Chapter 2

Temperature

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Introduction

Temperature is an indication of the thermal energy content of matter. The thermal energy content of plants affects many physiological processes, and the measurement and control of temperature are critical in all biological studies.

Growth chambers provide a means of controlling air temperature and, thereby, the temperature of the plants they contain and the matrix in which the plants are growing. Control is used either to investigate specific effects of temperature on some aspect of plant growth and development or to maintain a stable thermal environment in which temperature difference does not confound plant response to other environmental variables. In either case, it is essential to appreciate the principles that govern thermal relations of objects within the chamber and the natural limitations imposed by chamber design.

Thermal Environment

Energy Exchange

The temperature of plants in a growth chamber is determined primarily by the transfer of heat between plant tissue and the environment. Plants exchange energy with their environment by conduction and convection, by the absorption of radiation and re-radiation of longer wavelengths, and through evaporation of moisture. Most of these exchange processes occur at the interface between the leaves and air. Energy is exchanged constantly as the system tends toward a steady-state condition (although this is attained rarely in nature). The overall heat balance at equilibrium may be represented as follows:

$$E_S = E_I + E_R + E_C + E_L + E_M$$

where:

E_I = Total radiation absorbed.

E_R = Re-radiated long-wave radiation.

E_C = Conduction and convection.

E_L = Latent heat transfer (evaporation or condensation of water at the leaf surface).

E_M = Balance of heat produced (positive) and heat consumed (negative) in metabolic reactions, although this is generally insignificant relative to other temperature exchange processes.

E_S = Energy stored (causing an increase in temperature) within the plant. Under steady state conditions E_S is 0.

Radiation

Plants absorb radiant energy incompletely over a broad spectral range. All leaves have high absorptivities in the photosynthetically active waveband (PAR; 400-700 nm), but the energy used in photosynthesis is relatively small, representing less than 3% of the total energy budget and can generally be ignored in a consideration of thermal energy dynamics. The leaves of most species absorb poorly in the near infrared range (700 to 1500 nm); as these wavelengths are transmitted through or reflected from the leaf, they contribute relatively little to the input of thermal energy (Mellor et al., 1964). In contrast, absorption in the far infrared waveband (1500 to 30,000 nm), emitted essentially as blackbody radiation by lamps and all objects in the plant's environment, approaches 95% (Gates and Tantraporn, 1952) and can contribute significantly to the thermal energy load.

The sources of radiant energy to which a plant is exposed in the field differ from the sources in the growth chamber. Under clear, daytime field conditions, most of the radiation absorbed by the leaf is derived directly from the sun, whereas in the lighted growth chamber, lamps and reflectors are the primary radiation sources. Since gases in the earth's atmosphere absorb large quantities of radiation within the far infrared waveband, plants in the field receive relatively little of the radiation beyond 3000 nm. Lamps used in growth chambers, including incandescent, fluorescent, and high-intensity discharge (HID) types, emit large quantities of far infrared radiation (Thimijan and Heins, 1983; Tibbitts et al., 1983), little of which is absorbed by the growth chamber atmosphere. Therefore, plants grown in growth chambers are subject to a far greater thermal load than those grown in the field.

This problem is often addressed in chamber design by including a barrier of glass or plastic between the lamps and the growing area. This barrier will absorb much of the far infrared radiation from the lamps, thus reducing leaf absorbance of this energy. However, the barrier must be cooled, or it will heat up and emit far infrared radiation to the plants. Cooling can be accomplished by flowing temperature-controlled air or water across the barrier. Water works most successfully because it absorbs large quantities of the infrared radiation while cooling the barrier (Bubenheim et al., 1988), but it is more costly to install and maintain.

As much as 75% of the radiation absorbed by plants is re-radiated in the far infrared wavelengths (Gates and Benedict, 1963). Plants also dissipate thermal energy by conduction and convection and by the evaporation of water at the leaf/air interface (latent heat transfer).

