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GREENHOUSE ENVIRONMENTS AND CONTROL PROGRESS REPORT II

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Preliminary results indicate that low air movement causes a lower plant temperature compared to a situation where heated air is vigorously mixed. There is a very significant interaction between outside air temperature and plant temperature inside which is related to heating equipment operation. Forced air movement is likely to result in greater air temperature differences over the covered area compared to infrared heating where air movement is largely convective.

Progress Report I (CGGA Bulletin 407) described the computer program used to control temperature and record data in the CSU Bay Farm greenhouses, consisting of two 30 × 100 foot, ridge and furrow greenhouses, oriented north-south, with the west house heated by a two-stage, infrared system, and the east house by a two-stage, Modine, Fan-jet system.

Preliminary observations, with initial data recording in December, 1983, showed that conditions inside the greenhouses were different from what one might expect based upon comments made in technical literature. We were able to begin significant data recording in February, 1984, when Hewlett-Packard provided us with a plotter. Subsequent software modifications now allow recording of 8 separate inputs every 15 minutes over a 15 hour period, or 8 inputs as fast as the system executes a control cycle which reduces the total time to 1.5 hours (90 sec execution time). This data can now be plotted automatically for observation.

[1]*Professor, graduate assistant and professor, respectively.*

Calibration

Initial observations showed that some differences we observed were within the accuracy limitations of the system. For example, thermocouple systems for measuring temperature have two major errors: 1) the measuring system which comes with manufacturer specifications of about ±0.9 F in the temperature range we are dealing with, and 2) the thermocouple wire which is manufactured to specifications of ±1.5 F. If the temperature measured is 70 F, it could actually be 67.6 or 72.4 F. We were able to reduce this error to about ±1.0 F. Our humidity calibration probe comes with accuracy specifications of ±2% relative humidity over the range of 0 to 80% RH and a precision of ±0.1% RH, with the platinum RTD sensor having an accuracy of ±0.2 F and a precision of ±0.1 F. The results of calibrations for temperature and humidity are given in Table 1. We estimate that our wet bulb system provides a humid-

Table 1. Dry bulb temperature and vapor pressure calibrations. Data acquisition system initially calibrated with ice-water mixture. Comparisons between acquisition system and Vaisala capacitance-resistance humidity probe made nearly simultaneously over a 10 to 15 minute period.

	West		East	
	HP	Vaisala	HP	Vaisala
Air temperature (°F)				
Mean value	66.4	66.0	67.3	67.8
Standard deviation[1]	0.2	0.4	0.9	0.7
95% CI[2]	66.0-66.8	65.6-66.8	65.5-69.1	66.4-69.2
Vapor pressure (mb)[3]				
Mean value	17.1	16.9	16.5	15.5
Standard deviation[1]	1.2	0.6	1.9	1.9
95% CI[2]	15.7-18.6	15.9-17.6	15.2-17.7	14.2-16.6

[1]Standard deviation (σ) is a measure of the variation of the values about the mean ($\bar{x}$) and 68.3% will lie within $\bar{x} \pm \sigma$.
[2]95% CI = confidence interval. A value within these ranges is the same as the mean with 95% probability of being correct.
[3]mb = millibars vapor pressure.

ity accuracy of ±3 millibars vapor pressure. The latter would correspond, at a 68 F air temperature and 50% RH, to a range of 38 to 63%, or ±13%. A part of this variation results from the inability to maintain constant conditions and the rapid 3 to 5% RH variations found during actual measurement. A range of this magnitude, however, is typical of humidity determinations, particularly where the temperature measuring system is accurate only to within ±2 F.

