which shows the various processes occuring when chamber air flows through a conditioning system. In this case, only a cooling element is in the conditioning system; ma_1 is the mass of air in pounds entering the conditioning section which is equal to ma_2, the mass of air leaving, and re-entering the plant growth area.

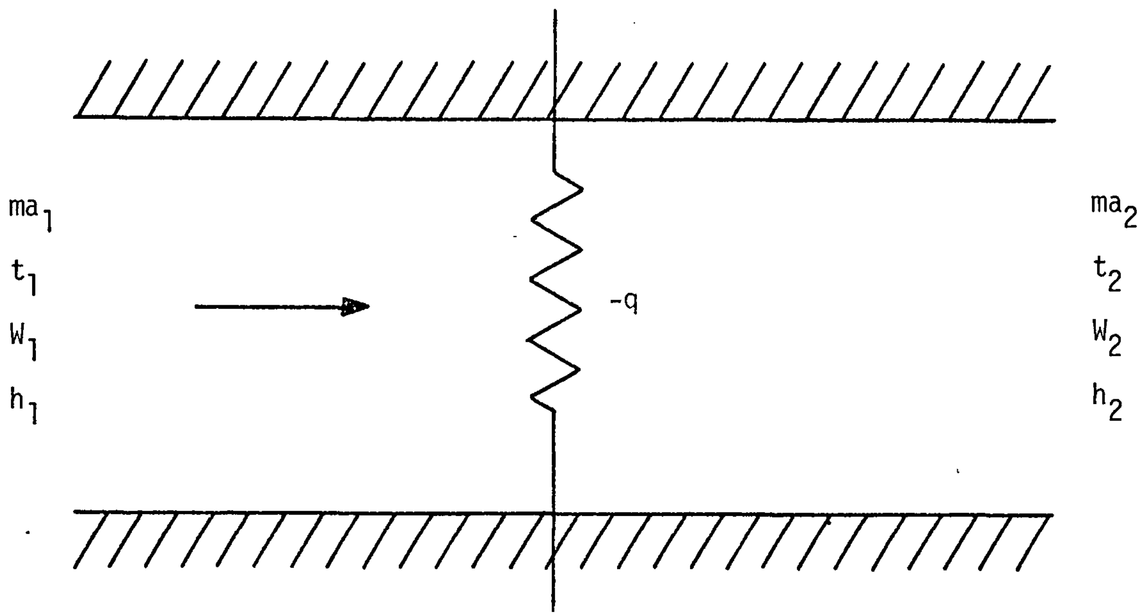


Fig. 1-11 Processes occuring when cooling air in a conditioning system.

Air enters the conditioning section at temperature t_1 and leaves at t_2. The entering and leaving humidity ratios (lb. of water/ lb. of air) and enthalpies (BTU/lb. of air) were W_1, W_2 and h_1, h_2 respectively. The heat added to or subtracted from the air stream is represented by q (BTU). Unless the control point is changing, entering air will be warmer than air at the exhaust of the conditioning section due to the positive heat load of the lights and other equipment in the chamber. The humidity ratio W_1 will be equal to W_2 if no water condenses on the cooling coil or is added to the air stream. The enthalpy change between the inlet and exhaust depends on the change in temperature and humidity ratio. For the sensible heating or cooling of moist air (not involving the addition or subtraction of water) the following heat transfer equations summarize the possible conditions of Figure 1-11 (Threlkeld, 1970).

$$ma_1 = ma_2 \qquad (1)$$

$$ma_1h_1 + q = ma_2h_2 \qquad (2)$$

$$ma_1W_1 = ma_2W_2 \qquad (3)$$

$$q = ma(h_2-h_1) \qquad (4)$$

and if $W_1 = W_2$

$$q = ma(0.24 + 0.45W)\ (t_2-t_1) \qquad (5)$$

A pound of dry air at 50% relative humidity and a barometric pressure of 14.696 Psia will have a volume of 12 cubic feet at 16°F and a volume of 14.5 cu.ft. at 98°F (General Electric, 1957). Therefore, if a fan circulated 1000 cfm at all temperatures and humidities, a greater mass of air would be circulated at lower temperatures than at higher temperatures. Changes in air mass will cause changes in fan power requirements. One wonders whether this effect should be considered in plant growth chamber research. At any temperature, and if $W_1 = W_2$, the amount of head added to or subtracted from air by the conditioning process equals the product of the mass of air circulated per unit time and the change in enthalpy of the air as it passes through the conditioning elements. Also, if $W_1 = W_2$, q will equal the product of the mass of air circulated per minute times a fixed coefficient related to humidity ratio times the temperature difference across the coil (Equation 5). For the transfer of sensible heat, Equation 5 allows the calculation of the heat transfer required to balance the heat load of the chamber. The value calculated will be the theoretical quantity of heat exchanged in a given conditioning process. In practice, however, the heat required will differ from q since a cooling coil is not a perfect heat transfer system. An ideal cooling or heating element would have low thermal resistance, extensive contact with the air moving through it, uniform temperature across the entire surface area of the element, and large face area relative to the volume of air circulated. The properties of a real cooling coil will be discussed later (Page 20), since humidity changes almost always accompany the operation of a cooling coil.

Two heating and cooling methods are commonly used on plant growth chambers. The first system involves a refrigerated cooling coil and a separate heating element. When cooling is demanded, the compressor of the refrigeration system is activated and the heating element is turned off. The reverse occurs during the heating cycle. If the heating and cooling elements are closely matched in their rate of heat exchange, satisfactory operation can result. However, there is a tendency for the thermal resistance of the heating and cooling elements to cause overshooting of a control point. If the overshoot and undershoot variations about a control point are sufficiently small, the problem can be ignored. Figure 1-12 shows how heating and cooling rates might vary with time in respect to a given control point and a desired ± 1/4^{o}C control. The efficiency of heat transfer of a heating or cooling element varies with temperature. Consequently, over the full temperature range in a plant growth chamber, the relation of the rates of heating and cooling may vary. It is possible to calculate whether the rate of either heating or cooling may be too great and cause overshoot (Threlkeld, 1970). Direct experimentation, however, is usually relied upon in prototype stages to discover undesirable performance. In practice, the air temperature is measured at a location sufficiently past the heating and cooling elements so that remixing of the conditioned air stream is nearly complete and before the influence of the chamber heat loads. A typical heating and cooling system is shown in Figure 1-13. In Chapter II, the importance of sensitivity and response time of the device controlling the heating and cooling elements will be discussed.

A conditioning technique more recently incorporated in plant growth chambers is the hot-gas bypass system (Figure 1-14). The differences from the preceding system are that the compressor operates continuously and the hot or vaporized gas in the refrigeration system is shunted past the condensor directly into the evaporator coil thus making the evaporator coil heat rather than cool. This technique is very efficient in reducing over- and undershoot problems. The effective thermal resistance of the

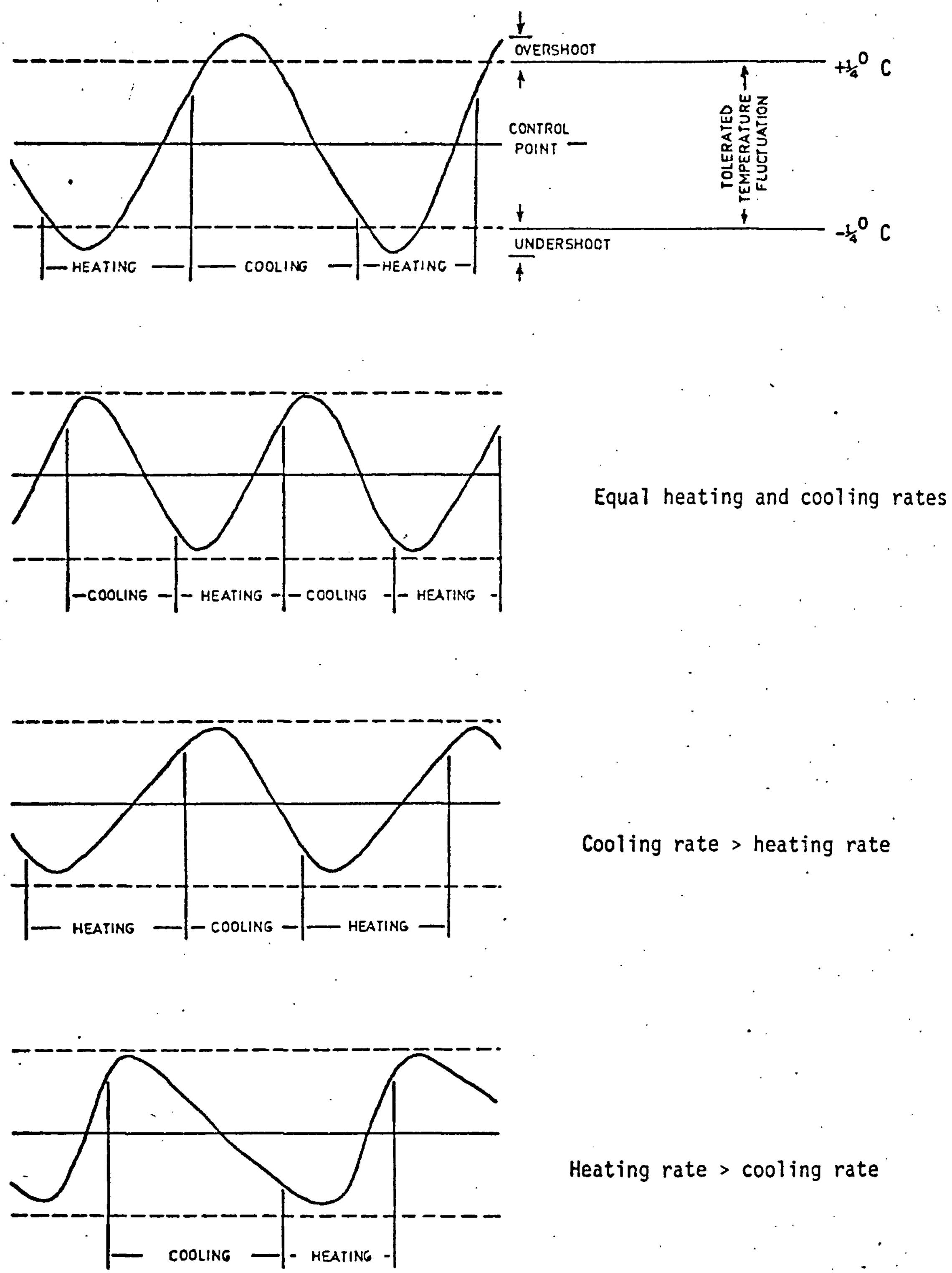


Fig. 1-12 Temperature variations about a control point caused by different rates of heating and cooling.

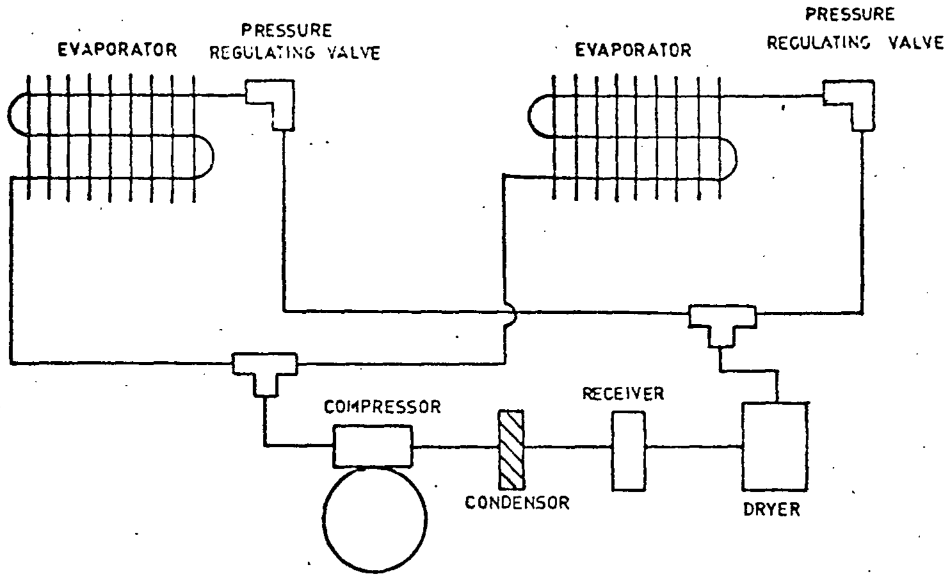


Fig. 1-13 The refrigeration system of the Percival Model PGC-78 growth chamber utilizing two evaporator coils. (Percival, 1963.)

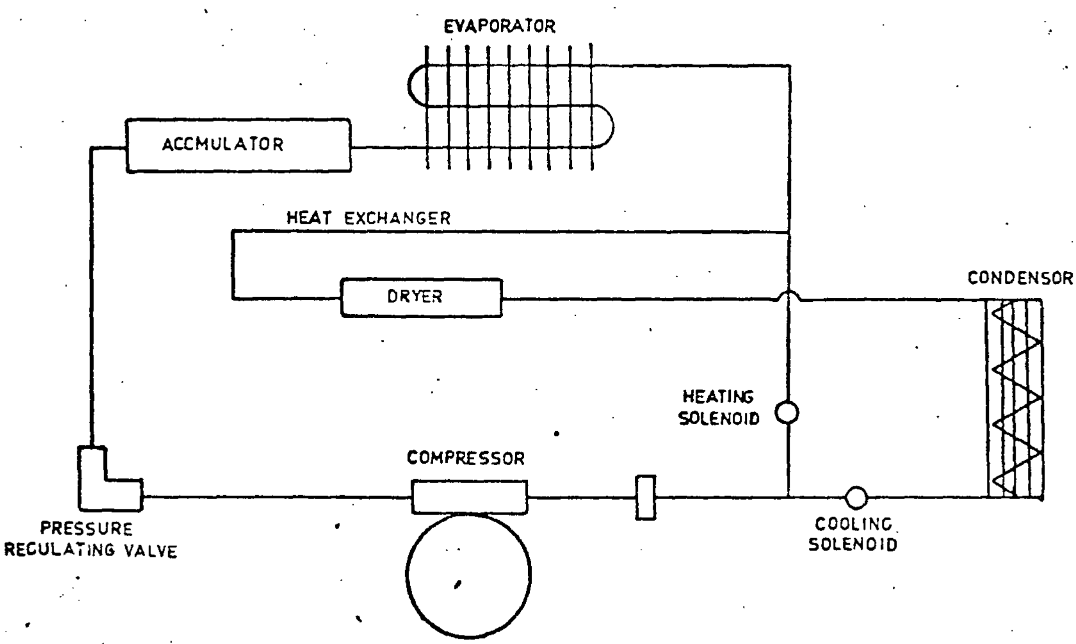


Fig. 1-14 A typical refrigeration system utilizing the hot-gas by pass technique of evaporator coil temperature regulation. (Controlled environments, 1967.)

evaporator coil is reduced by the introduction of hot gas. If a heating element is required, its wattage can be significantly decreased since the hot gas acts as a heating source. Temperature control within ± $1/8^{o}C$ can be realized with the hot gas bypass system.

Before proper conditioning capacity can be selected, the magnitude of the plant growth chamber's heat load must be determined for all practical ambient and chamber conditions. Generally, the light system is the largest heat source. Each watt of fluorescent and incandescent lighting yields 4.09 and 3.41 BTU/hour, respectively. These conversion figures allow the heat input of the light system to be calculated directly. Fan motors and other electrical and electronic devices in the air circulation system will add heat relative to their duty cycles and wattage. Heat transfer through the chamber's wall, root, and floor panels is the product of the surface area's involved (A), the heat transfer coefficient of the panels (K), and the temperature difference across the panels (t_2-t_1) (Kreith, 1964): $q = kA\ (t_2 - t_1)$ (6).

The infiltration of air into a plant growth chamber can provide a heat load if the exchange volume is significant and the inside and outside conditions are different. Ordinarily, chamber leakage becomes important only when extreme chamber conditions are attempted.

Fresh air make-up, which is the addition of a predetermined volume of air to a plant growth chamber to maintain normal CO_2 concentration levels, also acts as a heat load.

Once the general heat loads of a chamber are known, the effect of varying heat loads, such as diurnal light control, can be estimated. Discussion of such effects are presented in the following section.

(C) Humidity Control

Knowledge of the humidity in the natural environment is important to the study of plant growth. For example, the gradient of partial pressure of water vapor across the boundary layer of a leaf is the driving force of transpiration, the loss of water by evaporation from plants.

A plant growth chamber should provide some degree of humidity control to remove humidity fluctuations caused by the conditioning equipment. Humidity is a very complex variable of the environment, and therefore careful analysis of a chamber's proposed operating ranges is necessary to provide adequate humidity control. The inclusion of humidity control can double the cost of a plant growth chamber.

It is convenient to introduce additional equations which summarize the physical processes involved and the humidification and dehumidification of moist air. Table 1 gives the common terms used in psychrometric relations along with an example of how each of the terms varies with temperature.

An analysis of Figure 1-15 provides the following relations describing the cooling of air which results in condensation of water.

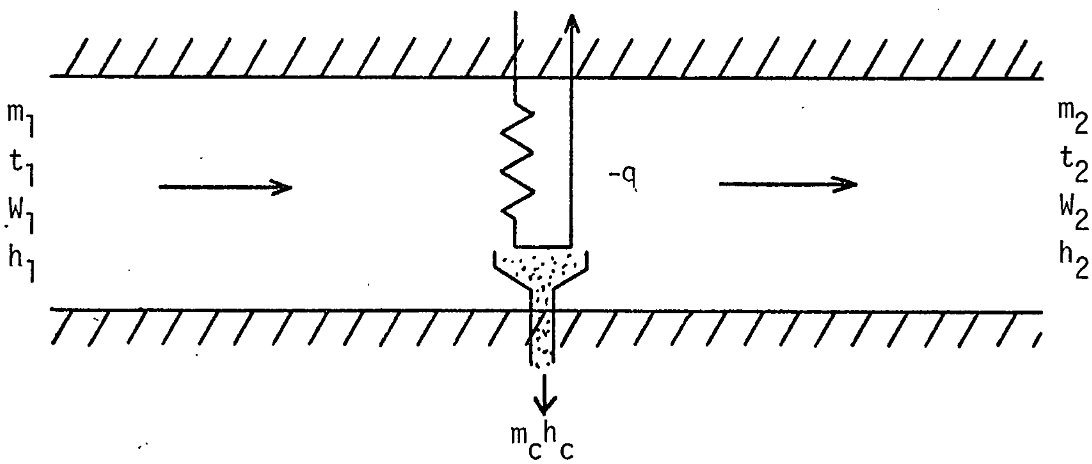


Fig. 1-15 Processes occuring when air is cooled and condensation results.

$$m_1 = m_2 = m \tag{7}$$

$$q = m(h_2 - h_1) - m_c h_c \tag{8}$$

$$m_c = m(W_1 - W_2) \tag{9}$$

In Equation 8, assuming ideal heat transfer, the amount of heat subtracted from the air equals m (the mass of air passing through per minute) times the enthalpy change minus the amount of heat contained in the water that was condensed. The amount of water that condenses equals m times the change in humidity ratio.

The humidification and heating of moist air is illustrated in Figure 1-16. The amount of heat added to the air equals m times the enthalpy change minus the heat contained in the added water. The amount of water added equals m times the change in humidity ratio (Equation 11).