Conduction

In the case of a temperature gradient, energy may move between a plant and its environment on the molecular level. Energy is transferred by conduction from the leaf cells to the air molecules in contact with the leaf; however, because the thermal conductivity of air is low, conductive heat transfer at the leaf/air interface is limited until convective movement of air molecules away from the leaf surface occurs. Conductive heat transfer also occurs for plant parts in contact with solid or liquid media, but the impact on the plant's energy balance is small.

Convection

Temperature gradients between leaves and the air result in corresponding gradients in air density and pressure, which cause turbulence and the initiation of convection. In still conditions, the boundary layer of air next to the leaf expands as it gains heat, decreases in density, and is replaced by cooler air in the process of "natural" or free convection. Heat is dissipated more effectively, however, through "forced" convection, under the influence of air movement around the leaves. Wind velocities of about 0.5 to 1.0 m s^{-1} at the leaf canopy level are required to promote adequate convective heat transfer in growth chambers. Higher velocities are not recommended because they might increase mechanical stress on the plant. Although we normally think of convection as a means of dissipating heat from the plant, the reverse also is true. When air temperature exceeds leaf temperature, heat energy is transferred convectively to the leaf. This condition occurs when air temperature is reduced or when transpirational cooling is large.

Latent Heat Transfer

At 25°C, there are 2436 J (Joules) used when 1 gram of free water evaporates. The substantial dissipation of energy through evaporation largely accounts for a plant's ability to regulate its temperature within physiologically acceptable limits. The amount of latent heat transferred from a leaf via evaporation varies directly with the vapor pressure gradient between the area of evaporative surface within the leaf and the air in the chamber. Under conditions of adequate water supply and fully open stomata, transpiration increases with increasing leaf temperature. Thus, latent heat transfer also increases as the leaf/air temperature difference increases. If transpiration rates are sufficiently high because of a large vapor pressure gradient, leaf temperature may fall below air temperature (Gates, 1968; Drake et al., 1970).

Control of plant temperature is an important aspect of growth chamber culture. A close interrelationship exists among the various heat transfer processes. Consider, for example, the possible effects of an increase in radiant flux from the lamps. Absorption of thermal energy by leaves increases and, as leaf temperature rises, increased amounts of energy are re-radiated. The energy emitted is proportional to the fourth power of the leaf temperature. The vapor pressure deficit between the leaf and air increases so that transpiration and latent heat loss also increase. Meanwhile, the increased temperature gradient between the leaf and the chamber air results in greater dissipation of energy by both conduction and convection. The overall result is a stabilization of plant temperature at some new value.

It is important to understand that most growth chambers are designed to control air temperature, but considerable deviation may exist between the air temperature and plant temperature particularly under high radiation loads. McCree (1984), for example, observed that sorghum leaves exposed to radiation from metal halide lamps (2.34 kW m^{-2} input wattage) in a growth chamber, with air movement at the plant canopy level of less than 0.1 m s^{-1}, were as much as 16°C warmer than the air. Such discrepancies may cause problems for the investigator, particularly since, in chambers with high thermal loads, leaves and shoot tips in the upper canopy often are warmer than those at lower levels. This should not, however, be considered an immutable drawback of growth chamber research. Limiting the input of thermal energy to the plant growing area by installing lamp barriers and increasing air movement are important design and operational considerations. Above all we should not be satisfied with measurements of air temperature alone. Measurements of plant temperature at various levels in the plant canopy can assist in the correct interpretation of results. Because empirical relationships between air and plant temperatures can be derived from these measurements under steady state conditions, chamber air temperature can also be used to control plant temperature at a desired value (Matsui and Eguchi, 1973).

Temperature Control

All growth chambers incorporate systems to control air temperature within specified limits. Air is circulated constantly in the chamber between the plant growth area and the "mechanical" area containing the temperature control equipment.

