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FOREWORD
Greenhouse Environment Control Considerations provides an introduction to the many options available in greenhouse controls. This document was prepared by NGMA members to familiarize you with the control technology available from our members, and assist in understanding the value of environment controls in your greenhouse operation. This document will help in the development of action plans and setting of priorities for the selection and purchase of controls for new greenhouse construction, and the retrofitting and expansion of existing greenhouses.

The NGMA does not intend to recommend or endorse any particular type of control system, brand or manufacturer. This document does not replace or supercede any electrical or building codes, or set standards of compliance among manufacturers.

THE BASICS OF CONTROL
A greenhouse environment is an incredibly complex and dynamic environment. The pressures of labor availability and costs, energy costs, and market demands increasingly make efficiency and automation key components for success and profitability. Environment control technology affects all of these critical areas, and many others, so understanding controls and implementing their use is more important than ever. Precise control of the greenhouse environment is critical in achieving the best and most efficient growing environment and efficiency.

The controls companies represented in the NGMA have developed a wide array of standard controls designed specifically for greenhouse control requirements and applications.

This document provides a general overview of:

1. The value of good environment control
2. Functions of environment control systems
3. Types of controls available
4. Considerations for selecting appropriate controls

HISTORY
Early greenhouse control was as simple as pulling a chain to open or close a vent, turning a valve to control heat or irrigation, or throwing a switch to activate a pump or fan. Over the years this evolved as greenhouse systems themselves became more complex and more reliable. Early automated control consisted of independent thermostats, humidistats, and timers. Even these simple devices allowed major advances in efficiency and product quality and made grower’s lives simpler. However, many of these control devices and methods cannot deliver the level of automation and efficiency needed in today’s dynamic, competitive environment.

The common problems experienced with using several independent thermostats and timers to control a greenhouse led to the development of early electronic analogue controls, also known as “step” controls. These devices made a major contribution to improving the growing environment and increasing efficiency by combining the functions of several thermostats into a single unit with a single temperature sensor.

As operating costs increased, and greenhouse systems became increasingly complex, the demand grew for increased control capability. The computer revolution of the late 70s/early 80s created the opportunity to meet the needs for improved control. Consequently there have been dramatic improvements in control technology. Today, computerized control systems are the standard for modern greenhouses, with continued improvements as the technology advances.

THE VALUE OF GOOD CONTROL

A DYNAMIC ENVIRONMENT
Greenhouse environments present unique challenges to good control. Temperature changes occur rapidly and vary widely depending on solar radiation levels, outside temperatures and humidity levels, wind speed and direction, the amount of plant material in the greenhouse, watering routines, etc. Proper control of this dynamic environment is indeed challenging, but the benefits of good control far exceed the costs.

Ultimately, the objective of any greenhouse system is to reduce the input cost per unit of production and maintain or increase the quality of production. While some investments effect the input cost and/or quality of one or two specific tasks (i.e. transplanters, soil handling equipment, etc.), a well-integrated environment system will have a positive effect on virtually every function in a facility. Even a small percentage of improvement in several areas will yield substantial improvements overall. Growers that own Integrated Control Systems report experiencing many real benefits resulting from improved control.

HIGHER ENERGY EFFICIENCY
Better equipment coordination and more accurate control can reduce heating fuel and electrical costs. Savings vary depending on how well you already manage your environment and the controls you purchase.

BETTER LABOR EFFICIENCY
Automated controls increase the productivity of workers by enabling them to attend to more valuable tasks. Increased output reduces the pressure for more labor.

IMPROVED MANAGEMENT EFFECTIVENESS
Perhaps the most important function of good control systems is the additional information available to managers and growers, enabling them to make better management decisions and spend more time managing the process instead of being or doing the process.

REDUCED WATER USE
With the modern irrigation control capabilities in many systems water application is more precise, and more timely. Growers report reduced overall water use and runoff of as much as 70% with the most effective irrigation controls.

REDUCED FERTILIZER USE
Constant monitoring and control provides higher accuracy that, when combined with efficient water use, can substantially reduce fertilizer application and improve its effectiveness.

REDUCED CHEMICAL USE
More precise control of temperatures and more effective use of DIF and other growth regulating temperature regimens reduce the need for growth regulators. Better management of humidity, irrigation, and temperature also helps reduce plant stress and diseases and, consequently, the need for fungicides and other chemicals.

REDUCED PESTICIDE USE
Greenhouses with better climate control and precise irrigation produce healthier plants. Healthier plants are less susceptible to disease and insect infestation. Growers report noticeable reductions in insect populations and pesticide use in well-controlled environments.

IMPROVED PLANT QUALITY & UNIFORMITY
Less disease, more effective irrigation and fertilization, improved grower information and management all combine to increase the health and uniformity of plants. Uniform crops are easier to handle and market.

REDUCED EQUIPMENT WEAR & TEAR
Poor control over-taxes equipment by over-cycling and increasing operation hours. Good control allows more precise management of the equipment. Continuous monitoring and alarms alert growers to pending breakdowns and other problems earlier, before more serious consequences occur.

Less Plant Loss from Failures
Good data logging and graphing of greenhouse conditions and sophisticated early warning alarm systems help reduce losses from catastrophic failures.

GENERAL CONSIDERATIONS

Not an Office Computer
The most qualified person to evaluate greenhouse control systems is probably the head maintenance person or grower, not the office computer expert. Do not use office computer standards to evaluate and select environment controls. Megabytes, Megahertz, Gigabytes, and other standards of measure for personal and office computers do not have the same relevance in evaluating greenhouse control systems. Greenhouse control is real time process control and the software and hardware requirements, costs, applications, and support requirements, have little in common with office computers. The important factors in evaluating greenhouse controls are reliability, precision, and control functionality. Speed, disk storage capacity, memory and software friendliness are all secondary considerations and, in some cases, may not be relevant at all.