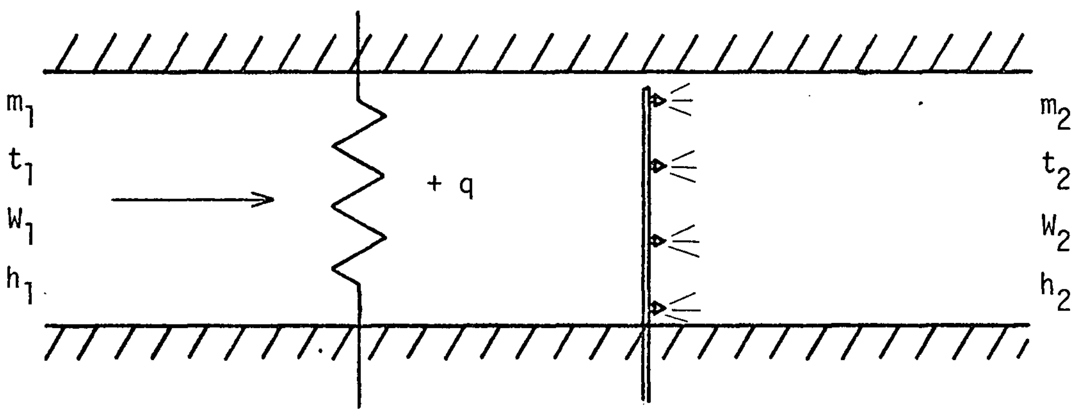


Fig. 1-16 Processes occuring when air is heated and humidified.

$$q = m(h_2 - h_1) - m_w h_w \tag{10}$$

$$m_w = m(W_2 - W_1) \tag{11}$$

TABLE 1 Psychrometric Terminology

TERM	SYMBOL	UNITS			
Temperature	t	^{o}C	10^{o} C	21^{o} C	32^{o} C
Humidity Ratio	W	lb_w/lb_a	.0038	.0080	.0152
Relative Humidity	R.H.	-	50%	50%	50%
Enthalpy	h	BTU/lb dry air	16.1	25.4	35.7
Volume	V	ft^3/lb dry air	12.9	13.55	13.9
Saturation potential	W_s	lb_w/lb_a	.0076	.0158	.0312
Saturation percentages	u	-	50%	50%	49%
Thermodynamic wet bulb temp.	t^*	^{o}C	6^{o} C	14^{o} C	24^{o} C
Dew pt. temp.	t_d	^{o}C	0^{o} C	10^{o} C	20^{o} C

Source: Threlkeld Psychrometric Chart, 1970.

The humidification of moist air when no other energy is added is a special case of the system in Figure 1-16. The amount of heat added by the water to the air equals m times the total enthalpy change. The amount of water added equals m times the change in humidity ratio.

$$m_w h_w = m(h_2 - h_1) \quad (12)$$

$$m_w = m(W_2 - W_1) \quad (13)$$

The adiabatic mixing of two streams of moist air occurs when fresh air is added to chamber air (Figure 1-17). For plant growth chambers, the volume of fresh air make-up is usually small, but its effect upon chamber air can be calculated. The make-up air may represent a significant water vapor load which should be considered when humidification equipment is designed. The effects of fresh air infiltration can be determined in the following manner. m_1, the mass of air returning from the chamber, mixes with m_2, the mass of make-up air, producing the conditions at point 3 in Figure 1-17 (Equation 14).

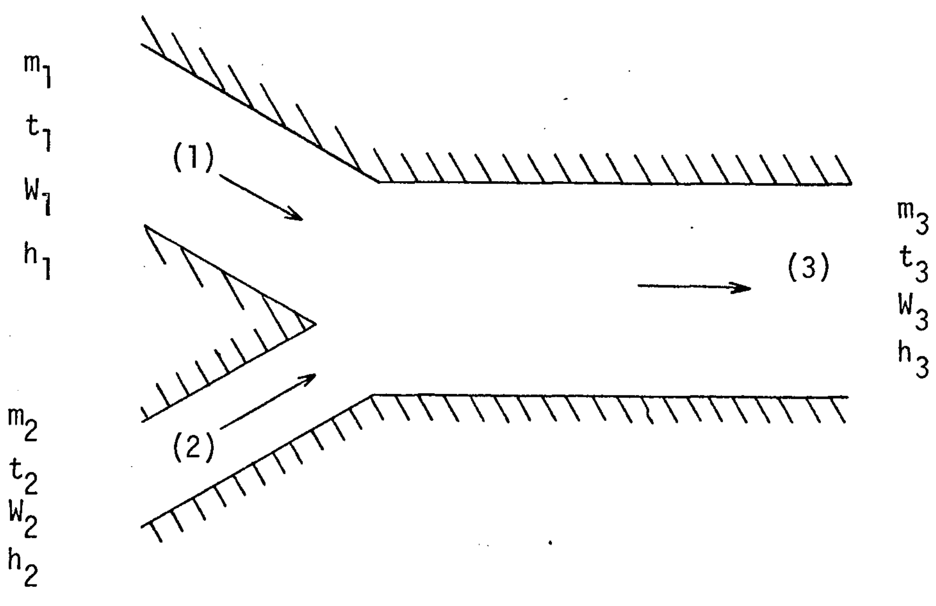


Fig. 1-17 Processes occuring when two airstreams are mixed.

$$m_1 + m_2 = m_3 \tag{14}$$

$$m_1h_1 + m_2h_2 = m_3h_3 \tag{15}$$

$$m_1W_1 + m_2W_2 = m_3W_3 \tag{16}$$

The air (at point 3) then enters the conditioning equipment. It is important to mention that a mass of air equal to m_2 must be exhausted from the chamber after conditioning and before entry to the plant growth area to compensate for the mass of made-up air introduced.

The above heat transfer relations assume that the heating, cooling, humidifying and dehumidifying processes are ideal. The non-ideal qualities of real conditioning elements are an important aspect of the overall performance of a plant growth chamber. The following discussion will develop problems and conditions that can occur in plant growth chambers, and will consider those chamber designs which provide the most practical solutions.

The hypothetical situation in Figure 1-18 illustrates the general affect of a cooling coil on moist air.

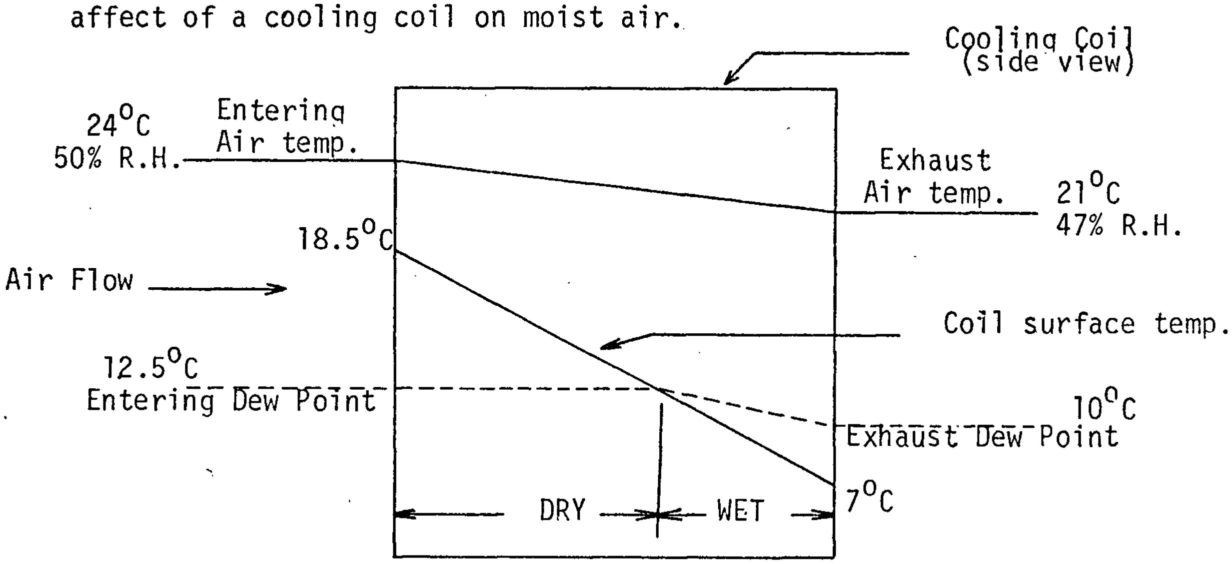


Fig. 1-18 Humidity and temperature changes occurring in a stream of air passing through a cooling coil.

Assume that the desired control point is 21^{o}C and 47% relative humidity, and that such air leaves the coil in Figure 1-18. After circulating through the plant growth area, suppose that the air returns to the cooling coil at 24^{o}C and 50% relative humidity. The heat and moisture loads of the chamber will determine the state of the air returning to the coil. Further assume that, in the coil of Figure 1-18, the temperature of the surface of the fins and tubes ranges from 18^{o}C at the leading edge where the air enters the coil, to 7^{o}C at the end where the air leaves the coil. The actual temperature gradient will be a function of the face area of the coil, the total outside surface area of the fins and tubes of the coil, the temperature and rate of circulation of refrigerant, the inlet face velocity, and the number of rows of tubes. A linear gradient is shown in Figure 1-18 for convenience.

The dewpoint of the air entering the coil in Figure 1-18 is 13^{o}C and of the air leaving, 10^{o}C. This implies that condensation has occurred since a change in dewpoint is possible only when the humidity ratio changes (at constant atmospheric pressure). Furthermore, part of the surface of the coil is above 13^{o}C, and will remain dry. Condensation will occur on the portion of the coil which is below the dewpoint. A drainage system should be provided for such condensation. The surface area of the coil which becomes wet is mostly determined by the surface area of the coil below the dewpoint of the entering air. When the coil surface temperature is lower than in Figure 1-18, even more condensation will occur from each pound of air circulated, since more coil surface area will be below the dewpoint of 13^{o}C. The mass of water that condenses is given by Equation 9.

Some of the water that is condensed may also be re-evaporated.

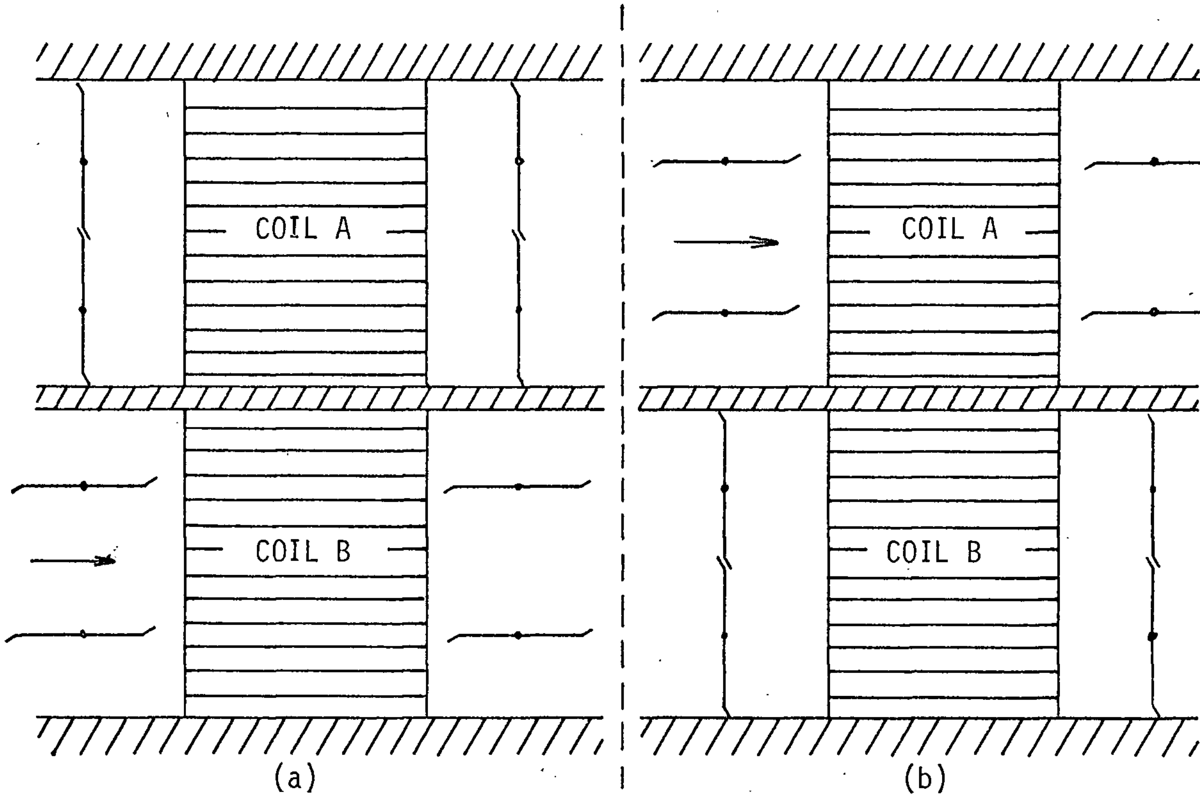
Since dehumidification is an inherent consequence of cooling coil operation, control of humidity within a chamber requires a source of water vapor to replenish the mass of water lost from the circulated air due to condensation. The capacity of equipment selected for humidification should be determined in relation to the highest rate of humidification expected to be required over the operating range of the chamber. In general, a plant growth chamber is designed to provide a particular humidity range over a specified temperature range. Close specification is necessary since some combinations of temperature and humidity are very difficult to achieve.

For example, low humidities at low temperatures are difficult to produce because the surface temperature of a cooling coil tends to drop below the freezing point of water. If frost forms on the coil, heat transfer is greatly reduced, causing less efficient air temperature control. At high temperatures, high humidities are often difficult to maintain since a very high rate of evaporation may be necessary. Wall temperatures may be lower than the dewpoint of such air, causing undesired condensation. A plant growth chamber may require careful sealing to reduce undesired water vapor infiltration or loss.

Installing dehumidification equipment is a much more difficult and expensive problem than humidification. First, the water that is removed from the air must be drained away from the air circulation system so that re-evaporation is not significant. Secondly, the temperature of the air being dehumidified should not be significantly changed by the process. Dehumidification capacity should be selected in relation to the lowest humidity desired at the highest temperature at which humidity control is specified. This condition will require the highest rate of dehumidification, in terms of pounds of water removed per pound of air, that will occur in the plant growth chamber. It is important to consider the effects of plant transpiration as a source of water vapor when dehumidification is performed. Several references contain data from which estimates of moisture load due to transpiration can be obtained (Salisbury and Ross, 1969; Geiger, 1965). To make an accurate estimate of transpiration such factors as light intensity, rate of photosynthesis, temperature, relative humidity, wind velocity, time of day, and atmospheric pressure should be considered.

As mentioned earlier, if frost accumulates on the surface of a cooling coil, the heat transfer efficiency of the coil is reduced. Defrost cycles, usually only a few minutes long, are programmed on coils when frost problems are encountered. A defrost cycle usually involves the shut-down of the refrigeration compressor and fan, and possibly the activation of a heater to melt the accumulated ice or frost. The length and required number of defrost cycles are usually found by experimentation.

During a defrost cycle, the air temperature of the plant growth area also rises. This is an unavoidable problem in chambers with only one compressor and cooling coil. One method that may be used to avoid the undesirable affects of a defrost cycle on temperature control is the two-compressor system. With two compressors and coils, which are independent, one coil can be processing the chamber air while the other is being defrosted (Figure 1-19). Of course, the expense is greater but chamber performance is improved.



COIL A Defrosting
COIL B Processing

COIL A Processing
COIL B Defrosting

Fig. 1-19 Dual damper-controlled cooling coil.

The effect of changing heat loads on humidity should also be considered in the design of a plant growth chamber. A good example of a varying heat load occurs in the diurnal control of the light system of a chamber. When the lights are on, some heat is added to the air which must be removed by the conditioning equipment before the air can be re-introduced to the plant growth area at a given temperature. With the lights off, no such heat is added to the air, but the conditioning equipment must recondition the air to the same temperature. Figure 1-19 indicates what occurs in the cooling coil in both lights-on (a) and lights-off conditions (b).

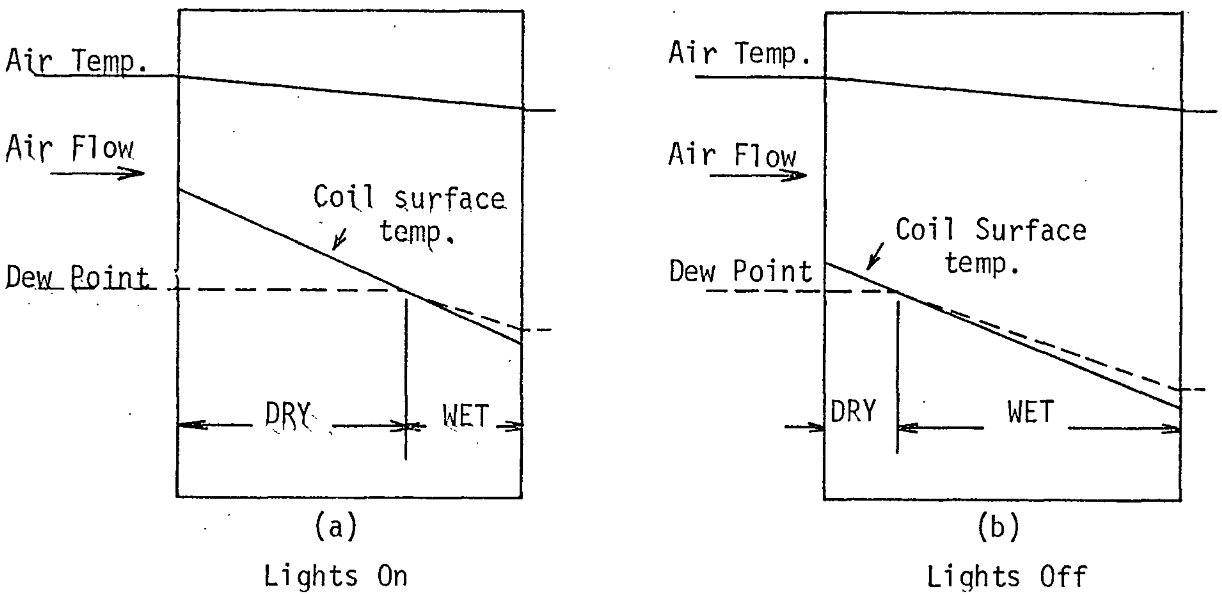


Fig. 1-20 The effect of varying heat load on cooling coil performance.

Since the refrigerant temperature in the coil is essentially constant, and if the face velocity is constant, the surface temperature of the fins and tubes of the coil will be determined by the heat load. The higher the heat load, the higher will be the average surface temperature of the coil. The result is that with the lights off, more water may be condensed since more of the coil may be below the dewpoint of the air passing through. It may be concluded that greater humidity fluctuations should be expected in lights-off operation of a coil relative to the lights-on condition.

(D) Air Circulation

The quality of the environment of a plant growth chamber will be a function of the uniformity of air velocity and temperature throughout the chamber. The provision of a proper quantity of conditioned air is one problem, while that happens to the conditioned air within the plant growth area, under intense lights, with shelves and foliage blocking air flow, depends on the design of the air circulation system.

