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PRECISION CLIMATE CONTROL IN GREENHOUSES

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During December-January, 1985, data on the CSU computer system was examined for comparisons and variability in four greenhouses identical except for coverings. In the majority of cases, the control system is capable of maintaining climate within the manufacturer's limits of accuracy. Precision is quite high.

The four, 960 sq.ft. greenhouses at CSU **(Figures 1 and 2)** have been the source of several bulletin articles (i.e., 334, 381, 389, 403, 404, 419) on greenhouse covers and plant response since constructed in the early 70s with CGGA's financial assistance. Faced with a control system no longer supportable, we undertook a major refit, with software development to provide complete climatic control. Some of the hardware was described in Bulletin 420, and a preliminary report for summer, 1985, was published in Bulletin 426.

During the early Fall, 1985, two of the houses were recovered so that two houses (1 and 4) were provided with a double layer, inflated PVF, and the remaining houses (2 and 3) now have a single layer, corrugated, Tedlar® coated FRP. Since shading screens were installed the latter part of January, 1986, in Houses 3 and 4 **(Fig. 3),** and all the gas consumption counters were not operational until Dec. 18, 1985, the period for study was limited to approximately Dec. 18 through Jan. 10 with the exception of some parts of **Tables 1 and 3** which began Dec. 1. However, the outside air temperatures varied over a 35°F range, and up to 57° if the first part of Dec. is included. Wind speeds ranged from 0 to 44 mph, with extremely variable solar radiation — up to a maximum of 662 W/sq.m. under partially cloudy conditions which, due to reflection from clouds increased total energy above normal for those periods.

Fig. 1: CSU "Heat Houses" for climate control development. The Tectrol CO_2 duct has been removed since this picture was taken. Houses are numbered one through four from left to right, oriented north-south. Houses 1 and 3 recovered fall, 1985, so that 1 and 4, and 2 and 3 are identical.

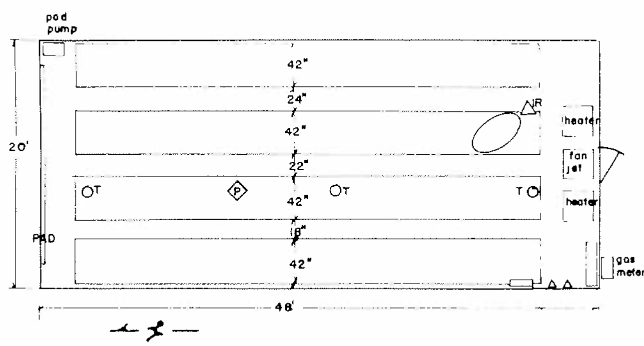

Fig. 2: Floor plan of one of four identically sized, quonset greenhouses undergoing computer control development. Circles marked "T" are aspirated shielded temperature sensors, approximately 3 to 5 feet above the floor. In houses 3 and 4, the end aspirators were moved toward the center about 3 feet in order to accommodate the shade. The symbol "P" denotes location for a silicon cell solar radiation detector (pyranometer), about 3 feet above the floor, and "IR" is the infrared, remote sensing thermometer with approximate vegetational area "seen" by the instrument. Roses are presently in the east, middle bench. The west, middle bench is occupied by cucumbers (January). The two side benches lack sufficient head room for tall crops.

[1] *Professor*

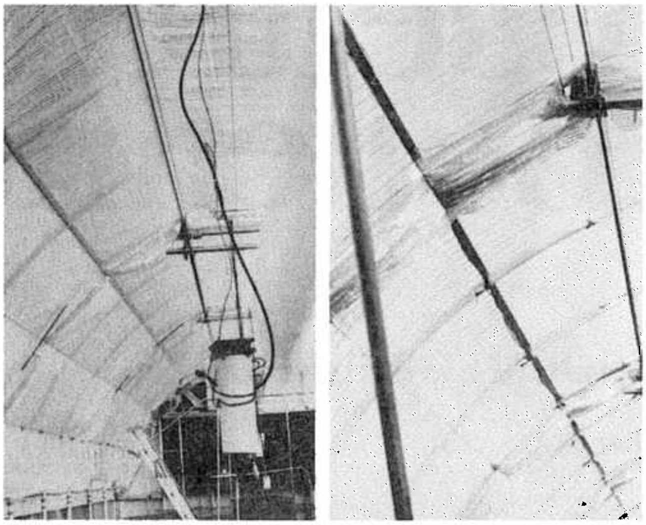

Fig. 3: Shade and thermal screen installation in House 3. The material is Swedish manufacture, designated as "LF-14", 40% shade, with aluminum strips interwoven with clear plastic. The control system closes the shade at night when the outside temperature is below the inside set-point, and also during the day if the total inside radiation exceeds 600 watts per sq.m. The curtains are opened if the outside radiation drops below 500 W/sq.m. Due to the shape of the houses, some difficulty occurs at the bottom edge (left picture) which is inadequately sealed at this time.