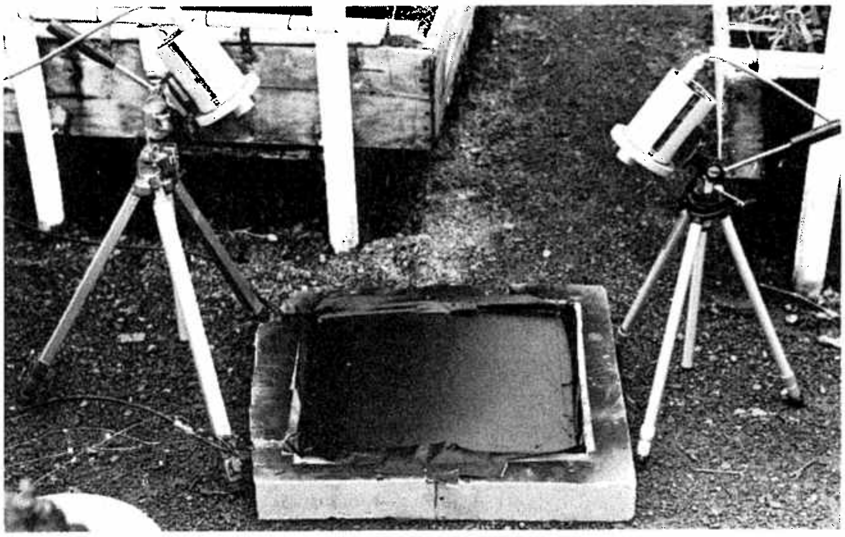
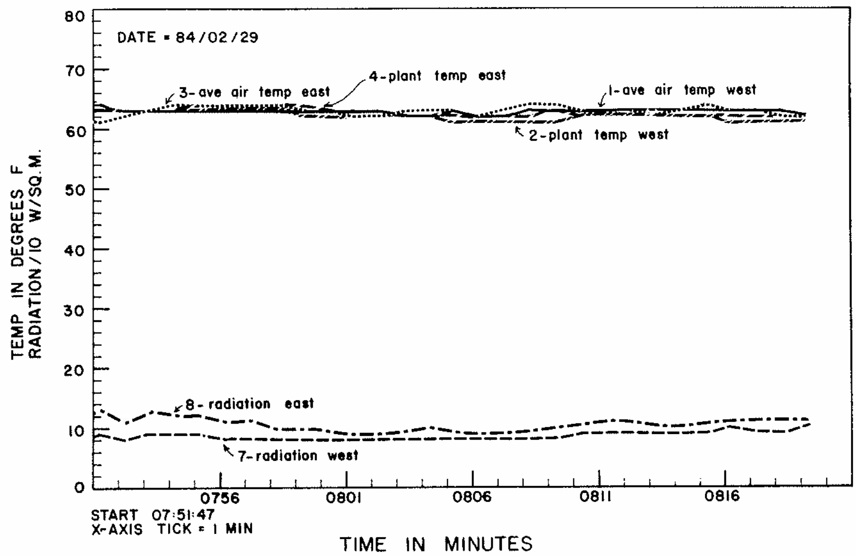


Fig. 1. "Blackbody" device constructed for simultaneous calibration of infrared thermometers. One-quarter inch copper tubing is soldered to the back side of the black plate. Water circulated through the tubing cools or heats the plate. Thermocouples are embedded in the back-side which allows the plate temperature to be monitored. During actual calibration, the entire apparatus, with the thermometers, is covered by an opaque, black cloth.