As mentioned earlier, a vertical air flow is most effective in chambers of the reach-in type (about 12 sq. feet of growing area). If the air flow is uniformly distributed at the base of the chamber, much more uniform vertical air flow is possible. The air will tend to go up through the plant foliage, and if the plants are evenly distributed in the chamber, the air flow will meet (nearly) the same amount of resistance across the chamber, making it more probable that all of the plants within the chamber will experience approximately the same resultant air flow. The development of a vertical air flow system is described in Chapter V.

The effects of the air circulation system upon humidity mainly reflect the effects of a temperature gradient from the chamber base to the light system. For example, once conditioned air has entered the plant growing area, the absolute humidity is constant (excluding transpiration and soil water evaporation for the moment). Therefore, if a temperature gradient does exist vertically in the chamber (with vertical airflow), a lowering of the relative humidity will be noticed along the gradient. The smaller the temperature gradient (or differential), the smaller will be the change in humidity. There will always be a temperature gradient (though it can be minimized or compensated for) since high-powered, intense light systems are constantly heating the air of the chamber and all the material in the chamber, including the chamber walls. This vertical temperature gradient is a function of the light intensity of the light system and the velocity of air circulation.

Because of the above effects, it is useful to define an environmental condition at a specific location in the chamber. By using such a reference point, the possibility of reproducing a special environment is greatly increased. Temperature, humidity, and air velocity gradients occur widely in nature, so the problems are not unique to growth chambers.

(E) Reliability and Service

For a reliable plant growth chamber, solid-state electronic controls should be incorporated wherever possible. The use of electromechanical devices should be reduced, as the number of operations in a continuously running growth chamber becomes enormous. For example, a relay which operates once a minute (not uncommon) will experience 526,600 operations in a year. Such electromechanical relays are used to control the solenoid valves of the refrigeration compressor. When a solenoid is energized or de-energized, a radio-frequency or high-voltage pulse travels the line, and when this pulse hits the contacts of a relay, a spark can occur. As a result, the contacts of a relay can erode until a short circuit occurs. A relay rated at 10^8 operations (mechanical) may last only 500,000 operations when it activates solenoids. The life of relay contacts can increase greatly by filtering the high-voltage pulse out of the line before it reaches the contacts. A General Electric thyrector or a "clipper" (diode) accomplishes this easily.

A schedule of light bulb replacement should be arranged so that a predetermined average light intensity and quality is maintained continuously over any period of time. The average light intensity that will be practical to maintain will depend on the number of light bulbs in the chamber, the cost, and the average lifetime until light output becomes too low. By following a schedule of light bulb replacement, the researcher can have greater confidence that short- and long-term variations in light intensity and quality within a chamber and light intensity differences between chambers will be minimimal.

Most of the mechanical devices and electric motors (e.g. compressors and fans) are either constructed with sealed bearings or are self-lubricating. Thus, service of these devices is a matter of replacement at the end of their lifetimes. It is good practice to maintain an inventory of critical components that are not readily available from local retail outlets. A critical component is defined as one such that if it failed, the operation of the chamber must stop until it is replaced.

Chapter II

INSTRUMENTS FOR THE CONTROL, INDICATION, AND MEASUREMENT OF ENVIRONMENTAL VARIABLES

(A) Control

At present, most commercial and custom built growth chambers provide only a minimum of light intensity control and moderate (e.g. $\pm 2^oC$) temperature control. Air flow is rarely found to be a controllable variable and humidity control is so expensive that few chambers have such equipment. Air flow, humidity, and atmospheric composition (O_2 and CO_2 concentration in particular) are generally assumed constant, which is not usually a safe assumption.

Controls for the light system usually consist of time clocks for varying the photoperiod, and moveable shelves or pulley systems for increasing or decreasing the light intensity to which the plants are exposed.

Temperature control in a plant growth chamber is more dependent on total chamber design, while light system control is largely determined by the properties of lamps alone. Three basic types of temperature controls have been used on plant growth chambers; bimetallic strips, hydrostatic thermostats, and electronic controls.

Bimetallic strips and hydrostatic thermostats were used on early growth chambers with hydrostatic controls still being used on less expensive equipment. Both methods lack a simple means of varying sensitivity (to the change in temperature between an on and off cycle), which is necessary to provide proper balance between heating and cooling loads. The bimetallic strip does not allow remote set point location, an important convenience for the chamber operator. Neither method provides a calibration adjustment for drifts in calibration with time, or a single pole, double throw output which is required for controlling both heating and cooling loads. The small dial usually provided may or may not be in temperature units and seldom is it possible for a specific temperature to be set directly on the dial. Several types of hydrostatic controls are not compensated for changes in ambient conditions around the chamber. The hydrostatic capillary tube extends from the sensor bulb (in the chamber) to the body of the control, which is usually mounted on an exterior chamber wall and is exposed to ambient temperature fluctuations.

Users of plant growth chambers often require diurnal or programmable temperature control. To provide such control, the Percival Model PGC-78, for example, uses a time clock that switches between two independent hydrostatic controls that are pre-set to day and night temperatures. Programming (multi-step) temperature control is not practical with hydrostatic devices, since a separate control would be required for each step in the program. Calibration of hydrostatic diurnal controls is more difficult than for a single control and since two controls are involved, there are more devices to fail in service.

Solid-state electronic temperature controls are more complicated and expensive than the above devices, but offer relatively simple solutions to all of the problems associated with growth chamber temperature control in presently existing equipment. Nearly all solid-state controls use the Wheatstone bridge technique with a temperature dependent resistance element as the sensor (Doebelin, 1968). The composition of the resistance element may be semiconductor (thermistors), wire of alloy composition (NiFe), or pure metal (nickel or platinum). The sensor can be made small so that its time response to a temperature change is very fast. If the resistance of the sensor is large (greater than 1000 ohms) lead resistance is negligible and lead lengths can be up to 200 feet with only small errors resulting. For low resistance sensors (less than 150 ohms), such as platinum, lead length compensation should be provided. Remote location is relatively simple when using a resistance sensor.

Remote set-point adjustment is also easily provided by solid-state controls. A potentiometer with a scale calibrated according to the temperature coefficient of the resistance sensor may be mounted on a panel convenient to the chamber operator. The length of the scale is usually about five inches, which allows a large temperature range (-20^{0} to 50^{0}C is typical) to be covered on one dial, without losing the capability of setting the temperature to within $1/4^{0}$C.

Calibration and sensitivity adjustments are also accomplished with potentiometers and can be made available on a convenient control panel. Calibration is required for compensation of sensor aging and to balance out the non-uniformity between the original and replacement sensors. Resistance elements are typically manufactured to tolerances of 1% or more. Sensitivity can be varied in several ways. A sensor may be wrapped with cloth or tape to increase its mass, which will decrease its response time to a given temperature change. A second technique is to reduce the voltage across the Wheatstone bridge, which reduces the signal to the control amplifier. It then takes more temperature change to make the amplifier switch from heating to cooling. Changing the bridge voltage is not as satisfactory a method of varying sensitivity since the current flowing through the sensor is changed, which alters the self-heating error of the sensor. Such a change can affect the overall calibration of the controller.

The best available method of varying controller sensitivity is accomplished electronically. By using a resistance-capacitance circuit in the feedback of the amplifier, the difference signal of the Wheatstone bridge is integrated. By varying either the resistance or capacitance, the slope of the integration can be changed, which directly changes the time response of the controller without interfering with the sensing element at all.

Virtually any type and capacity of output device can be provided with a solid-state temperature control. The most common is a single-pole double-throw electromagnetic relay rated at 10 to 25 amps (non-inductive). This form of relay allows control of heating and cooling elements. More recent solid-state control designs incorporate solid-state alternating current switches (Triacs) for the control of heating and cooling elements. Triacs eliminate the electromagnetic relay, a mechanical device with contacts that has proven to be the least reliable component of solid-state controls. The use of triacs can extend the mean-time-between-failure rating to years instead of months.

Diurnal temperature control is easily provided by solid-state control systems. For diurnal control, a time clock switches between two set-point potentiometers which are preset to the desired day and night temperatures. Instead of requiring two complete hydrostatic controllers, a single potentiometer is the only extra part. The same sensor and amplifier control both day and night temperatures, increasing accuracy while simplifying the total control system.

The programming of temperature with a solid-state control is an extension of diurnal control. One method is to switch a series of set point potentiometers by means of a stepping relay sequenced by a time clock. Proper switching must be provided (low contact resistance), and a circuit for calibration of the set-points devised. Only one controller is required for this type of programmer. The more familiar cam-type control is also adaptable to growth chamber temperature programming and gives stepless control.

Maintenance of hydrostatic temperature controls consists of replacement of the entire unit. For solid state controls, however, if a component fails, it can be located and replaced. If electromagnetic relays are used as the output of a control, they should be inspected first in diagnosing failure. Solid-state components have acquired a great reputation for reliability, and should exhibit a mean-time-between-failure of more than 10,000 to 20,000 hours operation.

In the future, it will be possible to have such controls on other environmental variables such as light intensity, humidity, and air speed. Complexity and expense prevents common use of such controls at present.

(B) Indication

The design of instruments for indication of environmental variables is more complex than for controls. Discussion here will be limited to those instruments and devices used in measuring light intensity, temperature, air circulation, and humidity for the data in Chapters III and V.

In the collection of light intensity information in the plant growth area of the Percival Model PGC-78, a photometric light sensor was utilized, since the light quality (made up of fluorescents and incandescents) remained essentially constant during the measurement period, and was far simpler to use than the only available radiometric light sensor. An International Rectifier silicon photovoltaic photocell (Serial No. S1020E4PL) was calibrated with a Gossen Tri-Lux foot candle meter. The response of the photocell was found to be linear between 300 and 2500 foot candles, a useable range for this application. The silicon photocell was attached directly across the input of a digital voltmeter with an input impedence of greater than 1000 megohms. The various readings were digitally printed on command by a Solatron Data Logging system. The surface area of the photocell was 1/2 inch square (1/2" by 1"), permitting measurements to be taken at close spacing (four inches) without overlapping occurring.

Temperature measurements were made with a copper-constantan thermocouple (wire diameter .032 inch). Radiation compensation was not necessary because of the small surface area of the thermocouple. Cold junction compensation was accomplished with a platinum regulated junction box (Solatron), accurate to $\pm .15^{o}C$. The thermocouple output was also connected to the digital voltmeter for measurement and recording.

Air circulation within the plant growth area was measured with a Flow Corporation Model 55B1 hot-wire anemometer, which is most accurate in the region below 200 fpm. For all the air flow measurements, the probe was held so that the hot-wire element was always horizontal. This was done in an attempt to obtain the vertical air velocity component, as much as possible; and to improve the reproducibility of readings at a given location.

The relative humidity in the plant growth area was measured with a Phys-Chemical Research Corporation Model 11 precision copolymer styrene plastic sensor. The resistance of this device is a function of relative humidity. The sensor was connected in an alternating current Wheatstone bridge and capacitively coupled to a null detecting amplifier. Accuracy was ± 1.5% R.H., sensitivity ± 1% R.H., and response time to a 63% change of R.H. was less than 30 seconds in still air. Response time in an air flow of 50 to 100 feet per minute was less than 2 seconds. The plastic sensor was temperature compensated with a thermistor bead mounted very close to the surface of the wafer. The plastic sensor was sensitive to light intensity and required shielding before measurements could be taken under the light system in the plant growth area.

(C) Measurement

The technique used for measuring the environmental variables was made as similar for each as possible. To accomplish this, a remote measuring system was developed to move sensors from one position to another without opening the door of the chamber. A variable length u-channel was made of Plexiglass with rubber feet mounted on the ends (Figure 2-1). The u-channel could be suspended between the end walls of the chamber by applying a slight pressure on an adjustable slide, and then tightening a thumb screw. A miniature battery-operated motor with a gear reduction unit was mounted at one end of the u-channel with a small pulley facing the center of the channel. At the other end of the u-channel, a second pulley was mounted also facing the center of the channel. A slide that closely fit the u-channel was then pulled back and forth by the motor and pulley system, by reversing the battery polarity. The various sensors could be attached to the slide and moved across the chamber. Wires were run from the motor and sensors to outside the chamber for manual operation.

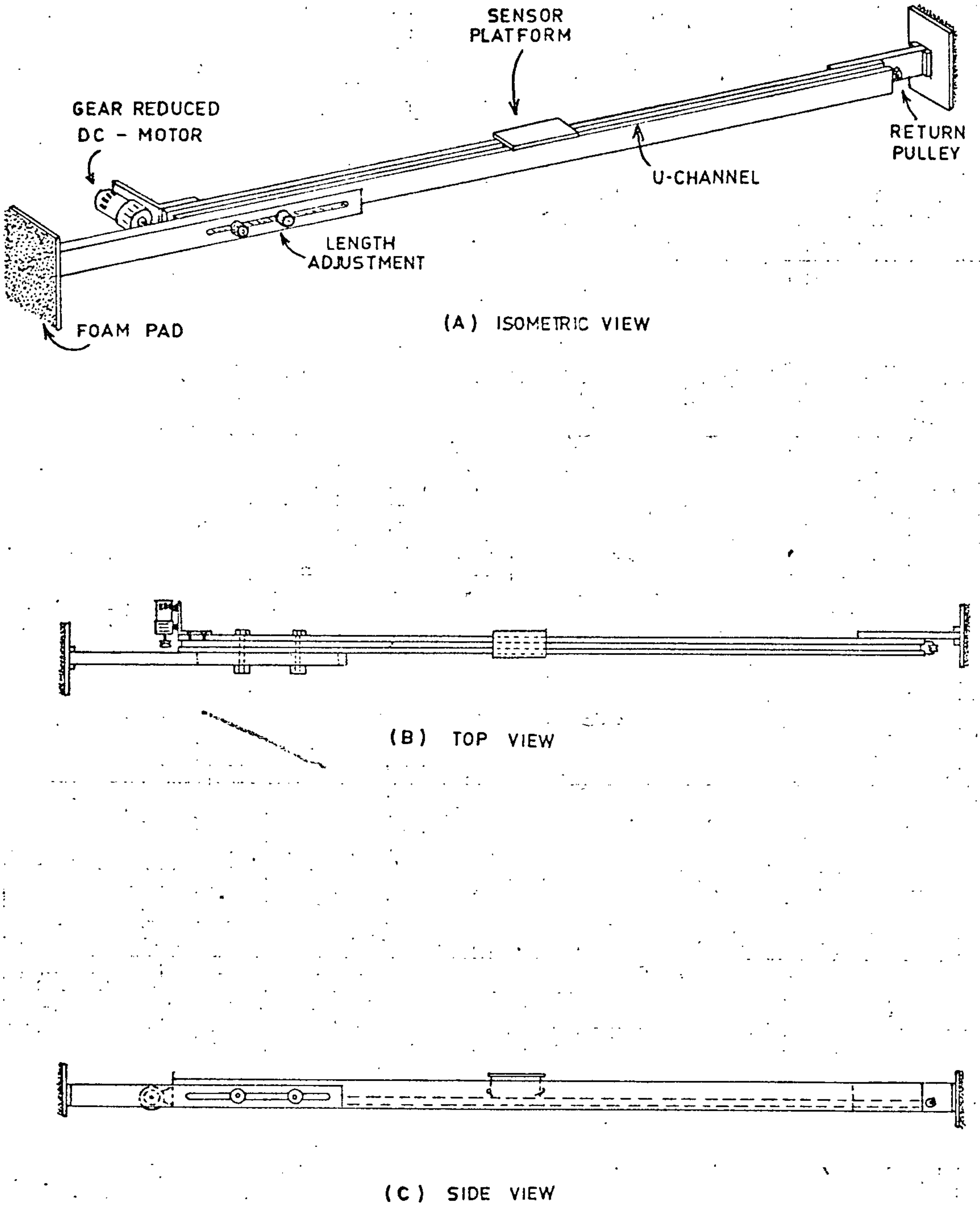


Fig. 2-1 Apparatus for the remote positioning of environmental sensors.

A four inch grid was placed on both end walls of the chamber being measured (with .100 inch wide tape) so that the ends of the u-channel bar could be moved in sequence, vertically and horizontally, with the four inch grid as reference so that one end of the u-channel was in the same relative position as the other end. Along the length of the u-channel, reference marks were made so that the sensor could be stopped every four inches.

The procedure for operating the device was to position the u-channel bar at one corner of the four-inch grids on the end walls. The sensor slide was then run along the u-channel in four inch increments with measurements made every four inches. When the length of the u-channel was traversed (consisting of thirteen 4 inch increments), the ends of the u-channel were moved to the next grid location on the end walls and the sensor slide moved back again in four inch increments. The chamber door has to be opened to reposition the ends of the u-channel bar, but only once every 13 measurements instead of once every measurement if a motorized sensor slide wasn't used. After opening and closing the chamber door, a sufficient amount of time was allowed for the chamber conditions to re-equilibrate.

Chapter III

COMMERCIAL GROWTH CHAMBER PERFORMANCE

INTRODUCTION

A thorough examination of the performance of a Percival PGC-78 will be presented in this chapter. The information obtained is valuable for researchers using these growth chambers, as well as to the designer and manufacturer of artificial environment equipment. The growth chamber selected for performance analysis was one of eight of the same model operated by the Department of Plant Science. The interior of the chamber was thoroughly cleaned and adjusted to approach original specifications as closely as possible. New fluorescent and incandescent lamps were installed and the screens for diffusing air flow were cleaned and straightened.

The information gathered will be compared to the advertised performance of the Percival Model PGC-78, and to the standards of plant growth chamber design presented in Chapter I. Controlled Environment Limited refrigeration and air circulation systems will be discussed and compared to the Percival system.

(A) Light System

The Percival Company advertises a maximum of 5000 foot candles (5.4×10^4 lux) light intensity within the chamber utilizing sixteen VHO 150 watt Cool-White type F72T12 fluorescent lamps, and ten 50 watt incandescent lamps. The distance from the light source at which the above measurement was taken was not specified. However, the maximum light intensity measured in a totally empty Model PGC-78 growth chamber in the Plant Science Department was 2500 foot candles (2.7×10^4 lux), with the measurement being taken six inches below the center of the light canopy. This measurement was repeated several times with a Gossen footcandle meter using fluorescent and incandescent lamps with approximately 100 hours operating time (for burn-in purposes) and with chamber temperature at $20^oC \pm 1^oC$. The user of a plant growth chamber can easily be confused by light intensity specifications that do not include the conditions under which the manufacturer measured the performance of his system. In any case, a maximum intensity rating is of little value, because of the progressive decrease in output of fluorescent lamps with age (General Electric, 1960). An average light intensity rating over a given period of time would be of more use to the researcher.

Light intensity profiles within the growth chamber were determined by measuring horizontal planes with the remote sensing apparatus described in Chapter II (Page 39). Eight horizontal planes, each including 91 measurements (7 x 13) taken at four inch intervals, were spaced between 12 inches and 44 inches from the light system in four inch increments. The shelves and other equipment were removed from the chamber leaving only the light sensing equipment, which was constructed of Plexiglass. An empty chamber provides the most reproducible situation for light measurement, and gives the operator a view of the total chamber capability. Measurements were taken with the chamber door and observation window closed. The spacing of the fluorescent and incandescent light bulbs and chamber door location are shown in Figure 3-1.