Greenhouse vs. Building Control
Conventional insulated buildings intended for human occupancy and materials storage are very different in nature and function from buildings intended for horticultural production. Consequently, the types of control systems that have evolved for each type of application are very different.

The most important distinction between building controls and greenhouse control systems is that building controls are primarily designed to manage air temperature and ventilation rates for human comfort, while integrated greenhouse controls are designed as production tools for facilitating horticultural growth processes. Therefore, the capabilities of a greenhouse control system usually extend far beyond air temperature management and ventilation, to the direct process control of biological growth parameters. Greenhouse control systems are developed with unique programs for operating specialized greenhouse equipment such as fog systems, CO_2 enrichment, shading and blackout curtains, roof vents, irrigation and nutrient control.

Since greenhouses are constructed of essentially non-insulating transparent or semi-transparent materials, they gain and loose heat at many times the rate of even the most poorly insulated or sealed conventional buildings. To compensate for the dynamic energy fluxes within these structures, extremely responsive heating and cooling equipment is required, as well as sophisticated anticipative control systems that can maintain setpoints within the narrow tolerances required for modern horticultural production.

Several attempts have been made to utilize “off-the-shelf” industrial programmable logic controllers (PLCs) sold by major electrical manufacturers. However, while horticulture-specific control systems have advanced in both sophistication and ease of use, PLC systems have proven to be comparatively much more expensive and difficult to use, while delivering much less capability than integrated systems developed specifically for horticulture and for use by non-programmer end users (farmers).

Control Voltages
Controllers use low voltage (24 volt), line voltage (115 volt), or a combination of both signals, to activate equipment.

The controller itself must:

- If you are retrofitting a facility with existing high voltage controls it will be necessary to address the interface between low voltage and line voltage.

For further information on electrical interfaces, see the Installation Considerations section toward the end of this document.

IMPACT OF GREENHOUSE DESIGN

Even the very best control system can't make your greenhouse perform beyond the limitations of the equipment in the greenhouse. A poorly engineered climate zone will yield poor results or at best will be difficult to control. If you are building a new facility, be sure to involve the control manufacturer in the process of designing the heating, cooling, and irrigation systems to assure proper integration with the control system.

OTHER CONTROL APPLICATIONS

Systems sophisticated enough to control a greenhouse environment can certainly control the environment in other areas that may be less dynamic but equally important. Heating, air-conditioning/cooling, lights, fogging, and more can often be controlled in areas such as this:

- Head houses & production buildings
- Coolers and freezers
- Offices
- Growth chambers

While most of these area can be easily controlled by simple thermostats or other building controls, some, such as growth chambers and seed coolers will benefit from the precision provided by the greenhouse control system. Additionally, the alarm and data recording functions included in many control systems can be used to monitor these environments and protect their contents.

CLIMATE CONTROL ZONES

Control systems are configured and priced based on the zones and equipment controlled, not per control unit or by greenhouse square footage, so understanding the definition of a climate zone is important. A brief definition of a climate zone is:

"A specific enclosed area with common temperature and humidity requirements served by common heating and cooling systems."

However, in practice it is often more complicated than that. The easiest climate zone to understand is a freestanding greenhouse. It is separated from other areas by walls, has common heating and cooling systems and the same temperature and humidity set-points. In a gutter connected range a single zone may include several houses or bays with common heating and cooling equipment and temperature and humidity set-points.

Ideally the houses in one zone should be separated from other zones with a wall or barrier to prevent cross control problems. If zones are not separated it will effect the accuracy of control and may create difficulties in maintaining precise settings. For example, if you try to maintain different air temperatures at various locations within the same enclosure, these zones may "fight" against each other. This may result in one area doing all of the heating, while the other area may end up doing all the venting. The result will be very poor control and wasted energy.

While it is very difficult to maintain multiple cooling and humidity settings with a single climate zone, it is often possible and desirable to maintain individual heating sub-zones within a climate zone. For example individual bench heating zones for propagation and germination areas are commonly used, and, of course, individual irrigation, misting, and lighting zones within a single climate zone are common.

COMMON/GLOBAL SYSTEMS

Boiler systems, main water supply systems, and fog systems, are nearly always shared across several zones. Each of these systems can be quite complex, requiring specific control management capabilities for optimum performance and safety. It is important that the control system be able to manage these individual systems while also coordinating them with the demands of the various zones. For example: A boiler system may require certain supply and return temperatures, staging requirements, and other operational minimums regardless of the heat demands of the zones it serves. Make sure the control system can manage the boiler system independent of the zone pumps and valves to optimize both.

PLAN AHEAD
When considering controls it is very important to look ahead several years to take into consideration both your present requirements and probable or possible future needs. Make sure the system you select is capable of expanding and changing with the needs of your entire operation. Even if you don't have or foresee an immediate requirement for functions such automated irrigation, lighting, or boiler control, include these in your considerations. Many growers start out by controlling only the basic heating and cooling functions, but quickly see the benefits of controlling other equipment systems. Most computerized control systems can be expanded through the purchase and installation of additional components. Make sure you understand the expansion capabilities of any control system you are considering. Growers that are initially unsure of the value of a greenhouse control system often end up finding more uses for them than they imagined and quickly look to expand their use.

LOOK AT THE WHOLE PICTURE
When reviewing your control needs, it is important to consider all functions of environment management in your facility, not just heating and cooling. Consider everything, including systems like irrigation, that you may not see a need to control at present. The following are many of the functions that may be involved. All of these systems are independent. They may effect or be affected by other functions, so controlling them in an integrated mater is important.