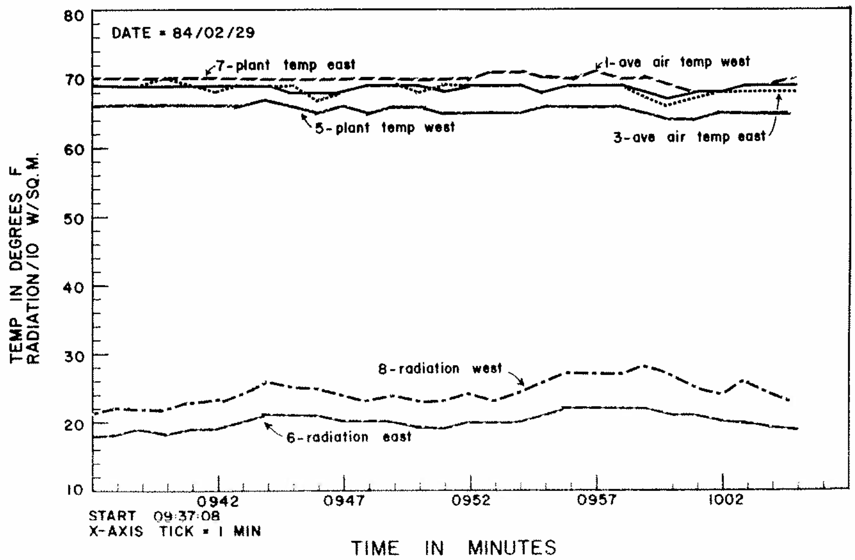


Fig. 2. Typical temperature and radiation data recorded over two consecutive 30 minute periods at one minute intervals. In these two figures, note the difference in radiation levels between the west and east houses, and the lower plant temperature in the west house (bottom figure). Under conditions of heavy heating (top figure, 0751 to 0824 hrs) a lower plant temperature in the west house was not apparent.

The latter is common with alcohol or mercury thermometers marked in 2 degree F divisions.

The differences found in plant temperature measurements required that we exercise particular care about making unsubstantiated statements. In addition to a special factory calibration, we constructed a "blackbody" (Fig. 1) which could be temperature controlled over the range of interest. As a second verification procedure, the infrared thermometers were switched three times this past winter, to ensure there was no significant bias between instruments. Unfortunately, we have not determined the "color" of the vegetation being measured, and assuming the usual values, the actual error for remote temperature measurements is probably within ±4 F. A temperature measurement with the infrared thermometers, which showed a vegetation temperature of 60 F could actually be 56 or 64 F.

The instruments for measuring total radiation were also calibrated over two consecutive days with the standard Weather Bureau, Eppley pyranometer kept at CSU for calibration purposes. Since a corrugated, fiberglass roof can be considered as a neutral density filter with diffusing characteristics, the usual problems of factors such as cosine response and direct shade by the greenhouse structure should be eliminated or reduced. Although the Eppley was located within 8 inches of the silicon cell pyranometers, however, some differential shading of the two instruments did occur which served to increase the scatter of the calibration data. This was particularly apparent in the infrared heated house where the overhead units introduced significant shading. When allowances were made for errors due to shading of one instrument, and not the other, the standard deviations were 0.007 and 0.008, respectively. This would mean that a radiation level of 0.5 cal per sq.cm.-min. could be 0.48 or 0.52 (about ±14 watts per sq.m.). There were no marked differences between the factory calibration and our own, although there appeared to be shifts in both slope and intercepts of the calibration curves compared to the originals.

Preliminary Results

One of the first things to be determined was the sampling rate at which data should be recorded. The slower the rate, the less computer memory required, and the longer the period of recording which could be covered. It has been our experience in the past that data acquisition in greenhouses at rates of 5 minutes or less are not likely to show significant variation, and the data is useless from the standpoint of statistical analysis. On a trial basis, we set the system to record once every 60 seconds (Fig. 2) on February 29, 1984, with the results showing relatively small variations