To summarize for the period covered by these data:

Houses 1 and 4: Double layer, inflated, polyvinyl fluoride.
Houses 2 and 3: Single layer, Tedlar® coated fiber-reinforced plastic.

Other than these conditions, all houses were identical and controlled identically.

1. **Air temperature**
   Night temperature, heat to 61°F.
   Day temperature, heat to 72°F.
   Cooling temperature minimum differential 4° above heating.

Both day and night temperatures were adjusted upward automatically to avoid "droop" due to staging differentials, with colder weather. Due to the heavier heating load for Houses 2 and 3, the adjustment for "droop" was twice as great compared to Houses 1 and 4. The ventilation temperature varied upward as outside temperature decreased so that, if the difference between inside and outside exceeded about 30°, no ventilation occurred regardless of solar load. The cooling fans were locked out at night if the external temperature was less than the inside setpoint. Under conditions of high outside temperature, the setpoints were decreased. Provision was made to adjust setpoints in accordance with solar radiation and CO_2 level, but were not implemented during this study. At switchover to day settings, the system was staged so that at least one hour was required before reaching day setpoints. This provided a gradual temperature increase with no override or maximum equipment operation.

Table 1: Similarity tests, CSU computer controlled greenhouses (Figures 1 and 2) for the day periods. Data are averages accumulated every 60 seconds throughout the period from Dec. 18, 1985, through Jan. 10, 1986[1]. Figures are rounded to whole numbers, prior to shade screen installation in Houses 3 and 4. Plus or minus values (±) to the right of each average are the standard deviation of the means rounded to whole numbers[2].

	Double inflated PVF		**Single layer FRP**	
	House 1	House 4	House 2	House 3
Average daily gas use (total cu.ft./day)	2380 ± 1200	1850 ± 1340	4500 ± 2060	4180 ± 2090
Average daily air temperature (F° all stations)	73 ± 1	74 ±2	72 ± 1	72 ± 1
Average daily air temperature each station (°F)				
North aspirator	73 ± 2	75 ± 2	72 ± 2	73 ± 2
Middle aspirator	74 ± 1	75 ± 2	73 ± 1	71 ± 1
South aspirator	72 ± 2	73 ± 2	72 ± 1	71 ± 1
Average daily plant temperature (°F)	75 ± 1	74 ± 2	75 ± 1	75 ± 1
Total average daily solar radiation (MJ/sq.m.)[3]	4.1 ± 0.9	4.0 ± 0.7	4.8 ± 1.0	4.6 ± 0.9
Average daily absolute CO_2 concentration (Pascals)	48 ± 6	44 ± 5	54 ± 5	50 ± 5
Average daily relative humidity (%)	72 ± 3	74 ± 3	75 ± 5	65 ± 2
Average daily vapor pressure (millibars)[4]	20 ± 1	21 ± 2	20 ± 1	17 ± 2
Average daily vapor pressure deficit (millibars)	8 ± 1	8 ± 0	7 ± 1	9 ± 0

[1]Gas consumption and radiation from Dec. 18 through Dec. 30, 1985. Shade operation began in House 3 after Jan. 10, 1986.
[2]Outside temperature extremes for this period were 54 to 19 F, with maximum wind speed of 44 mph, and maximum solar radiation intensity of 662 W/sq.m.
[3]Megajoules per square meter (1 mega = one million, 1 Joule = 1 watt-second).
[4]One millibar = 100 Pascals, a unit of pressure, 350 ppm CO_2 at Ft. Collins = 28 Pascals and 33 at sea level. Average atmospheric pressure at Ft. Collins = 847 millibars.

Table 3: Environmental extremes in the CSU Heat Houses, December 1 through 28, 1985. CO_2 was not measured at night.[1] Outside temperature range 56F to -2F, maximum windspeed 44 mph, maximum radiation 662 W/sq.m., relative humidity ranges 18 to 100%.