WHAT TO CONTROL
- Temperature control (heating & cooling)
- Boiler system management
- Air circulation & air exchange (HAF, jet fans, louvers & vents)
- Humidity management (fog, mist, dehumidification vents & heat)
- Shade curtain systems
- Lighting control (artificial lighting and blackout)
- CO_2 management (monitoring and injection)
- Heat storage
- Irrigation (pumping, capacity, valves)
- Chemical treatment
- Nutrient management (fertilization injection/mixing)
- Water supply and storage systems
- Heat storage systems
- Co-generation systems

COST COMPARISON
A full appreciation of the total capabilities of a particular control system is important.   Accurate cost comparisons are best made by examining the nominal cost per climate zone, rather than cost per square foot or cost per control unit. Cost per square foot varies significantly depending on the size of the operation and of each zone. Cost per control unit is similarly misleading, as it does not account for the capability of the system, complexity of each zone, or the number of zones. To compare costs, divide the overall costs of a system by the number of zones controlled to make the most accurate cost comparison.

LEVELS OF CONTROL
There are three levels of control requirements and equipment that need to be addressed in every zone.

EQUIPMENT LEVEL
Control of individual equipment: This refers to devices that control or interface with a single type of equipment. Examples include motor controllers to control vent operation, contactors and motor starters for pumps, fans, etc. Any control system must be able to manage the equipment based on its specific and unique operational requirements.

FUNCTION LEVEL
This refers to control of all equipment for a particular function, such as temperature management, irrigation, fertilization, etc. Individual controllers may be electronic (analog step controllers) or microprocessor based controls. For example, temperature controllers generally provide 5-12 control outputs, depending on manufacturer and model, that allow for 2 or 3 stages of heating, and 3-5 stages of cooling. Some models will control cooling vents and heat mixing valves.

SYSTEM LEVEL
Control of all equipment, functions, and systems: The operation of each piece of equipment in the greenhouse is effected by the operation of other equipment and changes in climate conditions. A single piece of equipment or system often performs more than one task (i.e. heaters both heat and dehumidify) and these requirements can occur simultaneously, or overlap due to time lags between an equipment operation and its ultimate effect. Fully integrated, system level control, is designed to bring all of the systems in the greenhouse facility together into a single well-orchestrated and coordinated system. These integrated systems can only be effectively managed by computers which can monitor and control every aspect of the climate simultaneously.

TYPES OF CONTROL EQUIPMENT

The following is a brief review of the types of control units and systems available, and how to analyze the costs of controls.

There are essentially four types of controls available.

1. Thermostats and timers
2. Analogue “step” controllers
3. Computer zone ccontrollers
4. Integrated computer controls

THERMOSTATS AND TIMERS
These simple devices are low cost and provide limited control. A typical greenhouse zone may require 3 or more individual thermostats to control heating and cooling functions, plus timers for irrigation and lighting control. Additional relays are often necessary to interconnect fans and louvers and other devices that must work together.

A simple zone will generally require 2 or 3 thermostats (1 for heat and 1 or 2 for cooling stages). More complex zones may require 5 or 6 thermostats, including multiple stage thermostats for some devices such as vents, plus individual controls or timers for irrigation and lighting.

Beyond the low initial cost there is little if any benefit. They provide very limited control, no coordination between equipment and functions, poor accuracy, and poor energy efficiency. The initial low price is deceiving. The increased energy consumption and the effects of lost production due to poor control devices far exceeds savings from their lower initial cost.

STEP CONTROLS
The primary benefit of these devices is their low initial cost, better equipment coordination and greater accuracy than either single or multiple stage thermostats. These units are not expandable and serve only one zone. They are generally most appropriate for simple greenhouse zones limited to 6-8 total stages of heating and cooling, and in smaller operations not anticipating expansion.

Step controllers bring two benefits to basic temperature control: automatic sequence of operation, and remote sensing. Consequently, a single step controller takes the place of several thermostats. Step controls use a single sensor element to control both heating and cooling functions in a greenhouse zone. That sensor can be located among the plants while the controller can be located more conveniently and safely outside the plant environment. These controllers divide the actions of the greenhouse heating and cooling equipment into steps, or stages, called a sequence of operation. While multiple thermostats with different settings can accomplish the same effect, it is difficult to keep their temperature readings synchronized. As a result, heating and cooling equipment can be on simultaneously though running both is expensive.

A single step can include one or more heat sources or one or more cooling sources. For example, in a zone with three exhaust fans, two unit heaters, three motorized shutters, and an evaporative cooling pad; the equipment might be divided into steps as follows:

Heating Step 1	First unit heater ON
Heating Step 2	Second heater ON (first heater still ON)
Cooling Step 1	1 exhaust fan ON 3 shutters OPEN
Cooling Step 2	2 exhaust fans ON.
Cooling Step 3	3 exhaust fans ON. Cooling pad pump ON.

As the measured temperature falls below the desired temperature, controller activates Heat Step 1. If the temperature continues to fall, it turns on Heat Step 2. As the zone returns to the desired temperature, the controller first turns off Heat Step 2, then Heat Step 1.

As long as the greenhouse remains near the desired temperature, the controller leaves all the equipment off. When the measured temperature rises above the desired temperature, the controller turns on Cooling Step 1, and if the temperature continues to rise, it activates Cooling Step 2, then Step 3. As zone temperature drops, the controller turns off each cooling step in last-on, first-off order.

Greenhouse step controllers incorporate greenhouse-specific features such as separate day and night temperature settings, gradual equipment startup after power failures, outdoor temperature influence, provision for humidity control, partial or complete lockout of cooling functions at night, adjustable time delay between steps, and display of the temperature at the remote sensing point.

COMPUTER ZONE CONTROLLERS

These devices bring the benefits of computerization to the step controller concept, providing greater control flexibility and programmability, and the ability to provide improved accuracy and better equipment coordination. They are generally designed to provide control and coordination of temperature and humidity in a single zone, although some companies offer units that are expandable to 2 or 3 zones. The number of outputs per zone controller is typically 10-15 outputs each and some units can be expanded to up to 24 outputs per zone, perhaps more. Irrigation, lighting, and/or CO_2 control is available on some control units.