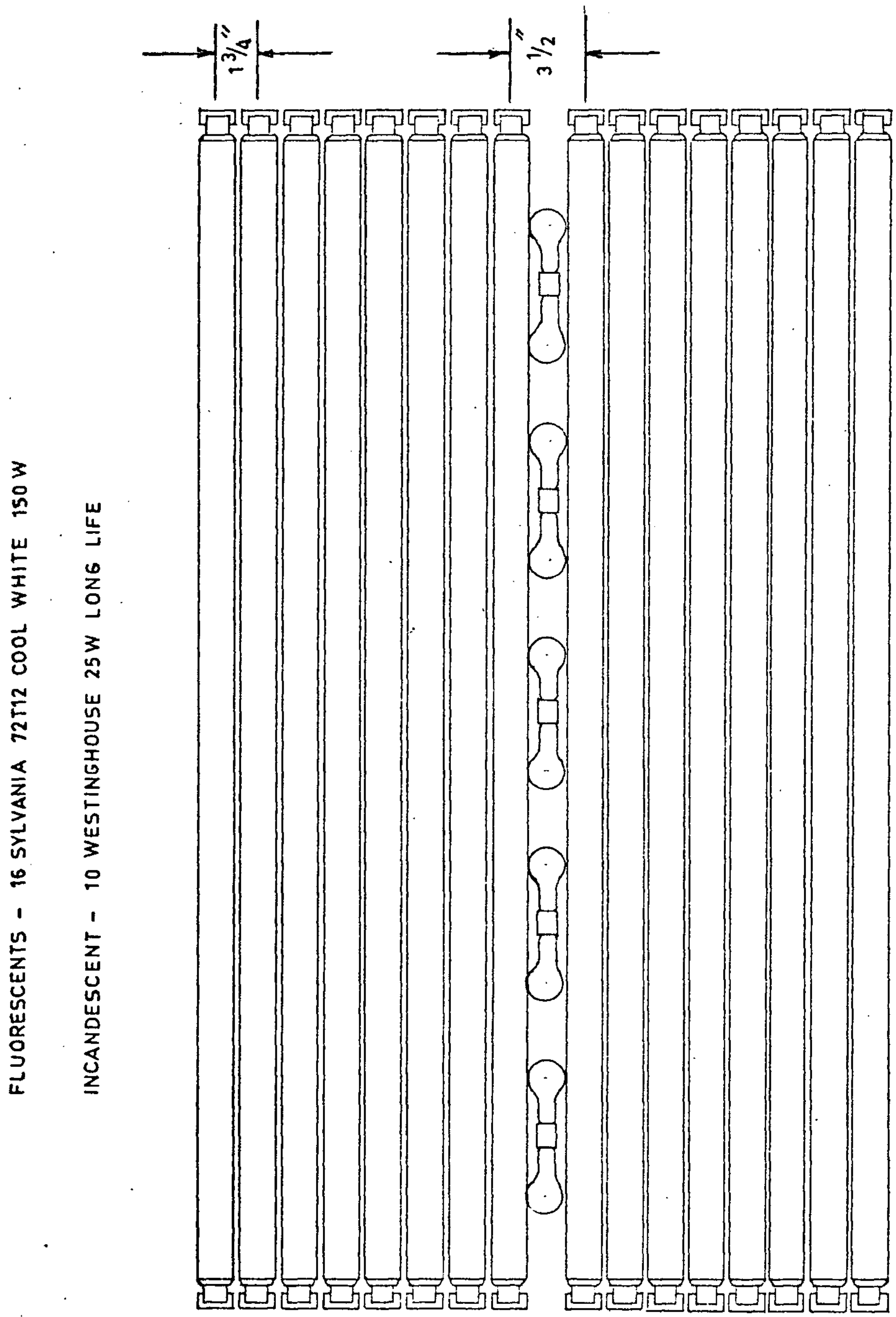


Fig. 3-1 The spacing and arrangement of fluorescent and incandescent lamps in the Percival Model PGC-78.

Figures 3-2 (a$\longrightarrow$h) show the light intensity gradients on horizontal planes in four inch intervals below the light system. The lines in Figures 3-2 (a$\longrightarrow$h) represent points of equal intensity with the difference between one line and the next being 50 foot candles (500 lux). The difference in light intensity of horizontal planes progressing down from the light system in the center of the chamber is approximately 150 to 200 foot candles (1500 to 2000 lux). This indicates that the light system, in association with reflective walls performs similarly to a diffuse-horizontal light source. The effect of distance from the light source on intensity is extremely difficult to minimize with this type of light system. The variations of light intensity in any one horizontal plane result from the difference in additive effects of light intensity in the center of the light system relative to the sides or ends of the light system. Even perfectly reflective walls would not eliminate the intensity variations near the edges of the light canopy. One solution, not always possible, is to make the size of the lamp canopy much larger than the growth area platform, and this technique is often used in open chambers and walk-in rooms.

The Percival Company specifies that up to 500 foot candles (50,000 lux) are obtainable in their Model PGC-78. It is clear that at 12 inches from the barrier between the light bulbs and the plant growth area, a distance that is much higher than would be practical to use, an intensity of 2000 foot candles (20,000 lux) is all that is available under the direct center of the light canopy (Figure 3-2a). This measurement was taken at 20^{o}C using lamps that had operated 150 hours. At three thousand hours operating time, the fluorescents can be expected to give out 75% of the initial 150 hour value and this would result in approximately 1500 foot

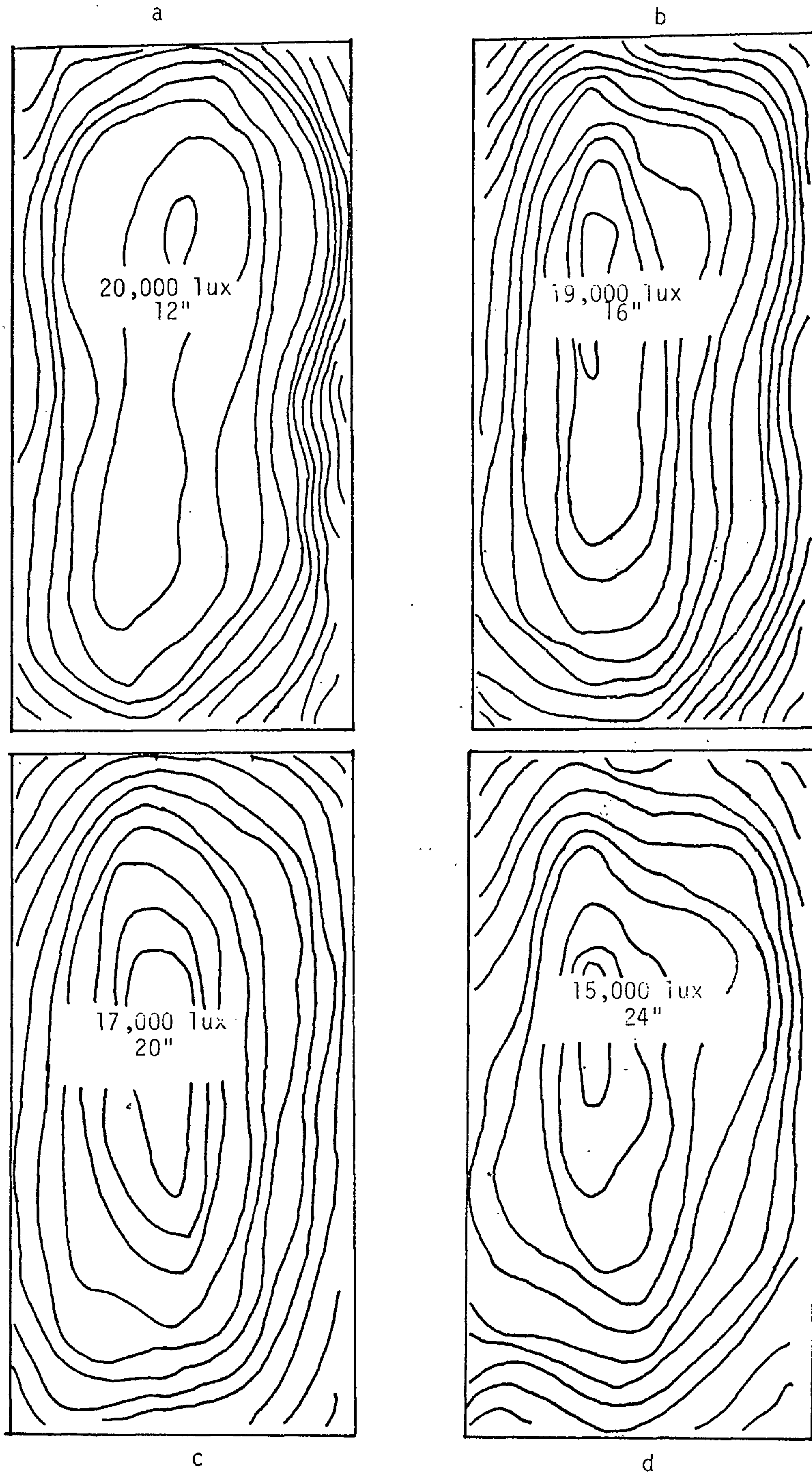


Fig. 3-2 (a-d) Horizontal light intensity profiles at 12", 16", 20", and 24" below the Percival Model PGC-78 Light Canopy (Door Closed) (500 lux intervals)

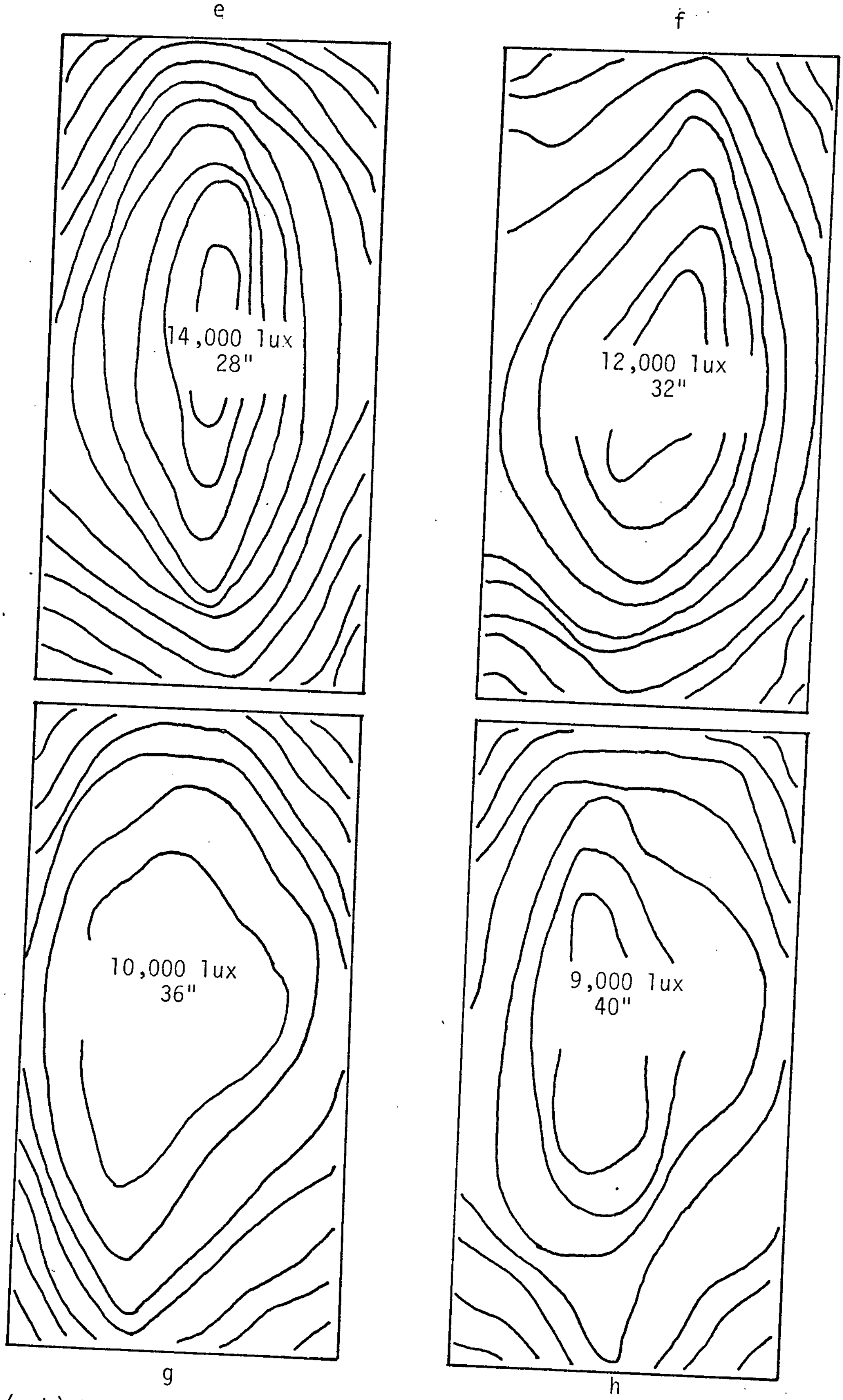


Fig. 3-2 (e-h) Horizontal light intensity profiles at 28", 32", 36" and 40" below the Percival Model PGC-78 Light Canopy (Door Closed). (500 lux intervals) candles (15,000 lux) at the same location (General Electric, 1960).

Because of these variations of light intensity in space and time, the specific influence of light intensity variations on plant growth would be difficult to measure in the Percival chamber. Such measurements would require all factors of the plant environment except light to be held at non-limiting, constant, reproducible levels, which would be a formidable task.

The addition of a few fluorescent lamps across the ends of the chamber and one placed vertically in each of the corners should considerably improve the horizontal uniformity of light intensity in the chamber.

The Percival Company states that the purpose of the mylar barrier between the light system and the plant growth chamber is to maintain optimum fluorescent bulb surface temperature (45^{o}C) for high light output (Bulletin Number 2B). Fluorescent bulb light output falls to nearly 10% of maximum when the chamber temperature approaches 5^{o}C. The mylar barrier blocks the circulation of chamber air around the bulbs. Fans mounted above the light system draw ambient air past the bulbs which is then ducted outside the building. As long as the ambient temperature remains constant, bulb cooling and surface temperature will be fairly constant if the chamber temperature is held constant.

However, the disadvantages of the barrier exceed the benefits. The mylar sheets used as a barrier by Percival are translucent and, when new, absorb a minimum of 12% of the visible radiant energy from the light system. With ageing, mylar tends to become more opaque and transmit less light (Rohm and Haas, 1968). Other problems associated with barriers are the collection of dust, water and other materials on the barrier and the possibility of exceeding the optimum surface temperature of the fluorescent bulbs. High ambient temperatures are very possible in a small room with several chambers operating. The removal of the mylar barrier is a cumbersome task often requiring a shelf to be moved.

It has been shown by several other growth chamber manufacturers that light systems without barriers are more effective over the chamber temperature range, require fewer components, and cost less (Sherer-Gillett, Controlled Environments, Engineered Environments).

(B) Temperature Control

For cooling chamber air, the Percival Model PGC-78 utilizes a 1 horsepower refrigeration compressor with an air cooled condensing unit and dual evaporator coils. For heating, a 300 watt strip heater is mounted below each of the evaporator coils. Two separate hydrostatic temperature controls (Penn Controls) operate the heating and cooling systems. Percival specifies a temperature range and control at $8^{o}C$ to $40^{o}C \pm 1.5^{o}C$ with a full light load.

Measurements of temperature uniformity were taken by mounting a thermocouple to the remote sensing apparatus. The measurements represent the average of two complete heating and cooling cycles by the conditioning equipment. Associated with each cooling cycle is a minimum temperature, and with each heating cycle, a maximum temperature, at each measurement location. Measurements every eight inches in a horizontal plane provided sufficient detail of the temperature uniformity (Figure 3-3). After discovering the nearly symetrical nature of the temperature profile, only one traverse was made down the center of the chamber to obtain the vertical profile since these measurements were very time consuming.

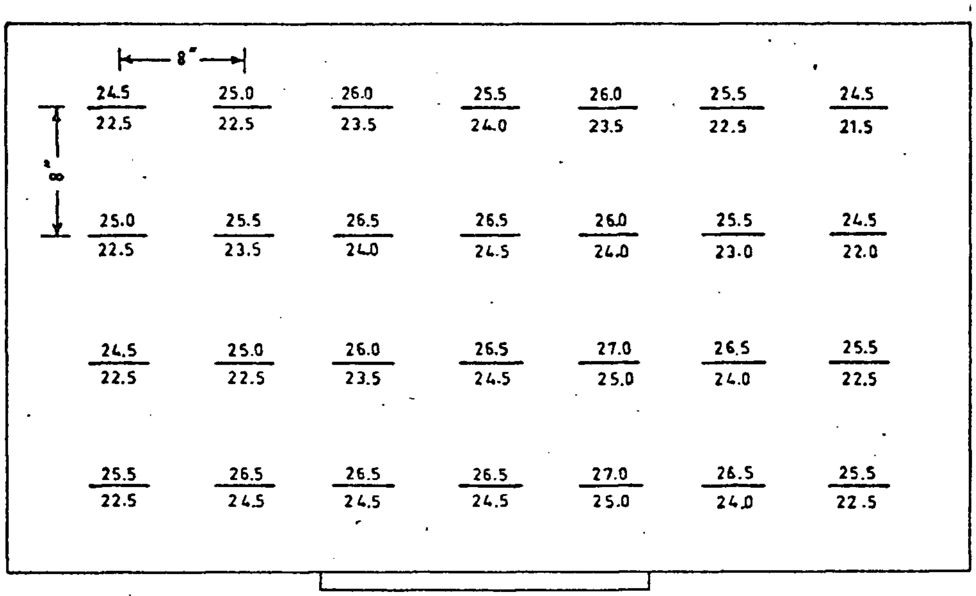


Fig. 3-3 Horizontal air temperature profile 14" below the light canopy barrier.

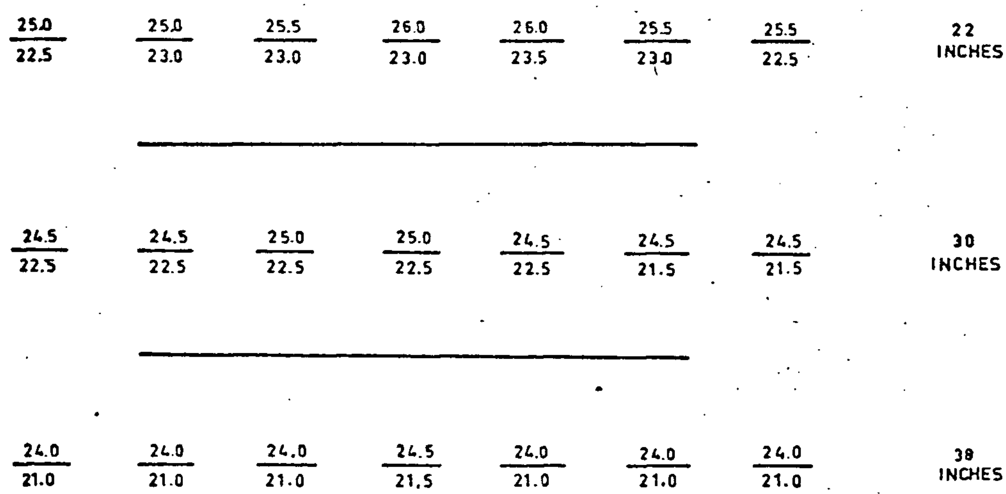


Fig. 3-4 Horizontal air temperature profiles through counter of chamber for 22", 30" and 38" from light canopy surface.