Heating and Cooling

Air temperatures rise because of lamp radiation, so cooling is the primary requirement during light periods. Older chambers were designed to alternate between heating and cooling in response to control signals from a temperature sensor. The simplest on-off system cycles the coolant through the cooling coils when the chamber is above the set point and turns heaters on and bypasses coolant when the chamber is below the set point. The on-off system causes significant cycling of temperature; fluctuations of 5°C on either side of the set point are not unusual. Although there is no evidence to date that temperature cycling has any significant impact on plants, the problem has not been rigorously studied. On-off systems are commonly programmed to provide a neutral temperature range in which the air is neither heated nor cooled. The use of a neutral range usually lengthens the heating-cooling cycles but reduces their amplitude and often completely eliminates the need for air warming when lamps are energized.

Better control of temperature can be achieved with a proportional or modulated system in which the rate of heating and cooling is proportional to the deviation of temperature from the set-point. These systems are more costly than a simple on-off control, but they significantly reduce temperature cycling. The incorporation of microprocessors has facilitated the development of modulated temperature control, and it is now standard in most growth chambers.

Chamber design has an important impact on the required capacity of the chamber heating/cooling system and on the uniformity of plant temperature within the growing area. The influence of high irradiance on plant and air temperature has already been discussed. When barriers are used between the lamps and the plants, different systems are required for handling the air above and below the barrier. A dedicated fresh air ventilation system or air conditioning above the barrier is essential to decrease temperature around the lamps because excessively high temperatures shorten lamp life.

In some chambers fitted with HID lamps, water rather than air is used for lamp cooling. Water is circulated around or within the luminaries to eliminate heat. A 2.0-cm layer of temperature-controlled water above a barrier can absorb and remove most long-wave radiation. This method is used successfully in several controlled-environment facilities (Warrington, 1978) and in high-irradiance chambers.

Cooling equipment generally consists of heat exchangers, which use as coolants either chilled water or ethylene glycol supplied from a remote refrigeration system, or refrigerant supplied directly from a self-contained refrigeration unit. Chilled water systems are commonly found in large installations where many chambers are grouped together. The operation and maintenance of a central refrigeration facility is more efficient and less costly than operating independent systems for each chamber. Chilled water systems, however, are limited in their ability to cool growth chambers and usually cannot reduce temperature below 10°C. Refrigerant systems can cool to temperatures below freezing, but the heat in the refrigerant must be removed by means of air- or water-cooled condensers.

When purchasing a unit with a water-cooled condenser, it is necessary to verify that cooling water requirements can be met either by tap water or through a cooling tower supply. If an air-cooled condenser is chosen, care must be taken to confirm that the heat that is released into the room can be removed by ventilation.

Electrical resistance heaters are most commonly used for air heating in growth chambers, although some units can cycle warm refrigerant vapor through coils to raise air temperature. Temperature sensors and measurement/control devices operate in conjunction with the heaters and heat exchangers to maintain desired air temperature.

Temperature uniformity across the plant growth area is maximized when air flows vertically within the growth chamber. Vertical air flow leads to gradients in air temperature between the upper and lower leaves of the plant canopy (Fig 1; Nitsch, 1972), but this is preferable to the gradients from one side of the chamber to the other caused by horizontal air flow. Temperature gradients can be measured to determine the variations by placing shielded sensors in a defined grid within the volume occupied by the plants (Nitsch, 1972).

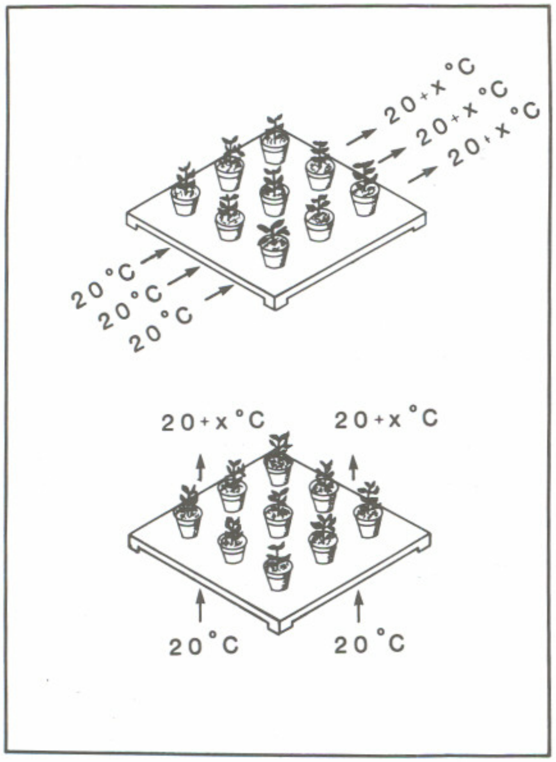

Figure 1. Typical temperature stratification among plants subjected to horizontal or vertical air flow in a growth chamber