The cost per zone generally starts slightly higher than for step controllers, depending on the capabilities offered in the controller and the amount of equipment needing to be controlled in each zone. Many computer zone controllers also offer the optional capability to connect to an office PC for storing and viewing data and graphs and for changing settings from a single PC location.

INTEGRATED COMPUTER CONTROLS

These systems combine the capability of several Step or Computer Zone Controllers, plus irrigation and lighting controls, and various other individual control devices such as timers, into a single, integrated computer system. Integrated Computer Controls (ICC) can provide coordinated control of virtually all greenhouse environment functions, including heating, cooling, irrigation, fertilization, boiler control, lighting, CO_2 management, alarms, and much more. Usually the need for any additional individual control units can be eliminated.

The cost per zone for ICC systems is dependent on the number of zones controlled and the total equipment to be controlled. The initial acquisition cost is higher than for the initial purchase of a single step or computer zone controller for a single zone. However, when compared over the cost of controlling 3 or 4 greenhouse zones, and more, the cost of ICC systems compares quite favorably. As ICC systems are expanded to control more zones and more equipment and functions, the average cost per zone and per output tends to decrease.

Since ICC systems provide substantially more capability than most individual zone control units, comparing costs can be difficult. It is important to consider all equipment and functions that may require control and future expansion plans in order to derive a fair comparison. Although generally favored for operations with 3 or more zones, ICC systems can be cost effective for operations with as little as 1 or 2 zones, if the zones are complex and control requirements are demanding.

There are two types of Integrated Computer Control systems:

1. Single processor control units
2. Multiple processor distributed controls

SINGLE PROCESSOR CENTRALIZED CONTROL

These systems have a single computer processor that controls all zones from a single unit. Sensors and outputs can be wired back to the central unit or connected to local stations that then communicate with the central processor unit. A dedicated terminal or PC generally accesses these units. This architecture was common in early systems and is still used in some systems, particularly European systems. Installation of this type of system generally requires more wiring and can be more complex. If the single control unit fails, the entire facility is without automated control until it can be repaired. The overall capability of these systems is comparable to Multiple processor controls.

MULTIPLE PROCESSOR DISTRIBUTED CONTROL

These systems are comprised of multiple control units, each with its own processor, connected together to share information and integrate the control of common or global systems such as water mains and boilers.

Each distributed control unit is typically capable of handling from 1 to 4 zones, depending on manufacturer and model. The control units are located in or near the zones or groups of zones to be controlled throughout a facility. Sensors and control outputs are wired locally to the control units at or close to each zone rather than running back to a central unit. The individual control units in the system are usually accessed through one or more computer terminals, which are usually a standard PC. In some systems the access is available through a screen and keypad mounted on the individual control panels, although most companies offer a central PC interface as an option or standard to provide centralized full-featured operator access.

Integrated control systems provide more than control. They also deliver substantial management information to managers and growers. Data Recording programs capture sensor readings and trends, and record the computer's functions, automatically saving this data for analysis. Growers can identify unacceptable environment trends in the greenhouse, such as insufficient temperatures or excessive humidity, or equipment malfunctions, before the plants are negatively effected. Previous successes can be more easily repeated by capturing and duplicating conditions that worked well. Light levels and quality, soil moisture levels, CO_2 levels, water application rates and quantities, nutrient and pH levels, and a host of other factors and conditions can be monitored and archived.

Maintenance staff can track equipment operation times and cycles in some systems, allowing them to set alarms for run-time and/or cycle related preventative maintenance functions, or to trouble shoot equipment problems. When combined with climate data, a detailed story can be pieced together to identify problems in the greenhouse. Managers can analyze greenhouse performance data to make wiser decisions about future greenhouse equipment purchases, or even plant variety selections and nutrient requirements.

TECHNICAL CONSIDERATIONS

CONTROL SIGNALS

Digital and Analog are the two types of control signals most commonly used in greenhouse control systems.

DIGITAL CONTROL

Digital control is simple on/off switch control and is used to control on/off devices such as motors, louvers, solenoids, etc.

DIRECT DIGITAL CONTROL (DDC)

Proportional devices such as vents, motorized valves, curtains, and other open/close devices can are also be controlled with a digital signal. DDC is achieved by activating an open or close relay for a period of time to move the device to the desired position. Proportional devices can then be controlled based on movement time. For example: if a vent takes 200 seconds to open, the controller activates the open relay for 200 seconds to open it 100%, or 100 seconds to open it 50%.

ANALOGUE CONTROL

Analogue signals such as 4-20 ma or 0-10 VDC are often used to control proportioning devices and variable speed motors. While DDC is generally simpler and less expensive method of control, there are special applications where analog control provides additional flexibility and may be desirable. Analog is the standard method of control for some equipment and for certain equipment manufacturers. Analog control is preferred where a faster equipment response is needed. Some manufacturers make equipment actuators available with either a DDC or analog interface.

OVERRIDES

It is preferable to have manual override switches, also known as hand/off/auto, on most control outputs. This enables any output to be controlled by hand, or switched to automatic control by the computer. Overrides are necessary for emergency (i.e. computer failure) and maintenance of equipment. However, they are not to be used for normal control operation. Analog outputs should also be equipped with on/off switches and a potentiometer to manually select motor speed or the opening percentage of analog actuators.

SENSORS

Sensor technology is an important consideration for controls manufacturers. The accuracy and responsiveness of the control system is limited by the accuracy and responsiveness of the sensors it uses. A computer may be able to read a sensor many times per second and resolve the temperatures to within 1/1000th of a degree, but if, for example, the sensor takes 2 minutes to respond to a change, it is of little value to the system. The reliability and accuracy of a sensor, and its construction, are of particular importance in the greenhouse environment, to its ability to withstand the generally unfavorable conditions of the greenhouse environment.