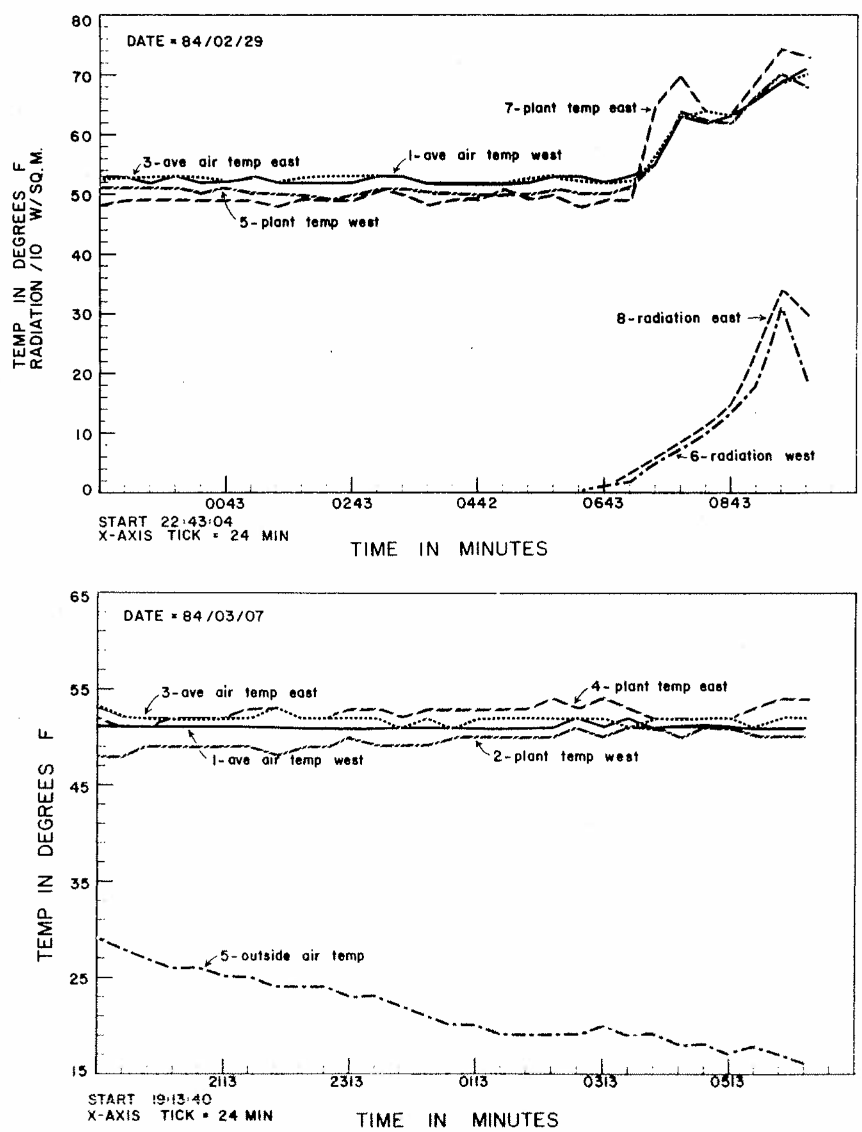


Fig. 3. Temperature and radiation levels in two greenhouses recorded over a 10 hour period at 24 minute intervals on February 29 and March 7, 1984. Note the rise in plant temperature of the east house at the time of night-day switchover, and this can be noted in Figs. 4 and 6. As the outside temperature dropped (bottom figure) carnation foliage temperature in the west house increased until, in the early morning hours, there was little difference between average air temperature and plant temperature in the west house. This change with heating load may be noted in Fig. 6 (bottom figure).

over two consecutive 30 minute spans. Although, with the exception of Fig. 6, the remaining figures were every 24 or 30 minutes, we feel that marked variation can occur at 30 minute intervals. Fig. 6 was recorded at 15 minute intervals

Fig. 4. Average air temperature and carnation foliage temperature under infrared heating versus forced air heating. Data recorded over a 15 hour period at 30 minute intervals. Note the high carnation temperature in the east house (Fan jet) at night to day switchover. When the system switches from day to night, the heating system ceases to operate, plant temperature in both infrared and hot-air systems dropped below average air temperature. As the hot-air system began to function, carnation foliage temperature began to rise.