Limit Controls and Alarms

Mechanical or electrical failures result in uncontrolled deviations from the set-point temperature. Irreparable damage to plant material and chamber components can be avoided if the entire chamber can be turned off quickly and an operator warned of the malfunction. A simple thermostat safety control allows the user to set upper and lower temperature limits. Deviations above or below those limits will initiate a power shutdown and activate an alarm. Commonly, high-temperature alarms deactivate the lighting system, whereas low temperatures deactivate the compressor. The high-temperature alarm should also disconnect the circulating fans and resistance heaters. Temperature limits should be set about 10°C above and below the set point so that small temperature changes, such as door openings, do not activate the alarm.

Sensing Systems

Many different types of sensors are employed in growth chamber temperature control. Sensor selection should be based on reliability, sensitivity to temperature change, and long-term stability. Thermistors often are chosen because they fulfill these criteria and are relatively inexpensive. Older chambers may use mechanical sensors such as liquid-in-metal or deformation-type thermostats. Both types of mechanical sensors have the significant drawback of a long response time, which leads to large temperature deviations. They are no longer used in manufactured growth chambers.

Temperature control requires accurate monitoring of temperature in the vicinity of the plant canopy. Control system sensors are usually located in aspirated boxes in the chamber or outside the plant growth area. In the latter case, a special duct or pipe is often used to draw air directly from the plant canopy to the sensor. Since a temperature gradient generally exists between air in the intake and return ducts (Morse, 1963), sensors should not be mounted in the main ducts where temperatures rarely represent air temperature around the plants.

Programming Temperatures

The maintenance of air temperature at a defined set-point is an essential operational feature of all growth chambers. Many experiments require a change of set point once, or several times, during a diurnal period. The investigator may further require that temperature changes gradually and continuously ("ramps") over a specified time period (Miller and Langhans, 1985). Temperature and programming systems have been designed to meet these needs.

Digital computerized systems for temperature control are available in many growth chambers and permit great flexibility in programming. Temperatures can be changed from minute to minute to create a gradual progression or regression. When used as part of a modulated system, these systems allow precise temperature control and, if desired, can provide close duplication of average field temperature conditions.

Low-Temperature Chambers

Controlled environment research on cold-hardiness and the effects of chilling on plants requires use of special low-temperature growth chambers. Most chambers are capable of controlling air temperature between 5 and 45°C with the lights on. Maintenance of temperatures below 0°C can be achieved in chambers that are well insulated and equipped with a modified refrigeration system. Low-temperature chambers generally incorporate two heat exchangers (evaporators). Liquid refrigerant is pumped through one evaporator for a preset period, then through the other. Warm refrigerant vapor is directed through each evaporator immediately after its refrigerating cycle to remove ice from the coils. The evaporators are generally separated from the main air duct by movable louvres, which close during the warm refrigerant cycle. Freezing of the louvre mechanism is a common problem in these systems, and electric heating cables may have to be installed to facilitate louvre operation. Requiring subzero temperatures places a particularly heavy load on the refrigeration system and presents some unique difficulties that require special design and engineering solutions (Robotham et al., 1978). Consultation with refrigeration engineers familiar with growth chamber design will be essential. When extremely low temperatures (below -15°C) are required during dark periods, it may be preferable to use a dual chamber system in which plants are moved between a conventional growth chamber and a freezer at the end of each photoperiod.