TEMPERATURE

Air temperature is best accomplished with an aspirated housing to move the air sample across the sensor and protect it from direct exposure to solar radiation. This ensures a more accurate representation of the air in the general greenhouse environment as opposed to a specific spot.

Soil temperature probes are typically used to control bottom heat systems. They are also used to monitor soil temperatures and the temperature within the microclimate of the plant. This information can be valuable for determining how and why the plant is responding and what measures the grower may want to take to improve performance or identify problems.

Pipe temperature sensors are used to monitor the water temperature and pipe surface temperature in hot water heating systems to control mixing valves, minimum pipe temperatures for dehumidification, as well as boiler output and/or transport system temperatures. There are three methods of sensing: 1)surface mount temperature sensors, 2)wet well sensors, and 3) dry well sensors.

Strap-on surface sensors are inexpensive and effective since the pipe surface closely follows the water temperature within. Sensing can be as simple as clamping a small thermistor on the pipe with a piece of insulation and a hose clamp or tie wrap.

Wet-well sensors are actually threaded into a hole (well) in the pipe and sense the actual stream of water. They provide the most accurate temperature reading, and the fastest response, although it is questionable if this accuracy is necessary in most hot water systems. Wet-well sensors are more difficult to service since the pipe must usually be drained or at least cooled and depressurized before they can be replaced.

Dry-well sensors are the most expensive but provide the best combination of accuracy and ease of service. A well is threaded into the pipe forming a permanent seal, and the sensor is placed in the well sometimes with thermal grease and can be easily removed for maintenance or replacement.

Irrigation water temperature can be monitored with a pipe temperature sensor, as above, or with a simple waterproof sensor dropped into the water.

Other temperatures can be monitored for a variety of purposes. For example, equipment operation can often be confirmed with a simple appropriately placed temperature sensor to confirm things like unit heater operation, an overheated irrigation or heating pump, even fan operation or open vents. Alarms can then be set in the system to alert staff when problems occur.

HUMIDITY

Controlling the humidity in the greenhouse can yield powerful benefits in disease reduction, improved water and nutrient uptake, and improved growth. It is too often under utilized and not well understood. Humidity control is a standard function of nearly all control systems.

Humidity measurement is expressed as a percentage of relative humidity. It is the amount of actual moisture in the air, relative to the capacity of the air to hold it. Humidity sensing is difficult even with the most expensive sensors, and these are typically not suitable or practical for the greenhouse industry.

There are three common types of humidity sensors: capacitive, resistive, and wet/dry bulb. Both capacitive and resistive solid state sensors are fairly common in U.S. production because they offer reasonable accuracy and, in the humidity range typical of most horticulture applications, maintenance is generally limited to cleaning once or twice per year. However, solid state sensors are susceptible to chemical contamination and high humidity conditions (i.e. over 90%), that may require more frequent recalibration or replacement.

Wet bulb/dry bulb sensors offers the best accuracy if maintained properly, particularly in environments with humidity levels consistently over 90%, such as germination chambers and fog houses. These sensors do require frequent maintenance that is easily performed by the user. Water reservoirs must be refilled and wicks trimmed and replaced regularly. The drier the climate, the more frequent the maintenance requirements. These sensors are more common in Europe and Canada, due to a number of factors, including tradition, more crops requiring closer humidity control, and climates more appropriate for this type of sensor.

LIGHT

There are three basic measurements of light: Global radiation, PAR, and photometric. Global radiation is the most common light measurement for greenhouse control because it measures the entire spectrum of energy producing light. It is measured with a Pyranometer, and is generally expressed in units of watt/m^2 .

Photosynthetically Active Radiation (PAR) is another method of light measurement. It measures the narrow band of light that is used by plants in photosynthesis. This is appropriate for use in research and for monitoring PAR light at the plant level. PAR is of minimal value for environment control, other than lighting, as it does not accurately relate the total solar energy that affects temperature or other aspects of plant morphology.

Photometric light meters measure luminosity, or the relative brightness of light to the human eye. They are not particularly useful for horticulture production, other than detecting the difference between night and day.

CO_2

Carbon Dioxide sensors are typically used in controlled CO_2 enrichment applications. The most common types of sensors employ an infrared sensing element. A separate sensor may be used in each zone, or to reduce costs, a single sensor may be used to multiplex samples from several zones. Control systems can initiate CO_2 injection from boiler stacks, CO_2 burners, or liquid CO_2 tanks based on light and temperature conditions and CO_2 target levels.

WIND SPEED & DIRECTION
Mounted on the outdoor weather station, an anemometer measures wind speed and the vane measures approximate wind direction. The controller uses this information to close or limit the opening of vents, roofs, and side walls during high wind conditions, or winds from a specific direction. This information can also be used to optimize the operation and effectiveness of windward/leeward vent systems, and even to make or modify irrigation decisions.

PRECIPITATION
These are sensors mounted on outdoor weather stations to measure precipitation. Simple rain "grids" indicate either the presence or absence of precipitation but not the volume. These simple sensors are commonly used to close or limit roof vents or retractable roofs when it is raining. They are the most appropriate sensors for this purpose because they allow a fast response. Heated rain grids enable snow sensing and differentiation between dew and rain.

Rain volume is normally measured using a tipping bucket rain gauge. This device collects the water in a small cup or spoon that tips when it is full, triggering a small switch. The number of tips are counted to determine the amount and rate of rain fall, generally as accurately as 1/00th to 1/10th of an inch. These can also be used to measure propagation misting, and irrigation application and leachate rates. Measurements from these should not be used for closing or limiting vents and roofs due to their slow response rate.