	Average temperature		Plant temperature		Relative humidity		CO_2 concentrations		Vapor Pressure deficit	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
Day regime[2]										
House 1[3]	81	67	88	62	85	56	193	21	12	4
House 4	85	68	89	51	84	59	76[4]	25	12	4
House 2	81	65	87	66	93	53	160	22	12	2
House 3	81	54	95	52	79	45	174	22	16	3
Night regime										
House 1	68	57	88	62	84	48			10	3
House 4	67	55	75	57	88	52			9	2
House 2	68	57	77	59	91	35			12	2
House 3	64	57	80	56	74	33			15	5

[1] *All temperatures in °F, relative humidity in %, CO_2 concentration in Pascals (pressure) and vapor pressure deficit in millibars (pressure), 28 Pascals = 350 ppm, 100 Pascals about 1200+ ppm.*

[2] *System switches from night regime to day regime when outside radiation is 70 W/sq.m. and returns to night regime at 10 W/sq.m. All maximums and minimums replaced 60 execution cycles after switchover (one hour).*

[3] *House 1 and 4 double, air-inflated PVF, Houses 2 and 3 single layer, Tedlar® coated FRP. Data recorded prior to shade screen installation in Houses 3 and 4.*

[4] *Sample lines clogged from condensation. Condensate traps installed January, 1986.*

The system measured aspirated air temperature at three locations in each house **(Fig. 2),** and the average used for control. This value was displayed **(Fig. 4)** and refreshed each time execution occurred (60 seconds).

2. Humidity

Maximum difference between saturation (100% relative humidity) and actual vapor concentration 12 millibars.

Wet bulb and capacitance humidity probes were installed in the center aspirator of each house. The capacitance probes proved to be more dependable than wet bulb measurements. The program calculated absolute humidity values and determined the vapor pressure deficit by subtracting the actual vapor pressure from the vapor pressure at saturation. If this value exceeded 12 millibars, high pressure mist (320 psi) was injected. No dehumidification cycle was included. With some exceptions, relative humidity did not exceed 90%, nor was it seldom below 65% except under heavy heating loads at night. Humidity was uncontrolled at night.

3. CO_2 concentration

Minimum concentration at inside radiation levels below 100 W/sq.m. 35 Pascals (ca 450 ppm), increasing 0.2 Pascals per Watt above 100.

CO_2 utilization increases with solar radiation. High concentrations are wasteful when cloudy conditions prevail. Because "parts per million" are relative, the system calculated absolute CO_2 concentration in pressure units (100 Pascals = millibar, 1013 millibars = 1 atmosphere = 14.7 psi at sea level: 350 ppm at sea level = 33 Pascals). At inside radiation levels above 600 W/sq.m., CO_2 level could exceed 1000 ppm.

Gas analysis was only during the daylight hours, using a system which continuously purged the lines with no injection until at least one sample was taken at switchover, with each environment sampled every 18 minutes. CO_2 injection from liquid storage was through a trickle irrigation tube running the length of the rose bench (Chapin Twin Wall, 4-inch) on the soil surface. Sampling was within the canopy, in the center of the bench.

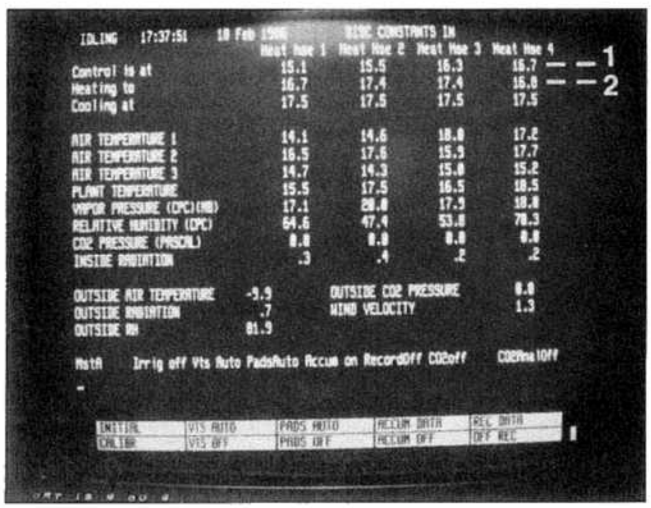

Fig. 4: Typical display on CRT showing conditions in each house. This display is refreshed each time the system executes (every 60 sec.), and some time is required to interpret what the operator sees. Item "1" is the average air temperature from 3 stations in the house. Item "2" is the re-calculated setpoints for heating and cooling which are compared to "1" for control purposes. Temperatures on this display are in degrees Celsius, vapor pressures in millibars and CO_2 levels in Pascals. The bottom line shows which houses are being watered, misted or injected with CO_2. The remaining, reversed display (black on green) refers to single stroke keys which the operator can use to control the system (i.e., manually water, turn off CO_2, turn mist on manually, accumulate data, call programs, etc.).