Measurement

Instruments

Monitoring temperature is essential in all growth chamber studies. Few chamber control systems will function flawlessly throughout the course of an experiment; it is the investigator's responsibility to be aware of deviations from preset conditions. Sensors and measurement devices that are useful for monitoring air and plant temperature fall into three main categories: 1) those that depend upon the expansion or contraction of a substance (metal, liquid, or gas); 2) electrical detectors, which depend upon changes in metallic resistance or current flow with temperature; and 3) remote detectors, which sense the temperature of plants or other objects by measuring the amount of infrared radiation emitted.

Expansion Thermometers. Several types of expansion thermometers are available. The most common is the liquid-in-glass thermometer, which is of limited usefulness for either plant or air temperature measurement because of its large size and slow response time. Liquid-in-glass thermometers traceable to, or calibrated by, the National Bureau of Standards, however, should be used for the periodic calibration of other sensors used in growth chamber temperature measurement (Tibbitts, 1986).

Other types of expansion thermometers use the deformation of a bimetallic strip (a bond of two metals with dissimilar coefficients of expansion) to move a pointer on a calibrated scale. If the scale is printed on paper and wound around a moving drum, a permanent, timed record of changes in air temperature can be recorded. But the bimetallic thermograph also suffers from the drawbacks of large size and slow response time. Usually, it is not possible to aspirate the metallic sensor in a growth chamber adequately, or to shield it from thermal radiation from the lamps. Furthermore, experience has shown these instruments require frequent calibration to preserve a maximum accuracy of 0.5 to 1 percent of scale range (Simpson and Pettibone, 1975). Their use in growth chamber studies should be restricted to providing a rough indication of temperature fluctuations or large deviations from set conditions.

Many growth chambers feature another type of expansion thermometer to record temperature on a circular time chart, mounted externally. This system (sometimes known as a liquid-in-metal thermograph) comprises a fluid-containing metal bulb connected by capillary tubing to a C-shaped or helical chamber. A temperature-induced change in fluid volume produces a degree of chamber deformation. The temperature-sensitive bulb usually is located in the chamber airstream, away from the influence of lamp radiation. These instruments also have a slow response time and cannot monitor the full extent of any rapid or cycling temperature change. Consistency and accuracy of measurement are difficult to achieve because of frequent shifts and distortion of the linkage of the pressure-sensitive chamber.

Thermocouples. Thermocouples consist of a pair of dissimilar metallic conductors joined to form two junctions in a simple circuit. An electromotive force (emf), proportional to the temperature difference between the junctions will flow spontaneously in the circuit. If one junction is held at a known (reference) temperature and an instrument capable of measuring the emf flow is included in the circuit, then the temperature of the unknown (measurement) junction can be calculated. The accuracy of these devices may be 0.1°C if reasonable precautions are taken.

Many metals and metallic alloys can be used to make thermocouples, but relatively few are used in biological studies. The most common is the copper-constantan, or type "T", thermocouple, which has excellent corrosion resistance and a nearly linear response over the 0 to 50°C temperature range (Simpson and Pettibone, 1975). Type "K" (Chromel-Alumel) thermocouples have a similar response and are preferred for reasons discussed at the end of this section. Thermocouples are relatively inexpensive and easy to construct. Two-conductor wire is readily available and can be soldered to form the measurement junction, but welding is preferred, especially with thin wire thermocouples, to reduce measurement errors (Spomer, 1975).

A significant advantage of thermocouples for temperature measurement in growth chambers is their size. Small-diameter wire (less than 0.1 mm) permits the construction of junctions with very low heat capacity to allow precise air temperature measurement. Junctions can be pressed closely to, or inserted into, plant tissue to measure plant temperature (Perrier, 1971). The small emf generated in response to thermocouple junction temperature requires sensitive measurement equipment. Most thermocouple instruments in use today incorporate independent electronic temperature sensors (a thermistor, or resistance temperature detector) to measure reference junction temperature. The temperature of the measurement junction is calculated electronically. Errors with thermocouples can be minimized by ensuring that measurement junctions are shielded from the direct effects of radiation. Wires connecting the measurement and reference junctions should be protected from heat or cold to prevent conduction of heat along the wires, and special care should be taken to ensure that all wires and connections are electrically insulated to prevent unwanted "thermocouples" from occurring in the circuit. The errors resulting from the conduction of heat down the wires can be minimized significantly by using type "K" (Chromel-Alumel) thermocouples, which eliminate the use of highly conductive copper wire. When installing thermocouples, investigators should check to ensure that the wires are not picking up an induced emf.