Percival specifies ± 1.5^{o}C control with no further qualification which implies that any point reasonably distant from the light source (approximately 10 inches) should be within ± 1.5^{o}C of the control point. The data of Figures 3-3 and 3-4 indicate that at any single point in the growth area, the temperature fluctuation is about ± 1.5^{o}C around some temperature that may be above or below the desired control point by as much as 2^{o}C. In fact, the actual set-point of the refrigeration controller was 19^{o}C, nearly 5 1/2^{o}C cooler than the average temperature at 14" from the light system, and below any temperature actually measured by 2^{o}C. This situation could exist because the hydrostatic temperature controls have no calibration adjustment, and they are also affected by ambient conditions.

It should be noted that temperature uniformity within a growth chamber is very much dependent upon air circulation, which is discussed in the following section.

(C) Air Circulation

The air circulation pattern within a plant growth chamber is an important but often ignored environmental variable. Uniform air circulation is a prerequisite to uniform temperature and humidity conditions throughout the plant growth area. The Percival Company states that in the Model PGC-78, chamber air is recirculated over the cooling and heating elements at a velocity of 50 to 100 surface feet per minute. The specified air flow within the plant growth area is a uniformly distributed 75 feet per minute.

Measurements of air velocity were taken at 8 inch intervals on horizontal planes at 14, 22, 30, and 38 inches from the light system (Figure 3-5). A Flow Corporation hot-wire anemometer probe was attached to the remote sensor apparatus, allowing the probe to be moved without opening the chamber door. Each reading represents an average of two minutes observation with the fluctuations about the average indicated as a plus and minus quantity. The fluctuation was such that the damped mode (Position 2) of the anemometer had to be used to obtain the data of Figure 3-5. The hot-wire of the probe was held horizontal to the floor of the chamber so that the largest velocity component of an observation should have been the vertical component. All shelves and instruments except probes were removed from the chamber. The distributing screens on the floor of the chamber were cleaned, straightened and tightly fitted in their proper positions.

Figure 3-5 indicates that there were significant air velocity variations and fluctuations across the horizontal planes. The greatest variations were at 14 inches from the light system (Figure 3-5a) with a 150 ± 15 fpm maximum and a 10 ± 5 fpm minimum. The horizontal planes at 22, 30, and 38 inches exhibited less total variation, but the ratio of highest to lowest velocity observed in any single plane still exceeded 10.

The significance of such air velocity variations within a plant growth area also depends somewhat on the type of experiment undertaken. In view of the fact that the above measurements were taken in an empty growth chamber, the problem of spacing pots on shelves to obtain uniform air circulation becomes even more complex. One user of the Model PGC-78 reported that certain pots within the chamber dried out considerably

14"

60±30	90±30	150±15	155±10
15±10	15±10	40±5	45±10
15±10	20±10	30±10	40±10
10±5	40±10	10±5	10±5
20±10	45±15	35±10	10±5
95±5	65±15	35±10	10±5
140±10	100±10	80±15	80±30

22"

30±5	75±15	100±15	55±10
20±5	35±15	55±15	100±20
15±5	40±10	30±10	25±10
20±5	40±5	25±10	10±5
55±10	65±15	40±15	15±10
110±10	90±20	65±15	30±15
55±10	100±10	80±15	100±10

30"

10±5	40±10	75±15	50±15
10±5	70±20	90±15	50±10
20±5	65±20	35±10	20±10
45±5	65±10	15±10	10±5
75±10	85±15	30±10	60±10
50±5	100±5	60±10	50±10
10±5	80±15	60±15	30±10

38"

10±5	15±5	30±10	40±10
30±15	95±15	65±15	90±10
40±15	65±10	30±10	30±10
20±5	70±10	50±10	30±10
20±5	90±15	75±15	40±10
15±5	115±15	125±15	60±15
10±5	40±15	40±10	25±10

Fig. 3-5

Fig. 3-5 Horizontal Air Velocity profiles 14", 22", 30", and 38" below the Percival Model PGC-78 Light Canopy (measurements spaced 8" apart).

quicker than others containing plants at the same stage of development (Gates, 1970). The non-uniform air flow often causes the leaves of some plants to flutter, while other plants in the same chamber are completely still.

Although the Percival Company advertises that the Model PGC-78 provides uniform air distribution within the plant growth area, no definite specifications are quoted. The engineering of the components of the PGC-78 air circulation system appears to have several deficiencies. Propeller bladed fans are used to circulate the air from the top of the growth area, down past the cooling and heating elements, and back into the growth area (Figure 3-6). The fans are mounted so that the air first hits the end wall of the chamber before going down through the conditioning system. The fans do not blow air directly at the coils. This situation, plus the flow resistance of the coils, the air distributing screens, pots and shelves, creates a back pressure that could easily exceed the pressure rating of a propeller-bladed fan. As evidence of this, blow-back into the chamber is observed around the fans.

The air diffusing screen supplied by Percival is a perforated aluminum sheet with .120 inch holes on .188 inch centers, which yields a porosity of 38%. NRC engineers (1962), have found that at the pressures and velocities encountered in growth chambers, a five percent porosity is the maximum for achieving a manifold pressure sufficient for achieving uniform air flow. Figure 3-5 indicates that the distribution screen must not have much influence on the air stream since the flow patterns are quite non-uniform with large (up to ± 50% of average) fluctuations.

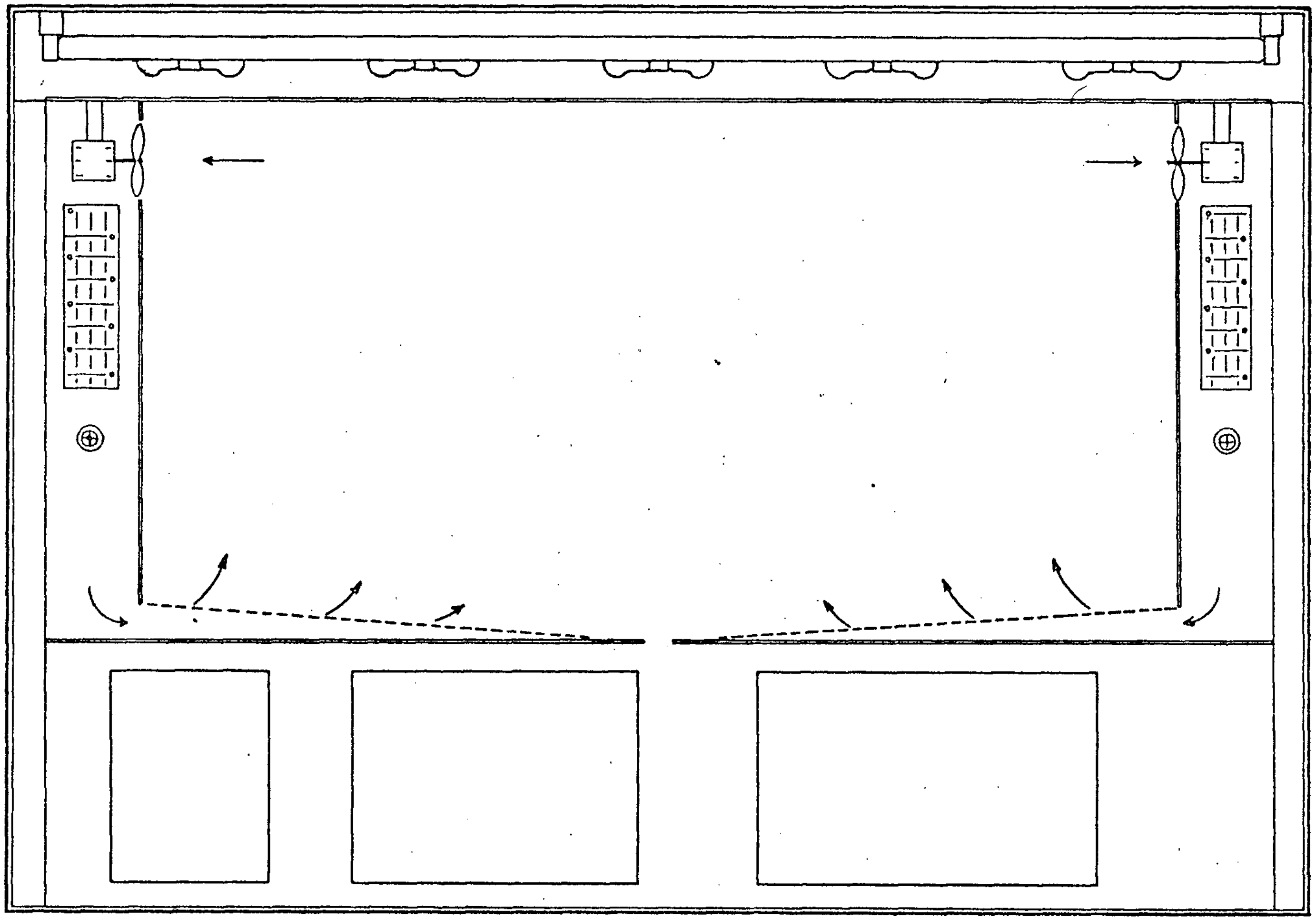


Fig. 3-6 General design of the Percival Model PGC-78 growth chamber.

Another problem is concerned with the fan motors, which are of the universal series wound type. Decomposition of the insulation on the wire in the motor is evidently caused by over-heating. Consequently, the motor slows down and eventually stops. The above measurements were complicated by this difficulty in that some fans were revolving faster than others. Non-uniform fan speeds occur in all of the Model PGC-78 growth chambers in the Plant Science Department.

(D) Humidity

There is no provision for humidity control on the Percival Model PGC-78. Special equipment for humidity control is an optional accessory. The Percival Company specifies that the relative humidity in the growth area will be in the range of 50 to 70% R.H., depending upon ambient temperature outside the growth chamber.

Measurements of relative humidity were taken with a PCRC Model 11 copolymer styrene sensor. One series of measurements was taken in the conditioning duct below the cooling and heating elements just before the air enters the plant growth area. The average readings were a low of 40% R.H. at 25^{o}C following a heating cycle and a high of 80% R.H. at 21^{o}C following a cooling cycle. In the chamber, centered between the walls and 30" from the light system, the humidity varied from 50% R.H. at 24.5^{o}C following a heating cycle and 70% R.H. at 22^{o}C following a cooling cycle. Humidity fluctuations of this magnitude may have some effect on plant growth, but such effects may be minimized by relatively short periods of heating and cooling (typically less than 2 minutes).

(E) Maintenance

The maintenance of growth chambers can be different for each model and manufacturer. The load on a chamber will determine what component in that chamber may be the least dependable, a fact the operator will seldom know. The experience of the Plant Science Department with eight Percival Model PGC-78 growth chambers illustrates the demanding operation of these chambers. The growth chambers are usually operated continuously 24 hours a day for what could be years at a time or until the equipment fails. All of the active components of the growth chamber have a finite lifetime, the length of which is dependent on the quality of the component and the harshness of the operating conditions.

Maintenance of the eight Percival Model PGC-78 chambers has primarily involved the replacement of light bulbs, thermostats, air circulation fans and refrigeration compressors. A schedule of light bulb replacement (discussed on page 2) would improve the current practice of replacing fluorescent and incandescent bulbs as they burn out. A predetermined schedule would provide more uniform light conditions as well as fixing the cost of light canopy maintenance. The thermostats (Penn Controls) have been the second most frequently replaced components following the light bulbs. Failure of these hydrostatic thermostats has been nearly exclusively due to contact seizure of the microswitch. The addition of an inexpensive component (a "clipper" diode) would minimize sparking caused by energizing and de-energizing solenoid valves and significantly improve the lifetime of the microswitch contacts. The third most frequently replaced components were air circulation fans. Two design problems appear to have affected the lifetime of the fan motors. First, air flow past the motor apparently is not sufficient to prevent decomposition of the motor winding insulation due to high temperature, leading to reduced motor speed. Secondly, the lubrication ports for the bronze bushings of the fan motor are inaccessible unless the chamber is emptied and the end panels removed. The motors are seldom lubricated and early failure is the result.

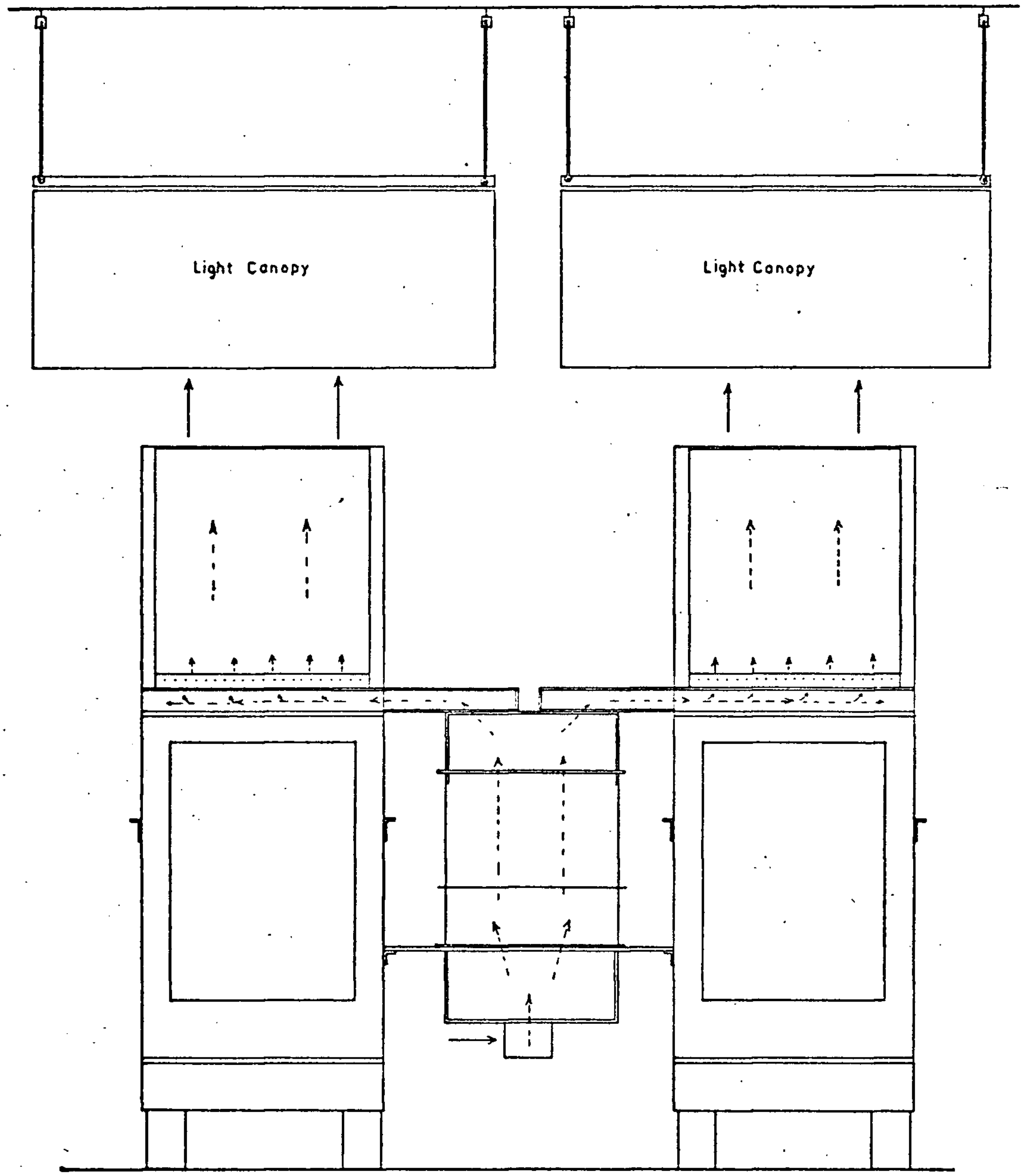
Chapter IV

LABORATORY SYSTEM DESIGN

To provide uniform controlled plant growth conditions, an artificial environment was developed which included the nutrient mist technique. Two identical chambers were constructed, each composed of a lower and upper section with air circulation ductwork to the upper section (Figure 4-1). The range and quality of environmental control eventually desired from this system is outlined in the Preface. The following discussion summarizes the system design in its present stage of development (December, 1970).

(A) Wall Temperature Control System

The two chambers and associated equipment were installed in a laboratory that is not air conditioned and is thermostatically temperature controlled. Room temperature can be as low as 20°C in the winter with a few periods as high as 30°C in the summer. This difference made it necessary to insulate the walls of the chambers completely from ambient fluctuations. The chambers are of relatively small volume (base area is four square feet), making it practical to use a water jacket for wall temperature control purposes. The water jacket around the lower or root chamber was very effective in controlling the air temperature in the lower chamber very close to that of the water jacket. The air temperature control is achieved by both conduction and radiative energy exchange with the water jacket. Thus, the air temperature in the lower chamber can be



Complete Air Flow System

Scale: 3/4" = 1'

Fig. 4-1 Design of the air flow system in the laboratory artificial environment changed by warming or cooling the water that is being circulated through the water jacket. The water jacket on the upper or shoot chamber supplements the temperature controlling action of the air circulation system, and also assists in removing heat that may be absorbed by the chamber walls from the light system.

Most of the upper and lower sections of the chambers were made of Plexiglass, which was chosen because of its ease of construction, modification, low upkeep, low cost and corrosion resistance. The main difficulty in working with Plexiglass is its flexibility and low resistance to stresses and strains. The water jackets had to be heavily reinforced to prevent bulging and subsequent breaking. Watertight seams were made by using silicon rubber glue supplemented with 4-40 machine screws placed in tapped holes on two inch centers. This procedure makes a strong seam and still allows the pieces to be disassembled for future modification. A more permanent method is to use a commercial glue (Cadco SC-94), which makes a Plexiglass to Plexiglass bond. Bonding is quicker and less expensive, but is not as strong or reliable under stress as the machine screw method. The first method was used on the chamber water jackets and the commercial glue was used on the ducting and manifold of the air conditioning system.

The lower (root) chamber was made with the outside dimensions of 25" x 25" x 36" (Figure 4-2). A four square foot chamber base (interior) was thought to allow sufficient space for four plants to be grown simultaneously without interference. Thirty-six inches was allowed for the length of a root system. This size will accommodate Phaseolus vulgaris (bush bean) approximately 8 to 10 weeks old. One quarter inch thick

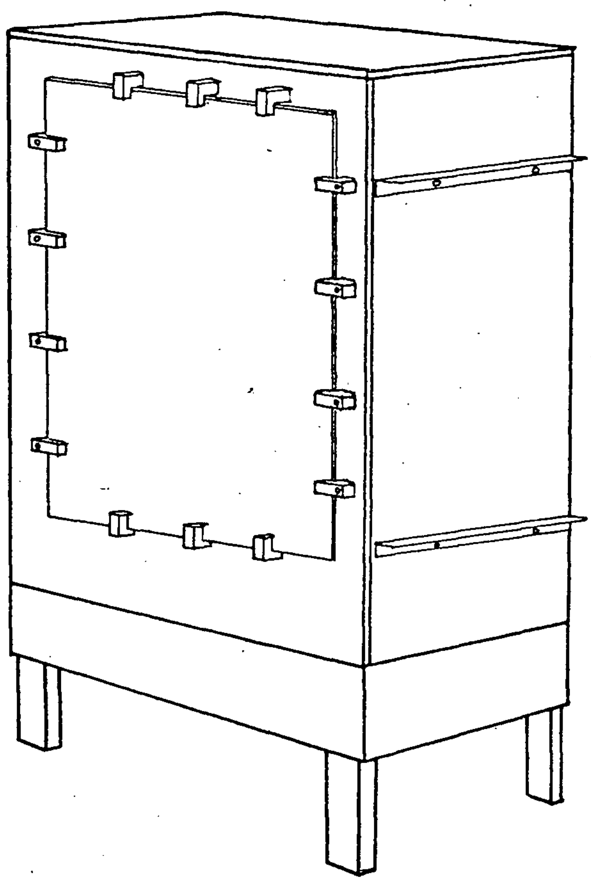


Fig. 4-2 Perspective view of Lower Chamber and Base

Scale: 1″= 1′

Plexiglass was used for the chamber walls, with two sheets being spaced one inch apart to make the water jacket. Only the two side walls and the rear wall were water jacketed. No jacket was made for the front panel so there could be access into the chamber. The front panel and top and bottom pieces of the lower chamber were made from one-half inch thick Plexiglass.