4. Irrigation

Minimum once daily, each irrigation thereafter requiring an accumulated energy level of 2200 kiloJoules/sq.m. (1 Watt-second = 1 Joule, kilo = 1000).

Irrigation was with six lines of trickle tube per bench with automatic fertilizer injection. At switchover to day, the system set accumulating registers to zero and watered the gravel benches once. When accumulated radiation exceeded 2200 kiloJoules, the system watered again for a period determined by the operator, with a record kept of the frequency. During this period, frequency varied from once daily to a maximum of three times daily.

5. Radiation

Switch to day settings at outside radiation level of 70 W/sq.m., returning to night at 10 W/sq.m. Shade screens not installed.

The variation in switching level was to avoid oscillation between day and night settings under cloudy conditions. Although not a part of this study, shade installations **(Fig. 3)** are programmed to operate as thermal screens at night when the outside temperature is below the inside; and during the day when inside radiation exceeds 600 W/sq.m. The shade opens when outside radiation drops below 500 W/sq.m.

In addition to the above controls, the system replaced all maximum and minimum values one hour after switchover, thus preventing night temperatures becoming the minimum for the following day period and vice versa. Each time the system executed (every 60 sec.), the readings were accumulated and checked for maximum and minimums. At each switchover, a summary of all data was printed for the preceding period. These data were stored and accumulated for one week with a printed weekly summary. Each greenhouse was also fitted with a remote sensing, infrared thermometer **(Fig. 5)** and a gas consumption counter.

Similarity tests

When the average temperatures were determined **(Table 2)** for the night periods, the variability of the averages was less than one-half degree F (given as zero). Even though the variability understandably increased during the day periods **(Table 1),** the standard deviation of the means remained well within the basic absolute accuracy of the temperature measuring system as specified by the manufacturer (ca ± 2°F). There were no statistically significant differences in air temperature between the houses for day or night regimes. The same could not be said for average air temperatures at each station in each house. Usually, the center aspirator showed a one to two degree higher average temperature than either of the two end locations. Given the standard deviation of one to two degrees F, one might state identical air temperatures for all stations with the exception of any difference in excess of 4°F. Average plant temperature was consistently higher than the air temperatures.

There was no statistically significant difference in total radiation between Houses 1 and 4 (double layer PVF) and Houses 2 and 3 (FRP) **(Table 1).** The large variability of daily solar radiation from the mean, as with total daily gas consumption, could be considered the consequence of large fluctuations in external weather conditions. There appeared to be a windbreak effect of the west houses on those to the east inasmuch as Houses 3 and 4 always consumed less gas when compared to Houses 1 and 2 respectively.

The ten percent lower, average relative humidity for House 3, during this period, was a calibration error. Although the

Table 2: Similarity tests, CSU computer controlled greenhouses (Figures 1 and 2) for the night periods. Data are averages accumulated every 60 seconds throughout the night periods from Dec. 18, 1985, through Jan. 10, 1986[1]. Figures are rounded to whole numbers, prior to shade screen installation in Houses 3 and 4. Plus or minus values (±) to the right of each average are the standard deviations of the mean, rounded to whole numbers[2].

	Double inflated PVF		Single layer FRP	
	House 1	House 4	House 2	House 3
Average nightly gas consumption (cu.ft./night)	9300 ± 1200	9000 ± 1700	17000 ± 4200	16700 ± 4400
Average nightly air temperature (°F all stations)	61 ± 0	61 ± 0	61 ± 0	61 ± 0
Average nightly air temperature each station (°F)				
North aspirator	60 ± 1	61 ± 1	59 ± 1	60 ± 2
Middle aspirator	63 ± 0	62 ± 1	63 ± 1	64 ± 2
South aspirator	59 ± 2	59 ± 2	60 ± 2	59 ± 2
Average nightly plant temperature (°F)	65 ± 1	65 ± 1	66 ± 1	67 ± 2
Average nightly relative humidity (%)	67 ± 5	70 ± 4	68 ± 7	58 ± 4
Average nightly vapor pressure (millibars)[2]	13 ± 1	13 ± 1	13 ± 2	10 ± 1
Average nightly vapor pressure deficit (millibars)[3]	6 ± 1	6 ± 1	6 ± 2	8 ± 1