Resistance Temperature Detectors (RTD). The resistance of certain metals changes with temperature, and this property provides a reliable and accurate means of measuring temperature in growth chamber studies. Resistance temperature detectors are usually constructed of copper, nickel, or platinum wire wound around a nonconductor such as glass or plastic. They are very stable and resistant to environmental degradation (Perrier, 1971). Although their large size makes them unsuitable for plant tissue temperature measurements, they are well suited to the continuous measurement of air temperature, provided normal precautions are taken to shield the sensor from lamp radiation.

The accuracy of RTD is similar to that of thermocouples; measurements accurate to within 0.1°C are possible. Measurement instruments used with RTD must be capable of measuring the resistance of the sensor as a small current is supplied, usually from a DC source in the circuit. Because changes in the electrical resistance of metals caused by fluctuations in temperature are extremely small, special circuitry and sensitive equipment are necessary. RTD are generally calibrated by the manufacturer. The calibration information supplied with the instrument permits the investigator to calculate temperature from the measured sensor resistance. In data acquisition systems, calibration information can be stored and used to calculate and provide direct readings of sensor temperature. The high cost of RTD restricts their use to studies in which stability and reliability are of paramount importance. For most applications, another class of resistance thermometers, the thermistors, is more practical and popular.

Thermistors. Thermistors differ from RTD in that, because they are semiconductors composed of metallic oxides and not pure metal, their resistance decreases curvilinearly, rather than increases, with temperature. For small temperature ranges, however, the output from the sensor can be linearized with appropriate circuitry, and many thermistors are supplied in this form. Many different types of thermistors are available. They range in size from disks of 1 cm or more in diameter to beads of less than 0.001 cm in diameter. The latter have a short response time and are suitable for plant tissue temperature and other point measurements (Sapoff, 1972).

Thermistors, like RTD, require a power supply and instrumentation capable of measuring changes in resistance or a voltage drop across the unit. Unlike the RTD, however, the change in thermistor resistance with temperature is large so that sensitivity over narrow temperature ranges is improved. Thermistors are used extensively for both plant and environmental temperature measurement in growth chamber studies. A poor tolerance of harsh environmental conditions and long-term instability are often cited as disadvantages of thermistors for biological studies. Sensors for use in chamber air or plant temperature measurement, however, are supplied encased in glass, epoxy resin, or stainless steel. These manufacturing techniques have improved stability and resistance to damage.

Semiconductors. Several types of semiconductor temperature sensors, based upon the temperature sensitivity of silicone, are available. These sensors have increased in popularity in recent years because they cost little and require no sophisticated measurement devices. The semiconductors consist of a two-terminal, temperature-sensitive current source encased in epoxy or stainless steel. When excited by a low DC voltage, a current flows which is proportional to the temperature of the device. Calibration usually is available from the manufacturer or can be compiled by the user. Since the output of semiconductor silicone sensors is a current, the sensor can be located at long distances from the current measuring device without introducing errors due to line "noise" or voltage change. Furthermore, special shielded wire is unnecessary, thus making the connection of many sensors to a central measuring device relatively inexpensive.

Infrared Thermometers. Physical contact with the plant or air is essential for accurate temperature measurement with all the previously described systems. Infrared thermometry provides an alternative for remote measurement of the temperature of objects (including, but not limited to, plants) in the chamber environment. The technique is based upon the principle that all objects radiate energy at a rate proportional to their temperature. The actual amount of radiation emitted or re-radiated is proportional to the product of the emissivity of the object and the fourth power of its absolute temperature (the Stefan-Bolzman equation). Emissivity is the ratio of the total radiation emitted by the object to the radiation emitted by a perfect blackbody of similar shape and size (Gates, 1962), and its value is always less than 1 for biological materials.