IRRIGATION
Measuring the use of and/or presence of water for irrigation purposes can be accomplished with a number of sensors depending on the purpose, growing culture, and required accuracy. Soil tensiometers and environmental control probes are used to indicate approximately how much moisture is available in the media. Evaporation trays are used to indicate the approximate evaporation rate of water in a particular environment. Water meters can measure the amount of water being fed to the plants. Accumulation gauges, such as a tipping bucket rain gauge, can be used to measure how much water is leached out of the media and, consequently, how much water the media absorbs.

NUTRITION
pH sensors are used to determine the amount of pH correcting concentrates required. Environmental control sensors are used to determine the level of salts in feeding solutions. Both types of sensors are used for nutrient control and for monitoring and alarm information in an irrigation system.

MISCELLANEOUS SENSORS
There are many sensors available to monitor and record a wide variety of conditions. Many control systems can use these sensors to improve control, set alarm conditions, activate equipment, or simply report occurrences. Here are some typical sensors and uses.

Certain safety or alarm related sensors can be incorporated into some computerized systems as well. An example may include flame smoke or heat sensors to detect fire. In some systems, particularly integrated computer control systems, the system could be programmed to, for example, open/retract the shade or blackout curtain systems and close vents to minimize the spread of fire.

Other sensors include:

- Flow switches to confirm proper pump operation, detect clogged filters and line breaks, etc.
- Pressure transducers to monitor water pressures, greenhouse pressures, fan output, etc.
- Potentiometers to monitor vent positions, mixing valve positions, etc.
- Micro-Switches to monitor closure of vents and doors, the position of watering booms, curtain systems, retractable roofs, etc.

IRRIGATION CONTROL

GENERAL

As reported by growers, one of the most significant benefits derived from automated control is the management of daily irrigation decisions. It is understandable that this is one of the most difficult areas for growers to turn over to the control system.

Growers using automated irrigation control report dramatically reduced water and fertilizer use, better growth, less disease, less chemical use, hardier plants, and less labor.

Much of the apprehension about automated irrigation is based on the following conceptions:

1. The grower is the only person that really knows when the plant needs water.
2. You can't grow without being in the greenhouse watering and checking things.
3. Control systems are not sophisticated enough to know when to water.

There are others but these represent the most frequently heard comments. Here are some perspectives on these subjects that are based in modern control experience:

1. "Only your grower knows for sure:" Absolutely correct. Growers know best how to determine when a plant needs water but humans are not the most reliable at making accurate measurements of when it actually needs to happen. Modern control systems allow the grower to "teach" the computer just how they want those decisions to be made. The control system can then implement those decision strategies much more reliably and with much greater accuracy than can any human.

2. "Got to be there:" Correct again. The grower does need to be in the greenhouse observing plants and managing people. That does not necessitate holding the watering wand or turning the valves and switches. Growers say they are actually better able to manage the performance of the plants and supervise staff when they are not preoccupied with other labor functions.

3. "Controls not smart enough:" Not true anymore. Irrigation control has come a long way in just the past few years and today's control systems provide sensor measurements and control methods that offer greater accuracy and timeliness particularly when managing large multi-zoned irrigation systems.

IRRIGATION DECISION MAKINGMANUAL

The grower makes the decision as to when to irrigate and uses the control system to implement that decision for timing and sequencing valves and pumps.

TIME

This typical control type triggers irrigation cycles for preset times at a pre-set time of day. Problem: Plants do not take up water based on the time on the clock.

ACCUMULATED LIGHT

A computer light sensor (pyranometer) measures the total energy input from the sun and triggers an irrigation cycle when a grower-set amount of light has accumulated. An increasingly popular method for determining when to irrigate as it most closely measures the primary factor that causes plants to require irrigation. This requires a computer controller to implement.

EVAPO-TRANSPIRATION MODEL

The computer measures the total energy input from light, humidity, and temperature conditions to model the rate of transpiration, need, and uptake ability of the plant. This sophisticated method is probably the most accurate although complex way of measuring the actual irrigation requirements and also requires a computer to implement.

VAPOR PRESSURE DEFICIT (VPD)
This method uses feed back from temperature and humidity sensors to determine when there is a VPD between the plant leaf and the surrounding air and triggers watering based on the plants ability to transpire.

SENSOR FEED BACK
Triggers irrigation when certain environment conditions exist, such as low temperatures for frost protection, or high temperatures for heat stress. Also used for with paddle sensors for mist control, or virtually any sensor feedback that a grower would use to determine the need for irrigation or to stop irrigation, for example, during rain periods for outdoor crops. Other examples of common sensors used:

Soil tension: Measures the relative level of moisture in the soil and triggers irrigation when the soil dries to a certain level.
Weight scale: Triggers irrigation when the weight of the pot indicates a dry condition.
Evaporation start trays: Triggers irrigation when the moisture in a tray is evaporated as measured by weight or moisture level.
Temperature: Triggers irrigation for freeze protection or to protect from heat stress.
Electronic rain gauge: Limits irrigation based on the amount of rainfall received by outdoor crops.

CAPACITY MANAGEMENT
Controls the cycling of valves based on the water volume and/or pressure available from the water source (well pumps or city water). This allows the grower to optimize irrigation for the plant while the computer manages the timing of the valves based on the available water capacity. Computers are able to manage on a second by second or minute by minute basis enabling a much closer management than is possible by a human. This may involve staging valves and pumps based on irrigation priority, pulsing irrigation cycles to serve several valves with a given capacity while meeting the plants total irrigation requirements.

CROP MODELING & GRAPHICAL TRACKING

CROP MODELING
This allows a control computer to use research generated models of different species and varieties of plants that predicts growth based on a history of environment conditions and a predicted model of the plants response to those conditions. Although somewhat futuristic, models already exist for some plants, including certain vegetable and cut flower crops, as well as Poinsettias and Easter Lilies.