[1]Gas consumption for Dec. 18 through 30, 1985 only.
[2]Outside temperature extremes for Dec. 1 through Jan. 10 were 55F to -2, with maximum wind speed of 37 mph, and relative humidity extremes of 100 and 18%.
[3]One millibar = 100 Pascals, a unit of pressure. Average atmospheric pressure at Ft. Collins taken as 847 millibars, 1013 mb at sea level.

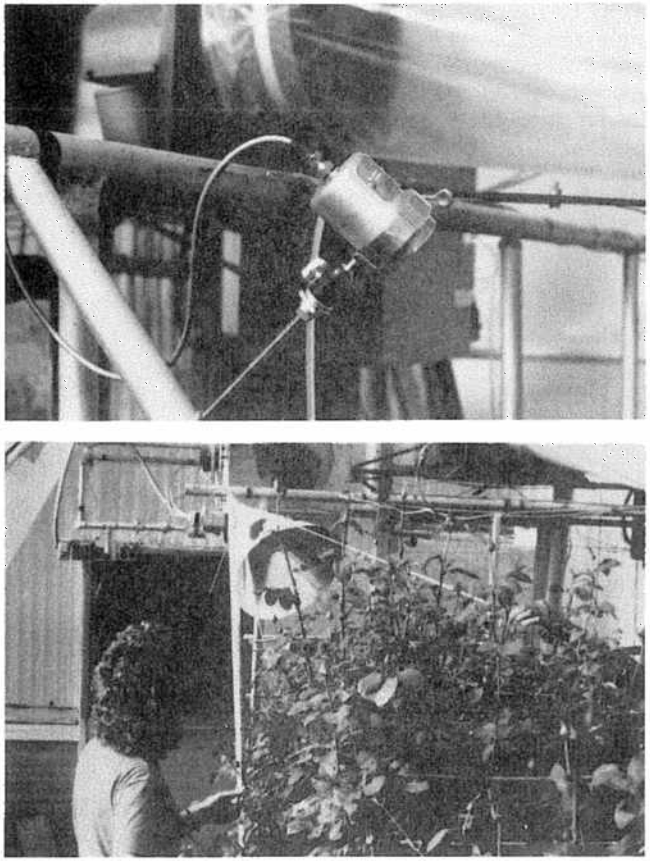

Fig. 5: Infrared thermometer with a 65° field-of-view (upper) for remote sensing of the crop temperature. The cone in the lower picture roughly indicates the vegetative area "seen" by the sensor. These newer, solid state devices, appear to be quite stable with very little drift compared to older units.

average vapor pressure and pressure deficit corresponded to the lower relative humidity, the average vapor pressure during the day was within the limits set by the system (i.e., 12 millibar deficit). The capacitance probe was changed and recalibrated. Data from the wet bulbs were not trusted and were not examined. Of particular interest was the fact that relative humidity during this period never reached 100 percent at any time **(Table 3).** Outside RH reached 100 percent only once or twice, indicating that a dehumidification program during the winter in Colorado is unnecessary in structures of this size.

In general, the extremes of air temperatures within these houses were less than 15° **(Table 3).** The exception was House 3 which might have been due to failure of the house to come to day temperature within one hour during the cold period first of December. Houses 2 and 3 could not maintain setpoints at -10°F or below in November. The extremes were greater during the day compared to night, as would be expected. Plant temperatures varied over a range nearly twice as great as the air temperatures. The very low CO_2 maximum for House 4 was due to condensation in the sampling line. Condensate traps were installed in all houses toward the first of January.

Summary

Extremes in climate within greenhouses might be more important than average temperatures. One or two extreme occurrences might not affect growth significantly unless, of course, biological limits are exceeded (ca 32 and 100°F). Several low extremes, however, might delay timing, even though the average is suitable. The system does provide what appears to be the best documented climate control to be found in the U.S., with an indication of potentials for climate control in Colorado. It becomes possible with such a system, to fine-tune greenhouse operation for maximum efficiency in energy consumption, CO_2, water and fertilization use. This should afford a significant economy, with good opportunity for high yield and quality.

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