Infrared thermometers gather radiation over a specified waveband (generally between 8 and 14 microns in those instruments designed for plant and animal study). The energy is absorbed by a blackened receptor/thermal detector (a thermistor or RTD or, in some cases, a thermopile consisting of 20 or 30 thermocouple junctions connected in series). Measurements of receptor temperature permit calculation of the energy flux from the target object and its temperature. The main use of infrared thermometers in growth chamber studies is the measurement of plant canopy temperature although it must be recognized that the reading provides an average of the temperatures of all of the leaf surfaces being viewed. Individual leaf measurements are possible using miniature narrow field of view sensors positioned within a few centimeters of the leaf. A significant factor for all measurements is the accurate determination of emissivity. The leaves of plants have an approximate emissivity of 0.95 (Gates and Tantraporn, 1952). Variations do occur, however, among species and with the physiological condition of the plant. Maximum accuracy of the infrared thermometer (roughly ±0.3°C) can only be achieved with emissivity known to three significant digits (Hanan, 1984). Such determinations are difficult for plant canopies (Fuchs et al., 1967) in the highly reflective conditions commonly found inside growth chambers. An approximate value must be used for emissivity; therefore, infrared thermometry techniques are best restricted to comparative measurements of plant temperature taken under similar biological and environmental conditions.

Sensor Location

Accurate determination of temperature in growth chambers depends not only on the absolute accuracy of the sensor and measurement system, but also on correct sensor placement to obtain readings representative of experimental conditions. Sensors must be shielded from the heating effects of lamp radiation (by covering with reflective material) and aspirated at an air flow rate no less than 3 m s^{-1} to maximize convective heat transfer. Because air temperature can vary considerably from location to location, it is difficult to obtain a truly representative air temperature measurement from a single sampling point. A minimum of five measurements should be taken in each chamber to establish an accurate average temperature for the plants in the chamber. Readings must be taken over time to compensate for temperature cycling.

Leaf Measurement

Leaf temperatures can be measured either directly by contact with thermistors or thermocouples or indirectly by infrared thermometry. Contact measurement requires that the sensor constantly touches, or is embedded in, the abaxial leaf surface. An extremely small sensor is necessary to approach an accurate estimate of tissue temperature, and even then many pitfalls and possible sources of error exist, which are difficult to overcome. Sensors that contact the leaf surface integrate leaf and boundary layer air temperature (Gates and Benedict, 1963), whereas embedded sensors may induce local changes in stomatal aperture and concomitant alterations of leaf temperature (Perrier, 1971). Thermal conduction along the leads to the sensor can cause appreciable measurement errors in growth chambers. This problem can be reduced by using thin wires (less than 0.1 mm) to connect the sensor to insulated extension wires. Embedding the sensor in the leaf eliminates measurement errors due to thermal conduction and, notwithstanding possible errors due to stomatal disruption, this is the best method, where leaf size permits.

Data Acquisition and Storage

Thermocouples, thermistors, RTD, and other temperature transducers can all be used with commercially available meters that allow continuous measurements and, in some cases, storage of data. These instruments vary considerably in their complexity. Hand-held meters are useful for checking chamber air temperature during programming and for spot-checks throughout the course of an experiment. Continuous monitoring and record-keeping are accomplished most conveniently with a data acquisition system (DAS) that can accept one or more sensor inputs. Some chambers incorporate a DAS that functions both as a control and monitoring system for the chamber. Such systems are convenient, but sensor drift or malfunction is not detectable unless a second system is operated simultaneously (Tibbitts, 1986). Cost and the type of record-keeping required will influence the investigator's choice of a DAS. If several chambers are used in an experiment, sequential monitoring and recording of temperatures will be a minimum requirement. Many systems allow direct interfacing with a computer to expand data storage capacity and permit analysis and collation of data.

Literature Cited

Bubenheim, D.L., B. Bugbee, and F.B. Salisbury. 1988. Radiation in controlled environments: Influence of lamp type and filter material. J. Am. Soc. Hortic. Sci. 113(3):468-474.