The upper (shoot) chamber was made with the outside dimensions of 25" x 25" x 25". Again this height allowance accepts Phaseolus vulgaris of approximately 8 to 10 weeks of age. For access into the upper chamber, the front panel was provided with 1/2" thick Plexiglass door insulated with 2" of styrofoam.

The plumbing for the upper and lower chamber was made from one inch and one and one quarter inch polyvinylchloride tubing. Large diameter tubing was used on the exhaust to prevent pressure from building up within the water jackets. Temperature controlled water was pumped into the base of the water jacket and an overflow drain was provided close to the top.

(B) Temperature Control System

For this project, a single source of temperature controlled water was provided for circulation through the chamber water jackets (Figure 4-3). A large capacity (approximately 80 liters) stainless steel water bath formed the main reservoir. A Blue-M refrigerated cooling coil immersed in the reservoir, provided the heating and cooling capacity (1000 BTU/hr). An electric stirrer was added to mix and circulate the water around the cooling coil. A magnetically coupled, plastic bodied pump drew water from

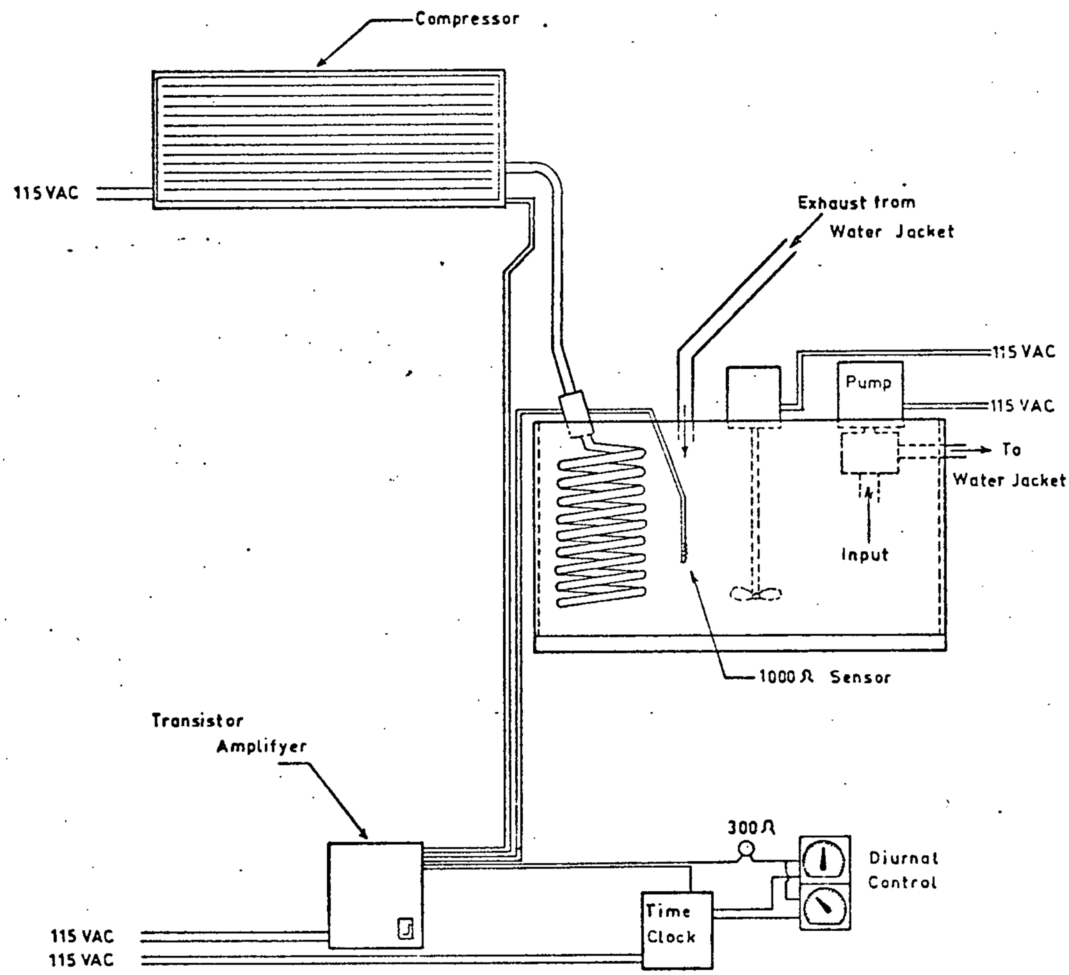


Fig. 4-3 Wall Temperature Control System

the reservoir and circulated it through the water jackets. A solid-state temperature control device was used to control the refrigeration system. The water in the reservoir was controlled at the temperature desired for the water jackets.

(C) Air Conditioning System

A good cooling facility was required to achieve the intended control of air temperature of at least ± $1/2^{o}C$. A face and by-pass damper-controlled cooling coil, a model of units made for industrial applications by Recold of Canada, was utilized for the control of air temperature. The operating principle of this cooling coil is such that when ambient air temperature is higher than the desired chamber temperature, all of the air passing through the cooling unit goes across water-chilled fins. As the chamber temperature reaches the desired control point, a modulating motor opens a damper to allow uncooled air to mix with that which has been cooled, thus providing a proportional control of the air temperature (Figure 4-4). The temperature sensing element was located inside the chamber manifold. It was connected to a small transistor amplifier that operated the modulating motor of the damper assembly.

Since the desired air velocity inside the chamber was of the order of seventy feet per minute, the total volume of air passing through the cooling system was correspondingly small. The low air flow requirement made feasible the use of a four hundred cubic feet per minute centrifugal fan. This type of fan was required since a positive pressure was needed to ensure smooth air flow and uniform mixing in the system, and to exceed the flow resistances of the cooling coil, the ductwork, and the plant

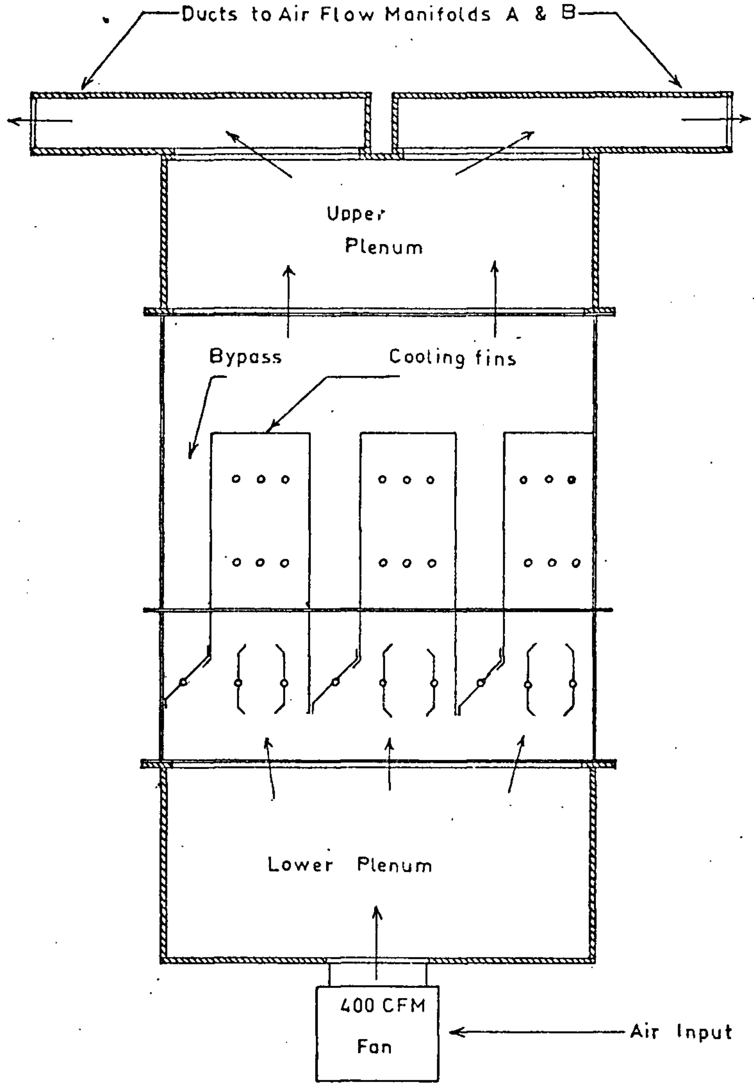


Fig. 4-4 Diagram of the air temperature conditioning system.

platform air diffusing system. The fan was driven by a shaded pole motor, the speed of which could be controlled by altering the voltage. Good control of the volume of air circulated could be achieved in this manner. Ductwork was provided to distribute the cooled air from the cooling coil to the chamber manifold. The system was designed so that the ducting for one chamber could be removed while the other remained in operation. The surfaces of the ductwork were insulated with 1/2" thick styrofoam to reduce heat exchange.

(D) Plant Platform Air Diffusing Manifold

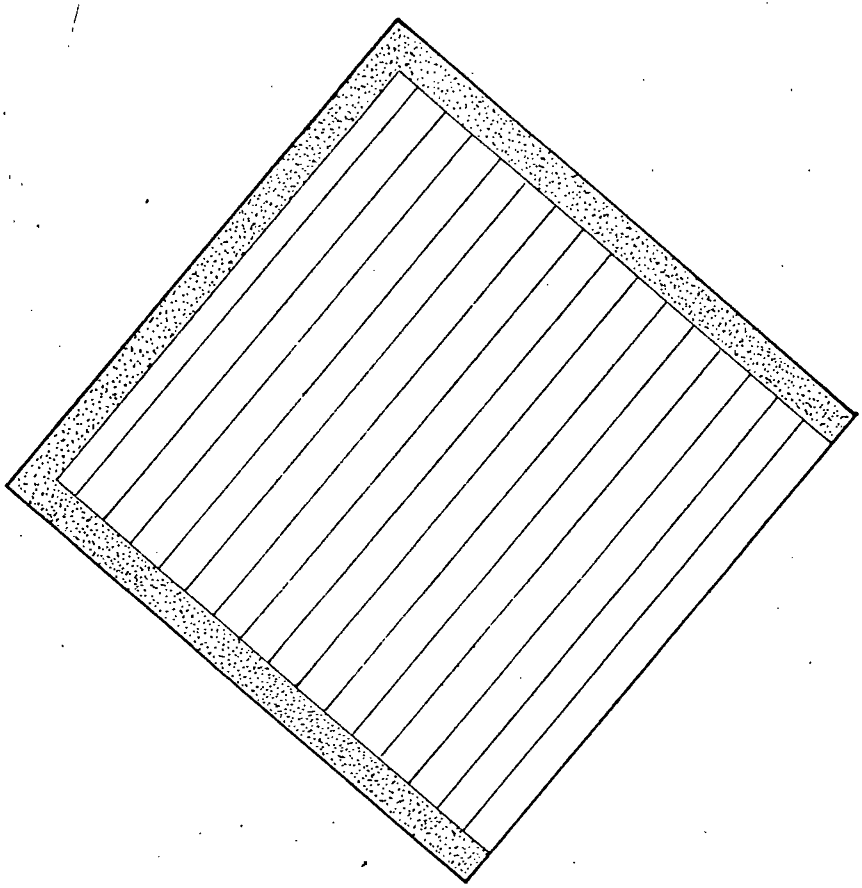
Air flow is one of the more difficult variables to control within a small enclosure. As discussed earlier, standard commercially available growth cabinets are limited in providing good air flow properties by their basic design. In particular, the air cooling facility is not able to remove heat from the light canopy and still maintain stable temperature and humidity conditions in the chamber.

The use of a vertical air flow about the plants has several advantages with respect to the engineering of growth cabinets. Most important is the fact that air passes directly through the plant growth area and is not circulated in the single or double cell fashion used with wall mounted fans (Percival, Sherer-Gillett, Controlled-Environments). Also, the conditioned air passes over the plants and is essentially out of the plant growth area before the major heat source, the light canopy, is encountered. A third advantage, which applies to all open systems, is that the chance of carbon dioxide depletion in the growth area is reduced by the continuous addition of fresh, filtered, laboratory air. The open system is best used when small volumes of air are required for circulation and the heat loads are large. Recirculating techniques are best suited for use in larger systems where a total loss conditioning system would be uneconomical.

The size of the chamber is generally limited by the length of the fluorescent tubes used. The open system allows the use of longer fluorescents by mounting the light canopy above the chamber wall structure (Figure 4-1).

The method chosen to diffuse the air from the plant platform came from a design by Kalbfleisch (1962). He tries several approaches to the problem of producing uniform air flow through a flat plate. He concluded that if five percent of the surface area of the plate were equidistantly spaced holes, uniform flow would result. The configuration involves 1/4" holes drilled at one inch centers over the entire surface. For use in plant growth chambers, corrugated sheet metal 1 1/4" on a side was used. This permitted the holes to be drilled in the vertical part of the corrugation which made it very difficult for foreign material to drop down into the manifold. This feature also made possible less interference to air entering the chamber from obstructions near the surface of the plant platform. For long periods of operation this removed the necessity of cleaning the base of the growth chamber; this, in turn, minimized disturbing the plants (Figure 4-5).

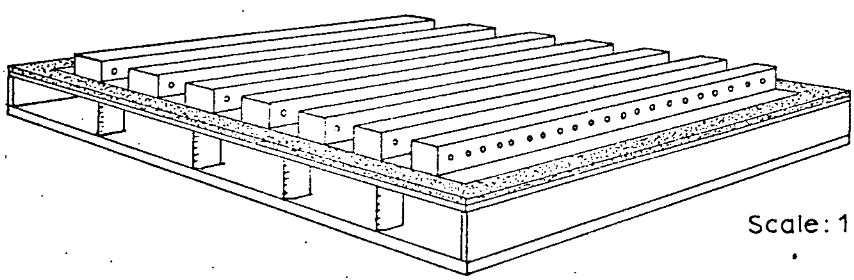
The requirement of a manifold below the air diffusing assembly that was no less than two inches thick required that a plant be at least two weeks old or tall enough so that the primary leaves were not disturbed by the manifold.



Top View

Fig. 4-5 Top view and perspective of the air distribution assembly.

Perspective



Scale: 1 1/2" = 1'

(E) Nutrient Mist System

The nutrient mist growth technique involves the suspension of the root system in a closed, dark, temperature-controlled chamber. For the purposes of this project, the crown of the plant was placed in an expanded foam cork which was fitted into a hole in a plate at the top of the lower chamber. The foam cork served as a barrier to water and heat transfer.

Two pneumatic spray nozzles were placed at the bottom of the root chamber to provide the mist to saturate the chamber. The nutrient mist, when saturating the root chamber, collects readily on the root systems (Figure 4-6). It is important that the spray does not directly hit the root system at high velocity, as several disturbances in root development can result. There is much experimenting to be done yet to find the best way to orient the spray nozzles in respect to the roots.

(1) Nutrient Solution

The nutrient solution selected for use in the nutrient mist was a modified Hoagland's No. 2 (Hewitt, 1965), consisting of:

50 ml.	1 M	$Ca(NO_3)_2$
50 ml.	2 M	KNO_3
20 ml.	1 M	$MgSO_4$
10 ml.	1 M	KH_2PO_4
10 ml.		Fe EDTA*
10 ml.		Micronutrients**

* Each ml. of the stock solution of Fe EDTA contains 5 mg. of Fe

** The micronutrient stock solution contains 2.86 gm. of H_3BO_3 (Boric acid), 1.81 gm. of $MnCl_2 - 4H_2O$ (manganese chloride), 0.11 gm. of $ZnCl_2$ (zinc chloride), 0.05 gm. of $CuCl_2 - 2H_2O$ (Sodium molybdate) per liter.

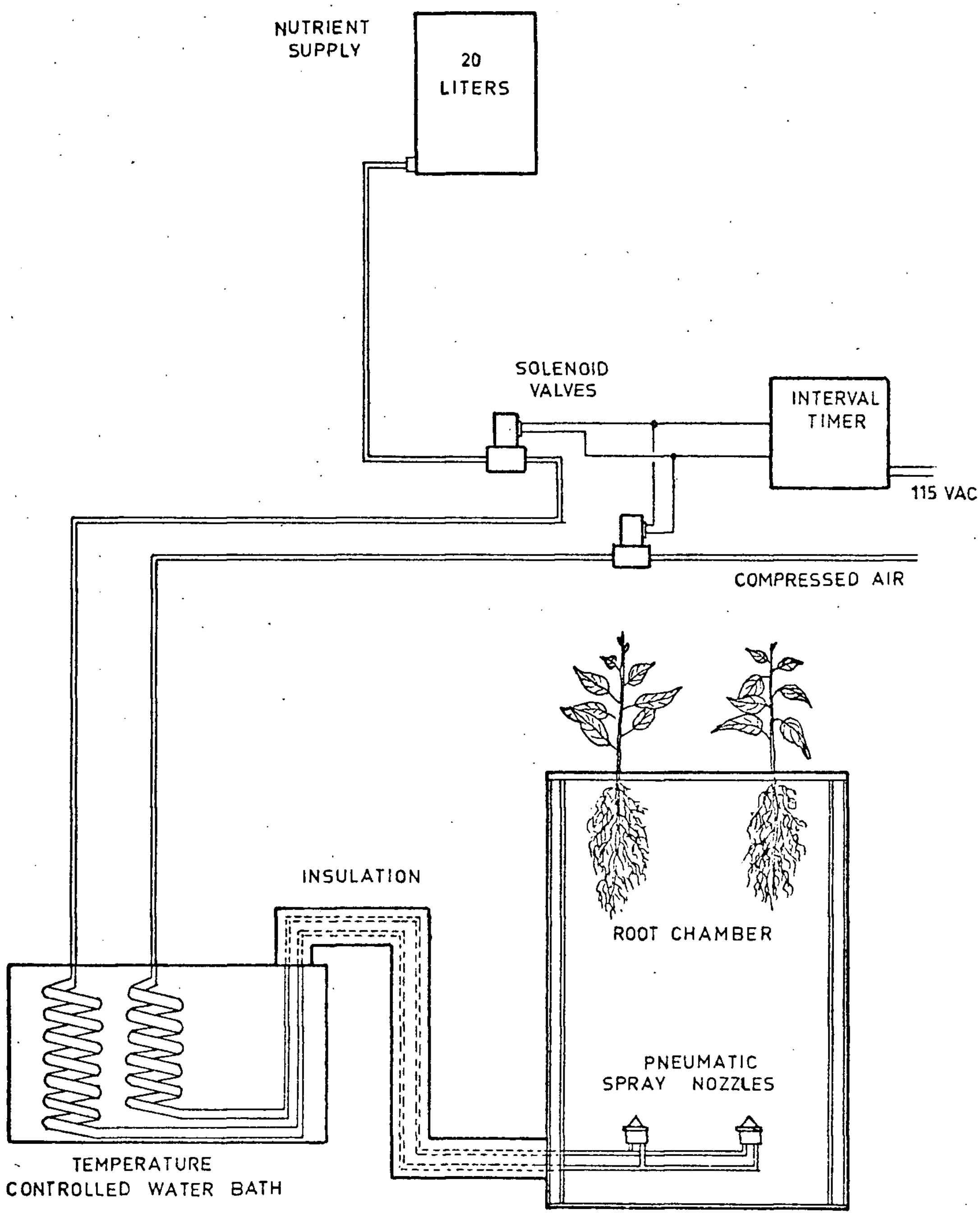


Fig. 4-6 Nutrient mist spray system.