GRAPHICAL TRACKING
Computer control systems can provide environmental data, such as temperatures and light levels, to be used in graphical tracking programs. These programs track the height and other habits of a plant and allow the grower to adjust greenhouse conditions to produce the best plant to meet market requirements and timing.

POWER MANAGEMENT
Integrated computer control systems can also provide a level of power management. Be sure to identify which are important in your operation.

Load shedding: The ability to shut down specific equipment during power outages or brown-out to match the load capacity of the generator or reduced power supply.

Peak shaving: The ability to shut down specific equipment, usually sequentially, to stay within a specified power budget. This may be needed to achieve savings available with special power company plans, supply from co-generation plants, interruptible power/alternate power supply plans, or simply to optimize an insufficient power service.

Phase-loss shutdown: The ability to shut down three phase motors and other sensitive equipment in the event of loss of one of the power legs in a three phase power supply.

Staged power-up: When power returns after a power outage, this provides the ability to activate equipment gradually in stages to prevent stalling the generator or tripping the overload protection of your power service.

INSTALLATION CONSIDERATIONS

Installing a control system requires a working knowledge of your greenhouse electrical system and reasonable familiarity with standard control wiring. Generally speaking, if you know how to install a group of thermostats, you can install a computer control system. It is not always necessary to use the services of an electrician for installation of the controls, although an electrician is generally needed for installing line voltage contactors and power transformers. Most control manufacturers can provide access to qualified installation contractors or company installers.

CONTACTORS & RELAYS

All electronic controllers must interface tiny electronic circuits with larger electrical loads. Electromechanical relays or solid-state relays can handle this interface. Both use a small electric signal from the controller to switch one or more devices. Electromechanical relays are most common, readily available and relatively inexpensive and allow switching of multiple devices with a single relay. Most control systems provide a signal that is able to directly control small loads and contactors that will control heavier loads.

Most manufacturers will also provide the line voltage interface/contactor panels that are matched to their controls. These can also be built on site by your electrician or supplied by other electrical component vendors. Be sure to investigate your options before deciding on the best method of supplying these relays and contactors. Discuss the matter with your electrician/installer and controls vendor to determine the most appropriate and cost effective route.

MOTOR CONTROLS

Most motor controls can be provided in the contactor panels. Some devices, such as fog systems, variable speed motors, or very large motors often come already equipped with motor controllers or need special starters. Motors for curtain systems, vent systems, retracting roof systems, and retracting side walls need special attention. These systems require reversing motor controllers that allow the motor to turn in one direction to open and in the reverse direction to close. This must be accommodated in the motor controller by the manufacturer or in the contactor panel. It is an often-overlooked item. All manufacturers of these systems offer motor controllers as an option. Make sure these controllers are accounted for in your design.

WIRING

Most low voltage (24 volt) control wiring consists of 18-22 gauge wiring. The selection of the wiring should be based on manufacturer recommendations or specifications. Some sensors are calibrated to a specific wire size and length. The size of wire to connect control relays to the devices or contactors they control is based on the amperage, voltage, and distance to run the wire. 18 gauge is the most common and is suitable for most connections but for longer runs or larger loads you should consult a wire sizing chart, electrician, or controls manufacturer.

CONDUIT OR WIRE TRAY

Most control wiring need not be run in conduit. Many growers simply tie it to the outside of existing conduit, pipes or structure frames. However, depending on local code, desired esthetics, overall quality of installation desired, it may be advisable to run wire in conduit or wire raceways/trays. Open raceways, although a bit more expensive than conduit, make installation easier and future changes or additions easier as well. Do not run low voltage sensor and communication wire in the same conduit as line voltage equipment wiring, or attached to line voltage wires, as it may interfere with low voltage signals, consequently yielding incorrect sensor readings.

PANEL LOCATIONS

Where control panels are located is dependent on four factors

1. Desired location for convenient access to override switches
2. Location of electrical service and consequent desired location of contactor panels
3. Type of control system purchased and type and location of interface (i.e. panel mounted screen and keyboard or PC terminal)
4. Ease of wiring sensors and contactors.

TRAINING & SUPPORT

Regardless of the systems you consider and ultimately purchase, one of the most important aspects of any system is the training and support available from the manufacturer. Make sure they can train your operators and have technical support available when you need it. It is important that the people providing your support be knowledgeable about greenhouse specific applications and have a good concept of how greenhouses work. The horticulture industry is far flung geographically so it is impractical for manufacturers to maintain support/technical staff in every geographical area. A few of the critical items:

- Are replacement components readily available overnight?
- Can the components be serviced or replaced by your own staff or is an on-site technician required?
- Is hardware and software support available by telephone and modem or are on-site technicians required?
- Does the manufacturer provide remote training by telephone and/or modem or is an on-site visits required?
- Is there adequate system and program documentation provided in either written form or on-line so you can help yourself with reasonably simple problems?
- Does the system provide standard programs to accommodate "typical" horticulture control routines and equipment or does it require custom programming and equipment?
- Can the system be accessed remotely by the vendor and the user? Is there an additional cost for remote access?

OTHER CONSIDERATIONS

- What is the software upgrade policy? How often is software upgraded? Are upgrades optional or mandatory?
- What is the typical cost of a software version upgrade? When is the next upgrade expected?
- What are the installation costs?
- What are ongoing maintenance and operation costs? Sensor replacements and recalibration, etc.
- What is the company reputation for after sales service and support?
- What levels of alarms and self-monitoring does the system offer?
- How fast are sensors refreshed and read by the system?
- Can the system be custom configured for special applications?
- What levels of lightning protection does the system provide? Are there additional costs to get this level?

GREENHOUSE CONTROL CONCEPTS AND TERMINOLOGY

This chart provides basic definitions and descriptions of terminologies often referenced relative to environment controls. Understanding these terms will helps understand how different system provide control of various functions.