Drake, B.G., K. Raschke, and F.B. Salisbury. 1970. Temperatures and transpiration resistances of Xanthium leaves as affected by air temperature, humidity, and wind speed. Plant Physiol. 46:324-330.

Fuchs, M., E.T. Kanemasu, J.P. Kerr, and C.B. Tanner. 1967. Effect of viewing angle canopy temperature measurements with infrared thermometers. Agron. J. 59:494-496.

Gates, D.M. 1962. Energy Exchange in the Biosphere. Harper and Row. New York. 151 pp.

Gates, D.M. 1968. Transpiration and leaf temperature. Ann. Rev. Plant Physiol. 19:211-238.

Gates, D.M., and C.M. Benedict. 1963. Convection phenomena from plants in still air. Am. J. Bot. 50:567-573.

Gates, D.M., and W. Tantraporn. 1952. The reflectivity of deciduous trees and herbaceous plants in the infrared to 25 microns. Science 115:613-616.

Hanan, J.J. 1984. Plant Environmental Measurement. Bookmakers Guild, Longmont, Colorado. 326 pp.

Matsui, T., and H. Eguchi. 1973. Feedback control of leaf temperature. Environ. Control Biol. 11:55-63.

McCree, K.J. 1984. Radiation levels in growth chambers fitted with high intensity discharge lamps, with or without thermal barriers. Crop Sci. 24:816-819.

Mellor, R.S., F.B. Salisbury, and K. Raschke. 1964. Leaf temperatures in controlled environments. Planta 61:56-72.

Miller, W.B., and R.W. Langhans. 1985. Growth and productivity of 'Grand Rapids' lettuce in diurnally fluctuating temperatures and day/night average temperatures. J. Am. Soc. Hortic. Sci. 110:560-565.

Morse, R.N. 1963. Phytotron design criteria—engineering considerations. Pp 20-37. In: Engineering Aspects of Environment Control for Plant Growth. CSIRO, Melbourne, Australia.

Nitsch, J.P. 1972. Phytotrons: Past and future. Pp. 33-55. In: A.R. Rees, K.E. Cockshull, D.W. Hand, and R.G. Hurd, eds., Crop Processes in Controlled Environments. 391 pp.

Perrier, A. 1971. Leaf temperature measurement. Pp. 632-671. In: Z. Sestak, J. Catsky, and P.G. Jarvis, eds., Plant Photosynthetic Production. Manual of Methods. Dr. W. Junk, The Hague.

Robotham, R.W., J. Lloyd, and I. J. Warrington. 1978. A controlled environment room for producing advective white or black frost conditions. J. Agric. Eng. Res. 23:301-311.

Sapoff, M. 1972. Temperature, Its Measurement and Control in Science and Industry. Vol. 4, Part 3. Instrument Soc. Am., Pittsburgh. Pages 2109-2121.

Simpson, J.B., and C.A. Pettibone. 1975. Temperature. Pp. 6-01 - 6-15. In: Z.A. Henry, ed., Instrumentation and Measurement for Environmental Sciences. Am. Soc. Agric. Eng., St. Joseph, Michigan. SP-0375.

Spomer, L.A. 1975. Simple controlled-atmosphere welding of thermocouples. Agron. J. 67:94-95.

Thimijan, R. W., and R. D. Heins. 1983. Photometric, radiometric, and quantum light units of measure: A review of procedures for interconversion. HortScience 18:818-822.

Tibbitts, T.W. 1986. Quality assurance procedures for environmental control and monitoring in plant growth facilities. Biotronics 15: 81-84.

Tibbitts, T.W., D.C. Morgan, and I.J. Warrington. 1983. Growth of lettuce, spinach, mustard and wheat plants under four combinations of high-pressure sodium, metal halide, and tungsten halogen lamps at equal PFD. J. Am. Soc. Hortic. Sci. 108:622-630.

Warrington, I.J. 1978. Controlled environment lighting: High pressure discharge lamp based systems. Phytotronic Newsletter 19:15-27.