The designated amount of each stock solution was added to distilled water and made up to 2000 ml.

A complete nutrient supplement is necessary when using a mist technique for plant growth. The modified Hoagland's No. 2 is easy to work with and provided sufficient nutrients for both tomato and bean plants used in preliminary tests. The phosphate concentration was kept purposely low to remove the possibility of a calcium phosphate precipitate. This precipitate can be avoided by adjusting pH, the value of which is dependent upon the relative concentrations of calcium and phosphate in the nutrient solution.

(2) Nutrient Mist Control System

The nutrient mist applied to the roots of a plant must be controlled at the same temperature as the root chamber water jacket. This was accomplished by passing the nutrient solution through a coiled copper tubing immersed in the water reservoir (Figure 4-6). The copper tube containing the nutrient solution was placed inside the over-flow drain from the root chamber water jacket so that the temperature of the nutrient solution was not affected by the ambient temperature. Subsequent temperature measurements showed no change in root chamber temperature when nutrient spray was applied.

The amount of nutrient solution necessary to maintain satisfactory growth is, at the present time, hard to specify. The best method determined so far is to observe the root system and adjust the amount of solution applied until the root system appears thoroughly covered with water droplets or a water film. More experience with the system should produce a better technique.

The capacity of the pneumatic spray nozzle was four or five liters per hour. Compressed air from the general laboratory supply provided the pressure for the spray. Intermittent spraying was required to conserve the nutrient solution, and excess nutrient solution was drained off the bottom of the chamber. An inexpensive time delay mechanism was constructed from a synchronous electric motor, a one-eighth inch thick, 10 inches in diameter Plexiglass disk, and a microswitch. The disk was rotated by the synchronous motor, and tabs placed on the perimeter of the disk operated the microswitch at predetermined intervals. The microswitch operated two solenoid valves which controlled the flow of nutrient solution and compressed air (Figure 4-6).

(F) Artificial Lighting System

The primary requirement of the light system for this project was to provide an intensity of approximately 2000 to 2500 F.C. (20,000 to 25,000 lux) at a distance of 24 inches from the light source. From tests reported by Kalbfleisch (Artificial Light for Plant Growth, 1963), it was determined that twenty Cool-White 48T12R VHO fluorescent light bulbs and fifteen 40 watt incandescent bulbs would produce the desired intensity and quality. Kalbfleisch also indicated that side curtains would greatly assist in producing a horizontally uniform light intensity below the light canopy. Eighteen inch long side curtains of sheet aluminum finished in a baked white epoxy were mounted on both of the light canopies constructed. Figure 4-7 shows the spacing of the fluorescent and incandescent lights in the canopies.

(1) Photoperiod Control

Three single pole, single throw time clocks were used to phase the light canopy on and off. The incandescents were switched on first in the morning, in an attempt to simulate the greater proportion of red wavelengths

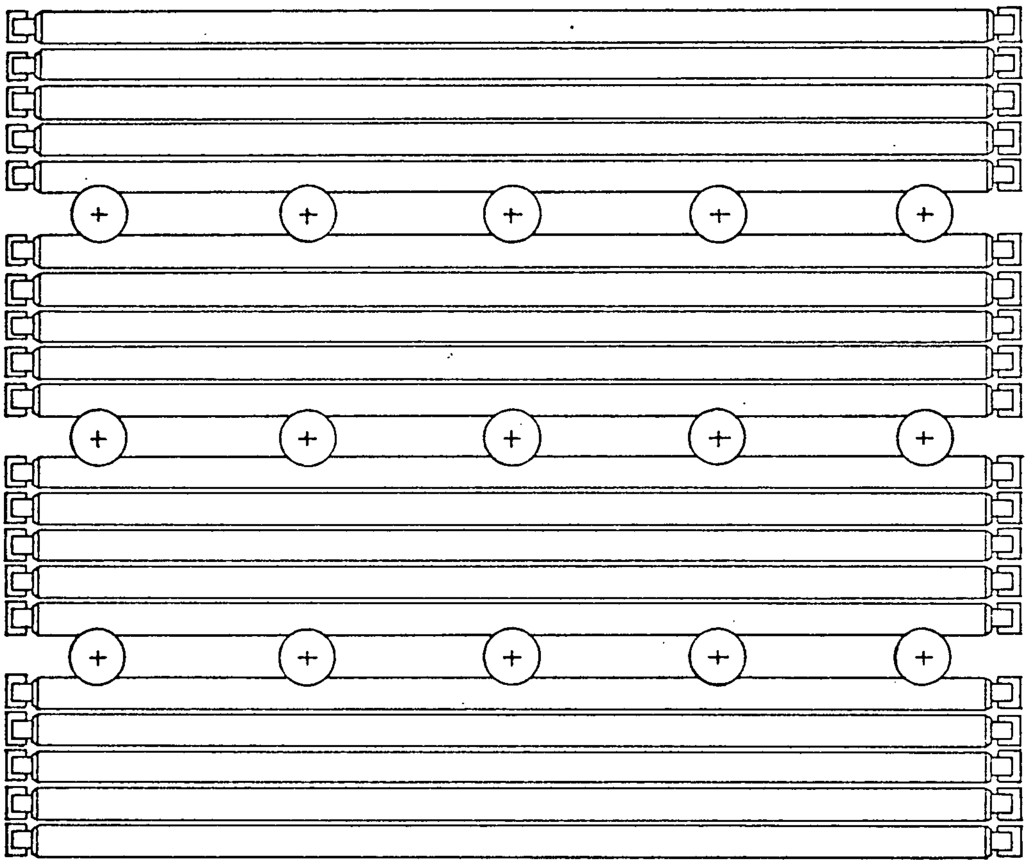


Fig. 4-7 Laboratory light canopy consisting of 20 48T12 VHO cool-white fluorescent lamps spaced 1 5/8" on centers with 15 40 W incandescent lamps spaced 10" apart in three rows.

in a natural sunrise. Approximately one-half hour later, one circuit of the fluorescents was switched on, and another one-half hour later, the second circuit of fluorescents was switched on. At the end of the plants "day", the fluorescents were phased out, and the incandescents switched off last, in an attempt to simulate a natural sunset. The actual photoperiod duration is determined by the length of time the incandescents are on. High ampere rated switches must be used since, for example, 20 one hundred and fifty watt fluorescent lamps will draw thirty amperes when in operation.

Chapter V

LABORATORY ARTIFICIAL ENVIRONMENT PERFORMANCE

The quality of environment that was set as a goal for the artificial environment developed in this project was outlined in the preface. The measurements presented in this chapter are an attempt at determining whether the system constructed approaches the intended environmental quality.

(A) Light System

A special twenty-two inch long motorized sensor apparatus similar to that described in Chapter III, was constructed for the measurement of light intensity profiles in the two foot square plant growth area. After several tests were made with silicon phototransistors and silicon photovoltaic cells, a selenium photovoltaic cell was selected as a light sensor since it offered greater linearity at light intensities above 2000 foot candles. The silicon photovoltaic cell became very non-linear above 2000 foot candles. The silicon phototransistor could not cover the required range without extra circuitry, and it showed greater sensitivity to temperature change than the selenium cell.

The fluorescent and incandescent lamps in the canopy had been operated approximately 200 hours before the measurements were taken. The light system was turned on and operated for two hours before the first measurement was recorded. This was done so that the light output had stabilized as much as possible. Before the light output remains stable, the lamps have to warm to operating temperature and evidently have to heat the surrounding equipment. From preliminary measurements, it was also noticed that the ambient temperature could noticeably affect the light output of the lamp canopy. Line voltage fluctuations may also account for some variation in light output. During a preliminary set of measurements, one half of the chamber was measured in the morning (at 10:00 a.m.) and the second half measured in the afternoon (3:00 p.m.). In this case, the light intensity in the afternoon was found to be 20% less at the same point in the chamber than in the morning measurements. To minimize this problem, the data presented here were measured in as short a time as possible (3 hours) with checks frequently made to positions measured earlier to make sure that the light intensity gradients being measured were not an artifact caused by changing conditions.

An equally difficult problem in measuring light intensity was the temperature sensitivity of the light sensor. This problem was circumvented by keeping a second light sensor, closely calibrated to the one in use, available for quick spot checks of the light intensity at a given location. The quick spot checks did not allow time for the second sensor to attain the temperature of the first and also served as an indication of sensor "fatigue", the phenomenon of sensor output dropping with time in constant light intensity. The selenium photocell did not require temperature compensation nor did it show any "fatigue".

The results of the light intensity measurements are presented in Figures 5-1a j. The ten graphs represent ten horizontal planes starting at two inches above the plant platform manifold and continuing up in two inch intervals to within two inches of the top of the chamber walls. Each horizontal plane consists of 100 measurements (10 x 10) spaced two inches apart. The measurements at the edges were spaced two inches from the

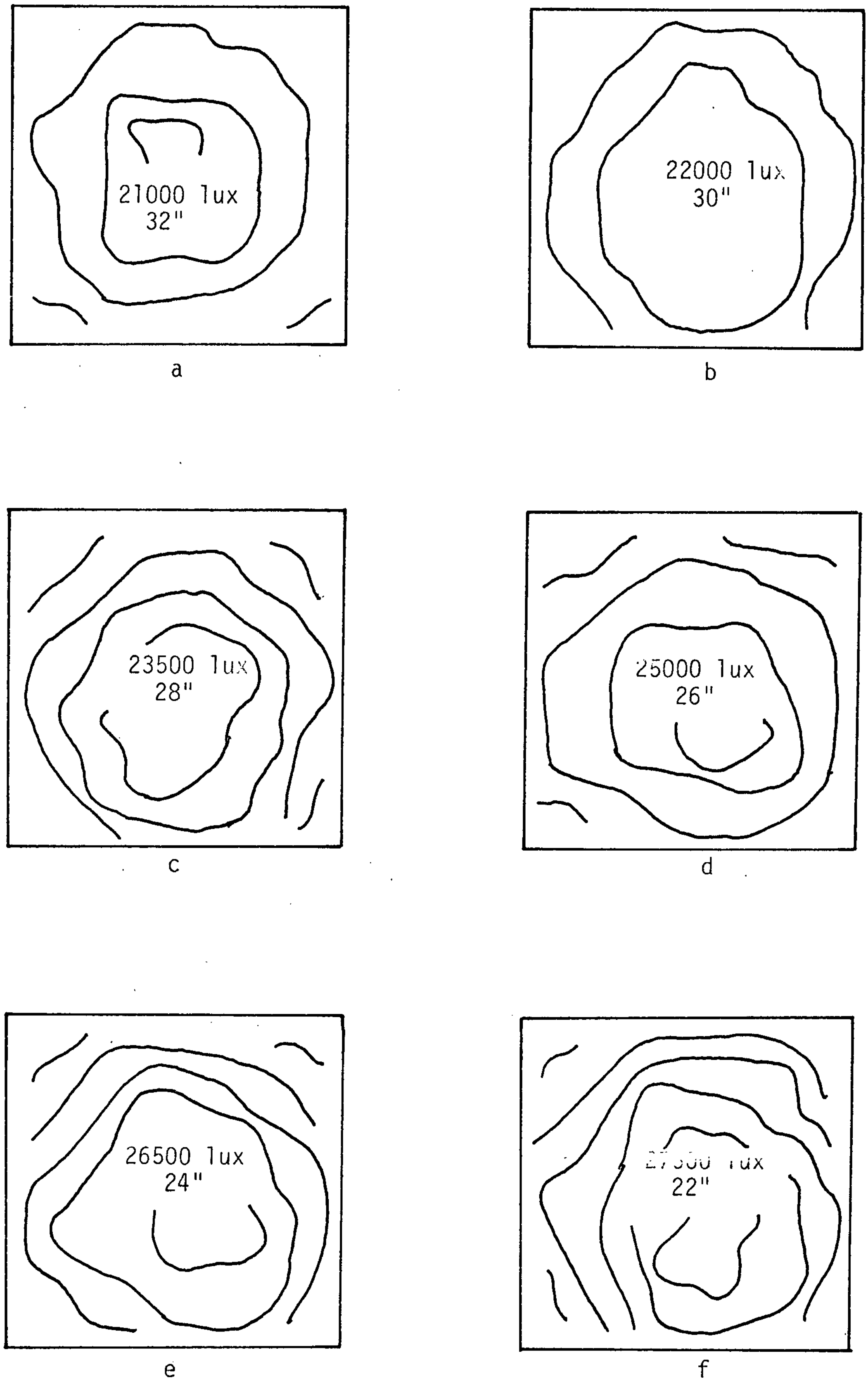


Figure 5-1 (a-f) Horizontal light intensity planes from 32" to 22" below the light canopy. (54 lux intervals).

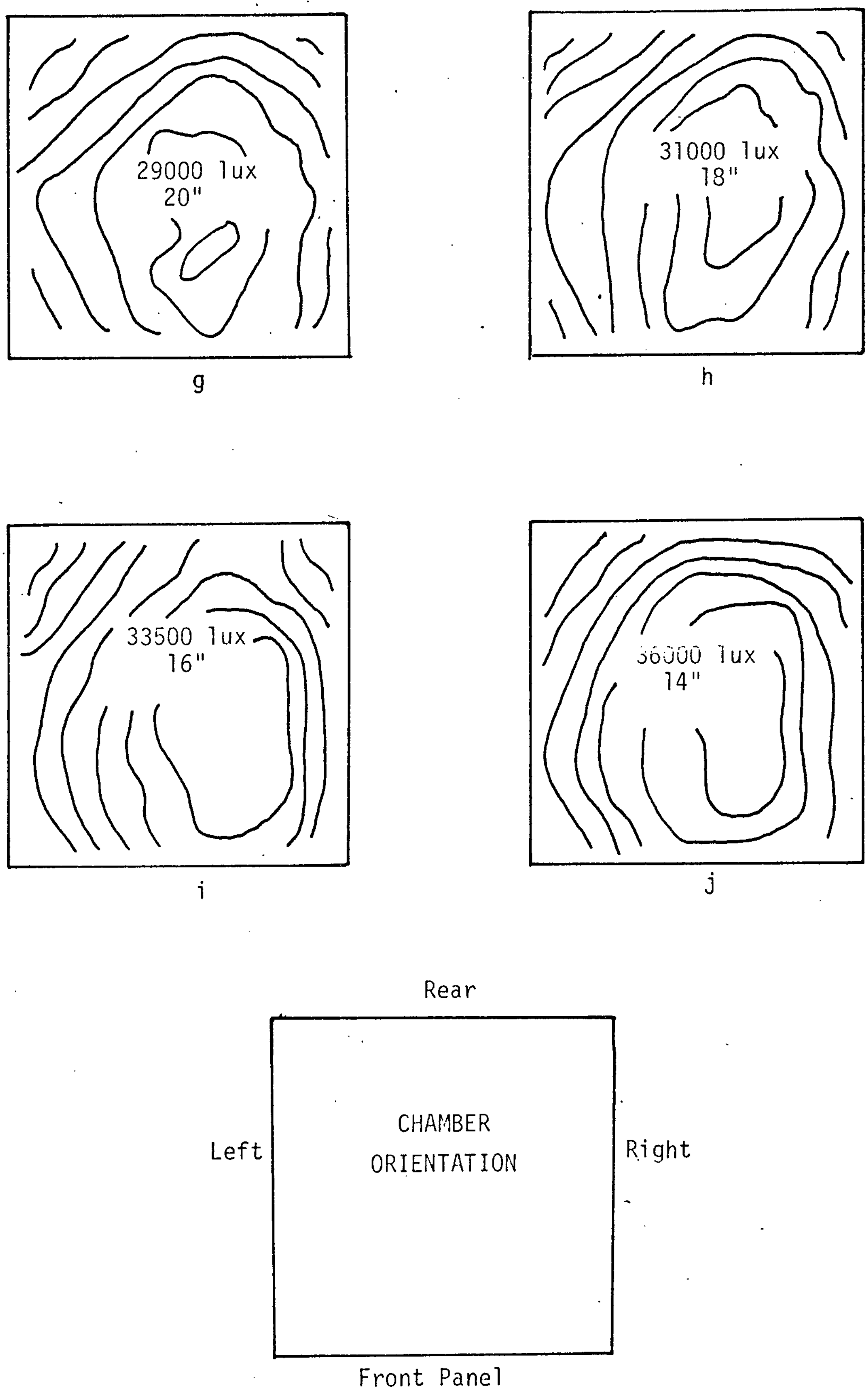


Figure 5-1 (g-j) Horizontal light intensity planes from 20" to 14" below the light canopy. (54 lux intervals).

chamber walls. The total of 1000 measurements were taken in less than a three hour period by means of the motorized sensor apparatus. The position of the lamp canopy relative to the plant growth area was as indicated in Figure 5-2. The lamps were a distance of 38" from the surface of the plant platform. The lowest horizontal plane (Figure 5-1a) was 32 inches and the highest plane (Figure 5-1j) was 14 inches from the lamps. There was a 54 lux (50 ft-c) change in light intensity between each line on the graphs in Figure 5-1a j.

Figure 5-1a was the lowest in light intensity with each plane above it increasing in intensity. This type of vertical intensity gradient was expected and is a consequence of the inverse radius squared law of radiation. Also, there was a gradual increase in the difference in intensity between adjacent horizontal planes. For example, in the center of the chamber, the difference between Figures 5-1a and 5-1b was 100 foot candles and between Figures 5-1i and 5-1j, 250 foot candles.

The variation of light intensity within each of the horizontal planes illustrates the importance of symmetrical design. Figure 5-2 shows that the chamber was overlapped by the light canopy on all sides, but that it was not squarely centered under the light canopy. As the upper horizontal planes indicate, the region of highest light intensity shifts forward and to the right of the center of the chamber, so that a plant oriented in that position could receive a significantly higher average light intensity than other plants in the chamber. In this case, the chamber was not squarely centered under the light canopy due to a lack of surrounding laboratory space, a condition which will be rectified in the future.