STEP CONTROL	Step control is used to apportion control responses in a number of discreet steps.	**Example:** **Step 1:** If the temperature rises 2°F above the cooling setpoint, start the first exhaust fan. **Step 2:** If the temperature rises 5°F above the setpoint start the second exhaust fan. Etc.	This method works quite well for equipment such as fans or unit heaters that can be staged. It does not work as well for roof vents and mixing valves that are capable of much finer full span operation.
INTEGRATED CONTROL	Integrated Control takes into account the interdependent relationships and multiple effects of the greenhouse equipment. Control response can usually be proportioned over the entire span between full on and off	**Example:** The control system operates the roof vents and the zone hot water mixing valve in an integrated manner to achieve both the temperature and humidity setpoints, as well as protect against wind gusts, snow loads, while correcting for wind direction, and outdoor conditions	This method has advantages over step control since a much finer degree of control response is possible, and the interdependent effects of control equipment are taken into account.

FEED BACK	The controller makes its decisions based upon differences between the actual measurements and control setpoints. Control reactions may be modified by time of day, and outdoor weather conditions.	**Example:** If the greenhouse temperature has fallen below the heating setpoint, the controller will start heating.	This type of control must wait for a deviation to occur before it responds. Therefore, the actual response may be somewhat sluggish, resulting in oscillations above and below the setpoint. Useful in situations that do not demand a high degree of precision.
PROPORTIONAL	Proportional control is used to deliver a control response in proportion to how far away from the setpoint the measured condition is.	**Example:** the control system will open a hot water mixing valve in proportion to how far away the zone pipe temperature is from the desired pipe temperature. If desired and actual temperatures are close, the proportional response will be small. If they are far apart, the proportional response will be greater.	Proportional response strategies are very useful in greenhouse equipment control since they enable the use of an appropriate response, somewhere between full on and full off.
INTEGRAL	Integral control is used to deliver a control response in proportion to how long a measured condition has deviated from its setpoint.	**Example**: if a measured condition has deviated only slightly, but for some time, an integral strategy will increase the rate of response the longer that the deviation occurs.	When used in conjunction with proportional control, this type of strategy provides a dual method for returning a deviated condition to the setpoint. The control system will respond to both the degree of deviation and the amount of time that the deviation has occurred.
DERIVATIVE	Derivative varies the degree of response with the rate of change of the measured condition.	**Example:** Derivative control, when used with proportional and integral calculations can shorten the time it takes to correct a control deviation.	Although useful for rapidly changing conditions or processes derivative control is seldom required for greenhouse equipment due to other process lags.
FEED FORWARD	Also referred to as anticipatory control. It is used in systems that employ Energy Balance Equations and where the control response is predictable for a given set of conditions. These systems calculate the effect that current conditions will have upon the controlled parameter, and activate the equipment prior to a deviation from the setpoint.	**Example:** a nutrient injector may be set to deliver a proportional rate of fertilizer concentrate based upon measured water flows.	This type of control generally provides greater precision than controls based solely on feedback, since the appropriate response can be predicted ahead of any deviations. Where feedback correction is used in conjunction with feed forward control, a high degree of precision can be achieved.
ENERGY BALANCE	The controller makes its primary control decisions by calculating the probable response of the environment based upon the current measured values of the inputs. Total heat gains are balanced with total heat losses.	**Example:** as outdoor light and temperature conditions change, an ongoing energy balance is calculated to determine how soon and by how much the climate temperatures may be affected if the condition continues. The system then initiates a control action if required to preempt the anticipated changes.	Control systems using energy balance equations can produce a very smooth control response over a wide range of outdoor conditions.

GETTING STARTED
The following process will help determine the controls needed and prepare to request proposals from control system vendors:

A. Determine the total existing areas to be eventually controlled now and in the future.

B. Determine the logical progression of purchase and installation phases and divide into three phases. The first phase being the area(s) having highest priority, phase two the areas, next most important, and phase three being all other areas, including probable future expansion areas.

C. Determine the number of individual, separate climate zones in each of the phases.

D. Create or copy an existing plan view map of the entire facility including greenhouses, outdoor production areas, offices, and utilities.
   1. Label each individual greenhouse block the way you identify it (i.e. Zone 2, Ralph's house, Back house, etc)
   2. Show dividing walls between climate zones
   3. Label main power and water services
   4. Identify boiler locations
   5. Identify the growers office and management office

E. Survey the environment control equipment in each of the zones, in logical order following the following categories, in the same order in each zone:
   1. Heat Source (boilers, heat transport system, etc.)
   2. Heating
      a. Number of heating zones
      b. Type of heat in each zone (i.e. unit heaters, under bench hot water, etc.)
      c. Heating control (stages of heating for unit heaters, mixing valves, pumps, zone valves, for hot water and steam)

   3. Air Circulation (HAF Fans, Jet Fans, etc.)

   4. Energy Curtains

   5. Cooling
      a. Type of cooling (natural ventilation, fan and pad, etc.)
      b. Cooling equipment (number and location of vents, fans, louvers, pads, etc.)
      c. Cooling control (stages of fans, pad pumps, separate vent groups)
   6. Irrigation
      a. Number, type, and location of water sources
      b. Location of fertilization stations (injector or tanks)
      c. Number of irrigation main branches
      d. Number of valves per branch

   7. Other Equipment (CO_2, etc.)
      a. List for each zone
      b. Describe type of equipment
      c. Describe functions
      d. Describe control requirements

F. Survey your maintenance staff and growers and ask them to identify their most important needs and considerations in controls.

G. Identify one or two qualified individuals that will be responsible for overseeing the purchase, installation, and management of the system and appoint them to do the research and get proposals from vendors/manufacturers.

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