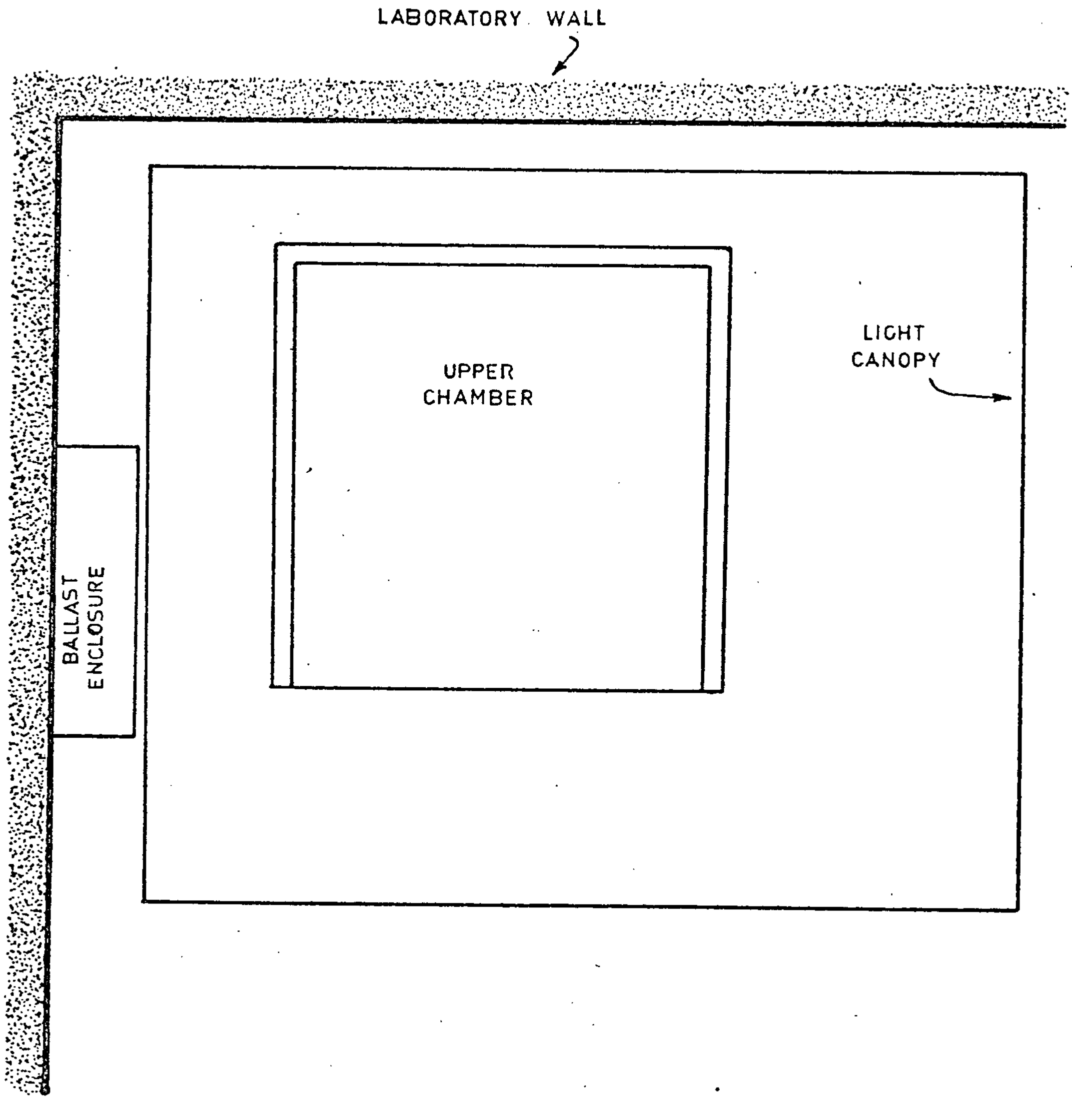


Fig. 5-2 Lamp canopy and chamber location relative to laboratory walls (scale 3/32" = 1').

Another factor not considered important at first was the presence of a dark walnut stained plywood box close to the left side of the chamber. This box covered the ballasts required by the fluorescent lamps. The dark surface of the box could possibly have influenced the light intensity within the chamber since the walls of the chamber were clear Plexiglass. Part of the significant increase in non-uniformity of light intensity in a single plane from lower to higher levels in the chamber may be due to this influence. In Figure 5-1a, the horizontal variation is about 100 foot candles and in Figure 5-1j, about 250 foot candles.

The above measurements of light intensity within the growth chamber do not come close to meeting the initial prerequisite of ± 50 foot candles variation on any single horizontal plane. As a result, a new design will have to be developed to improve the light intensity uniformity in the chamber.

(B) Temperature

The uniformity of temperature within the plant growth area was within the desired maximum fluctuation of less than ± $1/2^{o}C$. Ten thermocouples (copper-constantan, 28 gauge) were mounted at fixed positions every two inches from the plant platform to the top of the chamber. The front panel was installed and an average air velocity of 80 fpm was passed through the chamber. The total vertical temperature gradient was $1^{o}C$, with the 10 thermocouples placed in any location in the chamber. This uniformity of temperature was due to the uniformity of air circulation.

The total fluctuation of temperature at any given point was less than $\pm 1/4^{o}C$ about a control point of $20^{o}C$, which was approximately $5^{o}C$ below ambient laboratory temperature. A significant difference between this system and commercial chambers is the complete lack of heating and cooling cycles and the accompanying temperature changes.

The temperature within the root chamber was extremely stable and uniform with less than $\pm 1/8^{o}C$ temperature change detected over a 24 hour period. This is a result of the chamber being entirely enclosed (no changing heat loads) and having three water jacketed walls.

(C) Air Circulation

Obtaining uniform air flow velocity across a four square foot plant growth area was not as easy as originally thought. The plant platform manifold described on page 68 was greatly modified as a result of the measurements described in this chapter. The initial air flow patterns were as described in Figure 5-3. Two main problems were evident. The first was that air entering the plant platform manifold continued through the diffusing system into the chamber creating a velocity profile as in Figure 5-3. The result was a tremendous velocity gradient across the chamber, from 10 fpm on the entrance side to 200 fpm at the end of the plenum. After considerable experimentation, a series of 150 baffle strips positioned by hand produced an air flow in the plant growth area of satisfactory uniformity. Measurements at four, six, eight, twelve, sixteen, and twenty inches from the platform surface indicated an average air velocity of 75 fpm ± 5 fpm on the undamped mode of the Flow Corporation

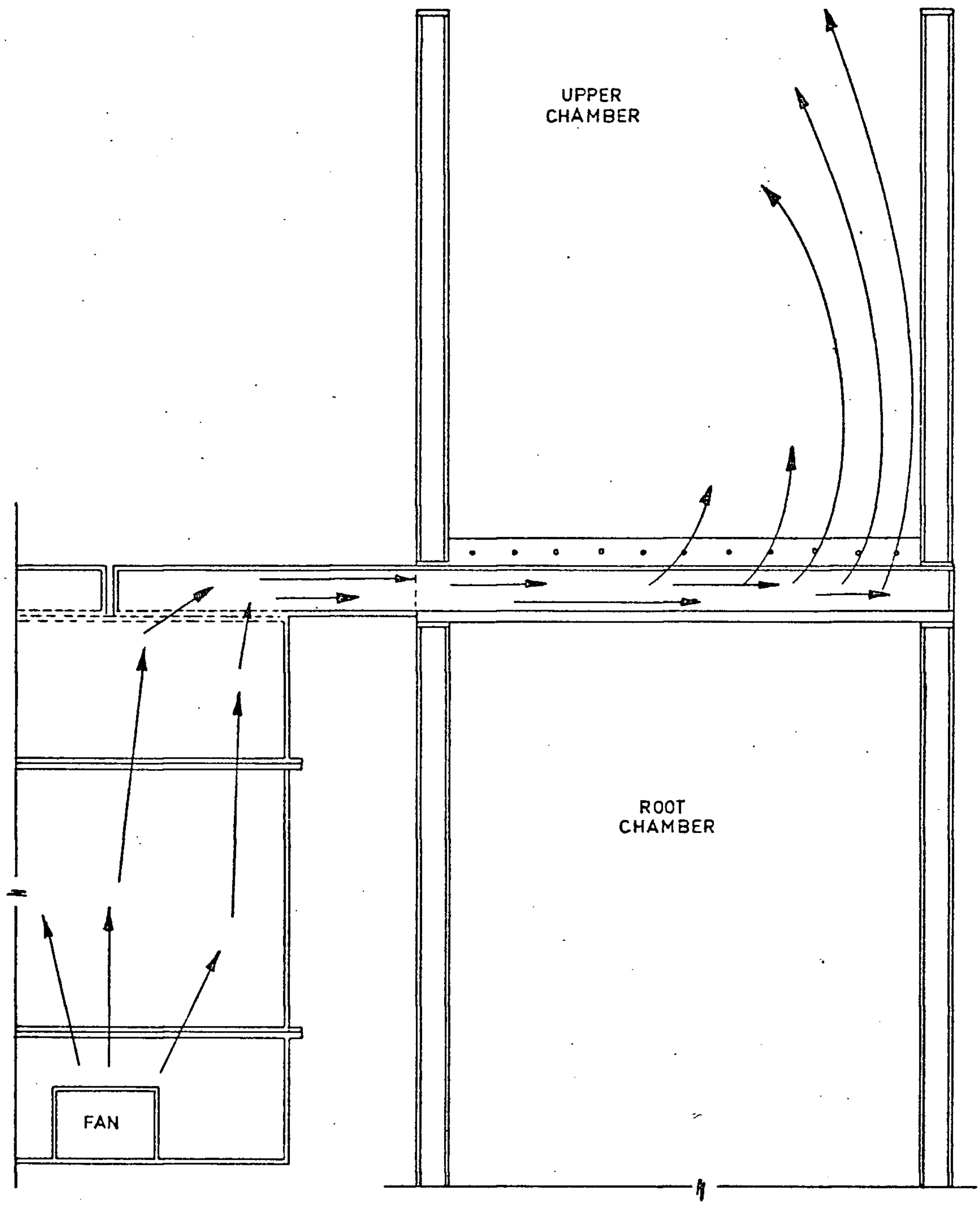


Fig. 5-3. Original nonuniform air flow pattern in upper chamber of laboratory system (scale 1/8" = 1")

Model 55B hot-wire anemometer. This was accomplished only under experimental conditions and would not have permitted the growth of plants in the chamber due to the obstructions in the manifold. The second problem with the basic design was the asymmetrical duct from the post-conditioning plenum to the plant platform manifold (Figure 5-4). Special baffles were required to balance the air flow across the duct as it entered the platform manifold. The asymmetrical duct was required since the cooling coil was narrower than the chamber.

As a result of the above difficulty in achieving uniform air flow, a new design will have to be developed before plants are used in the system.

(D) Humidity

Since the air used by the conditioning system is drawn from the laboratory, and since these tests were made at below ambient temperatures, the humidity in the system ran consistently higher than the humidity in the laboratory. The laboratory humidity was usually between 40 and 45% relative humidity with the windows in the lab closed. A chamber humidity of 55% was recorded with laboratory temperature at 25°C and the upper chamber's temperature at 20°C with 15°C water flowing through the cooling coil. Like commercial growth chambers, the average level of humidity in the upper chamber in its present stage of development is completely dependent upon ambient conditions. However, the absence of heating and cooling cycles in the laboratory chamber prevents the cycling of humidity that occurs in commercial chambers.

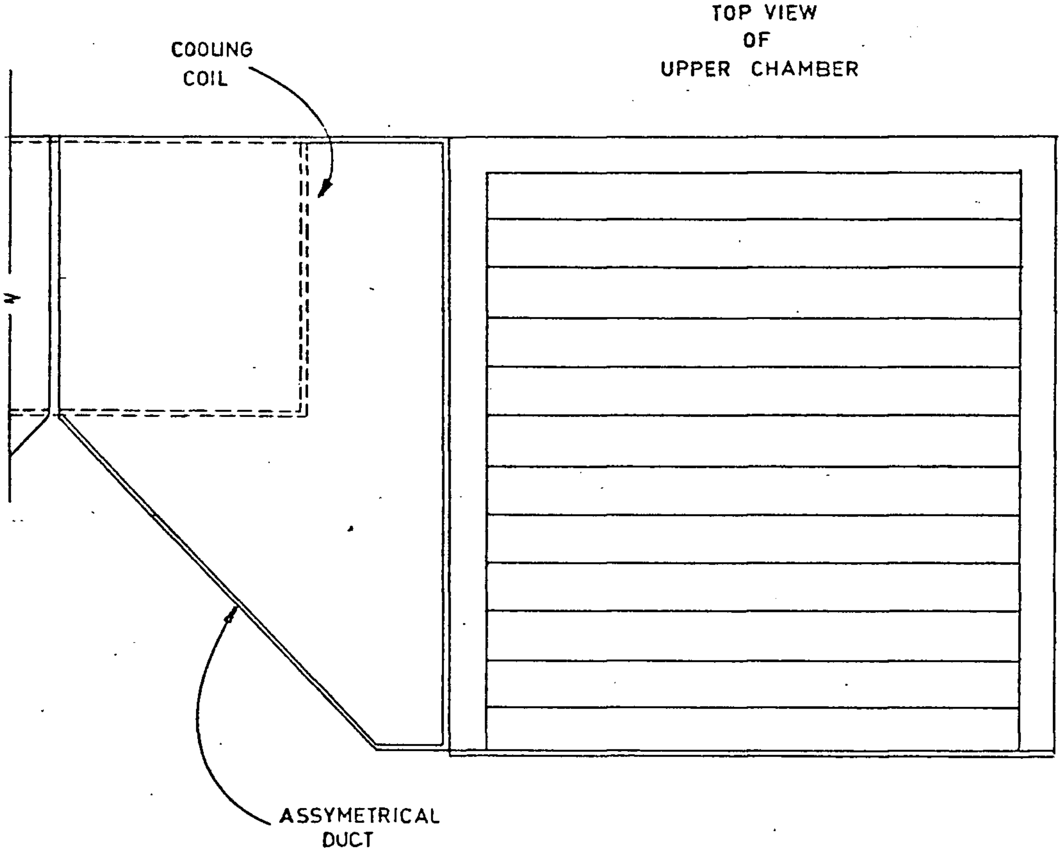


Fig. 5-4 Asymmetrical duct from cooling coil to upper chamber of lab system.

(E) Summary of Laboratory System Performance

The temperature control system of the laboratory chambers provides more stable and uniform temperatures than the Percival PGC-78, and more than satisfies the quality of temperature control outlined in the Preface. The technique of modulating control, rather than On-Off control eliminates temperature and humidity fluctuations due to heating and cooling cycles.

The light intensity measurements indicate that a higher light intensity was available in the laboratory system than in the PGC-78, but that both horizontal and vertical gradients still exist. Further improvements could result from the use of reflective wall coatings and louvers at the top of the chamber to generate more uniform light distribution. The achievement of a uniform 1000 lux intensity in a growth chamber still appears to be a very difficult engineering problem.

After considerable experimentation, satisfactory air flow conditions were achieved in the laboratory system. The final design provided a uniformity of air flow which was better than the ±10 fpm variation originally specified. However, the use of many baffles to achieve this uniformity is an adequate arrangement for one flow rate only, and a more adjustable arrangement would be desirable.

The control of humidity was not attempted in the laboratory system mainly because of expense and because of inexperience with humidity control mechanisms. Effective humidity contol requires satisfactory temperature control and this was achieved in the present system. A saturate and reheat air conditioning system could be adapted to the existing design and would probably provide excellent humidity control.

SUMMARY

This research has led to the construction of prototype growth chambers which incorporate the nutrient mist technique and which provide improved environmental control in comparison with a commercially available system.

The development of an artificial environment for critical studies of the physiology of plant growth is a complex problem. The design of an artificial light source for a plant growth chamber requires consideration of the characteristics of the lamps used, the reflectiveness of the chamber interior, and the influence of the lamp canopy and chamber geometry on the horizontal and vertical light intensity profiles. In a small chamber, the walls, whether reflective or not, are the main cause of horizontal and vertical light intensity gradients (in the absence of plants).

Temperature control systems for plant growth chambers must be engineered to provide precise control over a much wider range of conditions than are generally encountered in conventional air conditioning. Solid state temperature controls provide the required calibration, sensitivity, set point adjustment and programming capabilities for artificial plant growth environments.

Variations in relative humidity are inherent in artificial plant growth environments using evaporative cooling refrigeration systems. The hot-gas bypass technique assists in reducing humidity fluctuations.

Uniform air circulation in an artificial environment is dependent on the characteristics of the air, the design of ducts and shelves, and the spacing and development of the plants being grown. A special manifold can be constructed to provide an airflow at 80 ± 10 fpm across the plant growth area.

Instruments used for the measurement and indication of environmental variables must be stable, rapid in response, and must not affect the environment being measured. A traveling sensor was developed and was found to be particularly useful for the rapid, reproducible remote measurement of the profiles in plant growth chambers.

The Percival Model PGC-78 growth chamber contained large gradients in environmental conditions and did not conform entirely to advertised specifications. The specifications were considered to be unsatisfactory in extent and could be misleading to an operator.

The laboratory growth chambers constructed during this research produced more uniform environmental conditions than did the PGC-78, and satisfied many of the original criteria for a satisfactory artificial environment system. The chambers were particularly effective with respect to the uniformity of temperature and air flow. In a small chamber, water jacketted walls and a modulated air conditioning system that lacks heating and cooling cycles can be used to provide temperature control to within $\pm 1/4^{o}C$ of a control point. Nevertheless, additional improvements in the control and uniformity of light intensity, and in the regulation of humidity, are required to improve the effectiveness of the chambers in plant research.

LITERATURE CITED

1. Bulley, N.R., Nelson, C.D. and Tregunna, E.B. 1969. Photosynthesis: Action spectra for leaves in normal and low oxygen. Plant Physiol. 45: 89-101.

2. Cooper, J.P. and N.M. Tainton. 1968. Light and temperature requirements of tropical and temperate grasses. Herb.Abstr. 38: 167-176.

3. Controlled Environments Ltd. 1969. Growth chamber design. Technical Bulletin No. 70. Winnipeg, Manitoba.

4. Doebelin, E.O. 1966. Measurement systems: Application and design. McGraw-Hill, New York. pp. 502.

5. Gates, J.Wayne. 1970. Personal Communication.

6. General Electric. 1957. Psychrometric Chart.

7. General Electric. 1960. Fluorescent lamps. Technical Manual No. TP-111.

8. General Electric. 1960. Plant Growth Lighting. Technical Manual No. TP-127.

9. General Electric. 1961. Incandescent lamps. Technical Manual No. TP-110.

10. General Electric. 1963. Light measurement and control. Technical Manual No. TP-118.

11. Hewitt, E.J. 1966. Sand and water culture methods used in the study of plant nutrition. Technical Communication No. 22 (Revised 2nd edition). Commonwealth Bureau of Horticulture and Plantation Crops, East Malling, Maidstone, Kent. pp. 302.

12. Kalbfleish, W. 1963. Requirements of environmental facilities for the growth of plants. Engineering Research Service, Research Branch, Can.Dept.Ag., Ottawa, Canada.

13. Kalbfleish, W. 1963. Artificial light for plant growth. Engineering Research Branch, Can.Dept.Ag., Ottawa, Canada.

14. Martin, E.V. and F.E. Clements. 1936. Significance of transpiration. Plant Physiol. 9: 165-172.

15. Percival Manufacturing Co. 1967. Refrigeration System. Bulletin 2-B.

16. Rohm and Haas Co. 1967. Plexiglass Design Guide.

17. Salisbury, F.B. and C. Ross. 1969. Plant Physiology. Wadsworth Publishing Co. Inc., Belmont, California. pp. 513-518.

18. Threlkeld, J.L. 1970. Thermal environmental engineering. Prentice-Hall Inc., Englewood Cliffs, N.J. 07632. pp. 205-256.