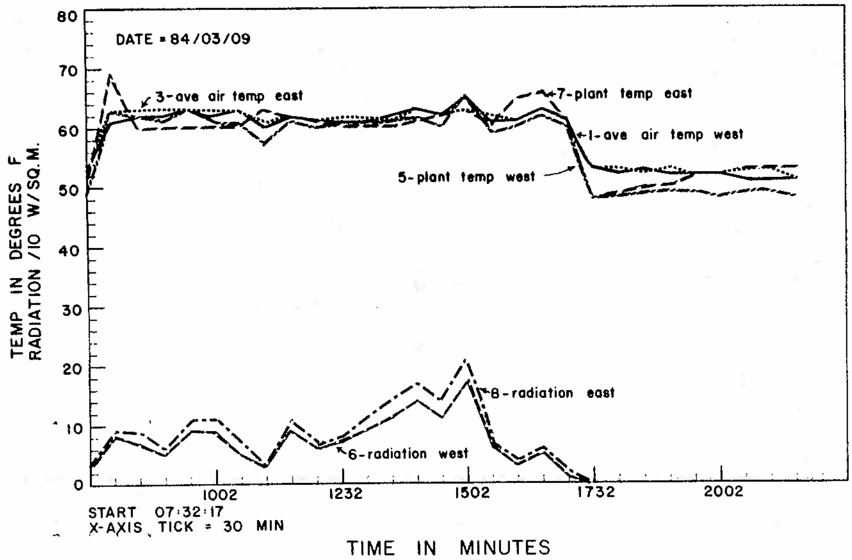
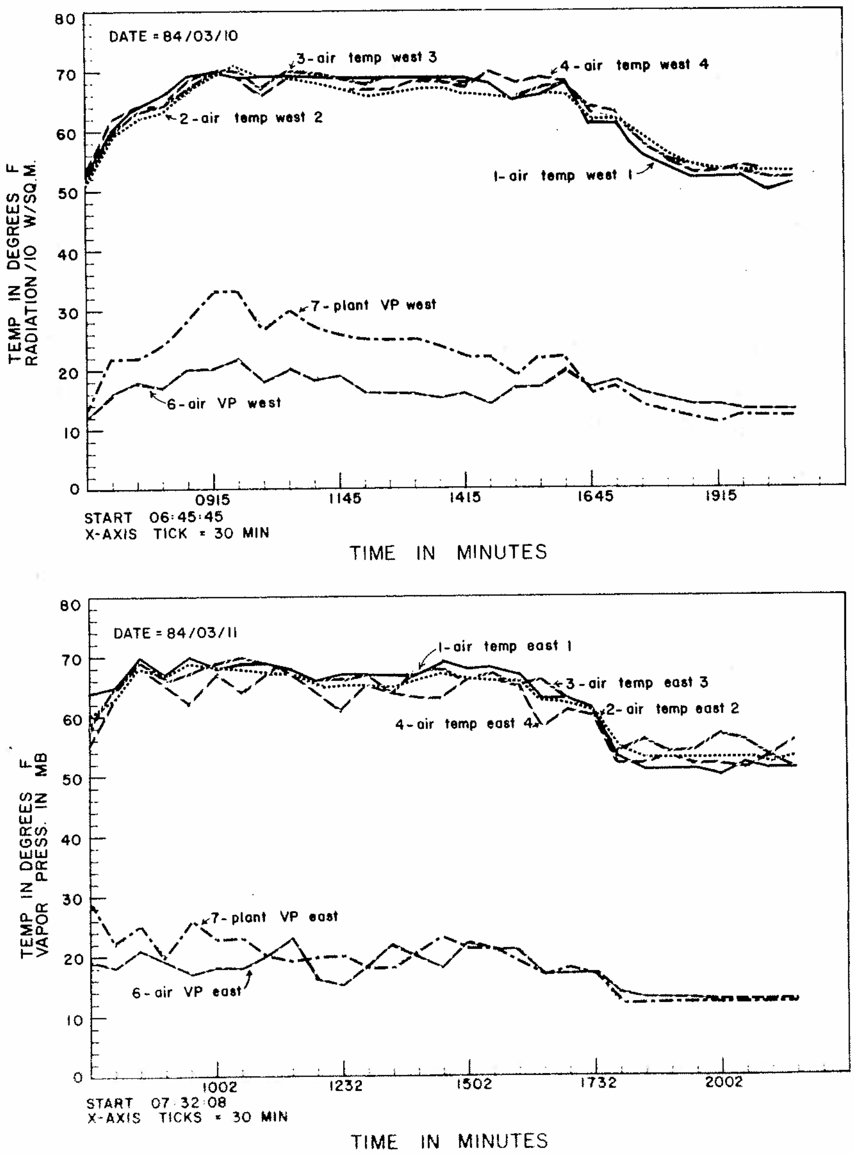


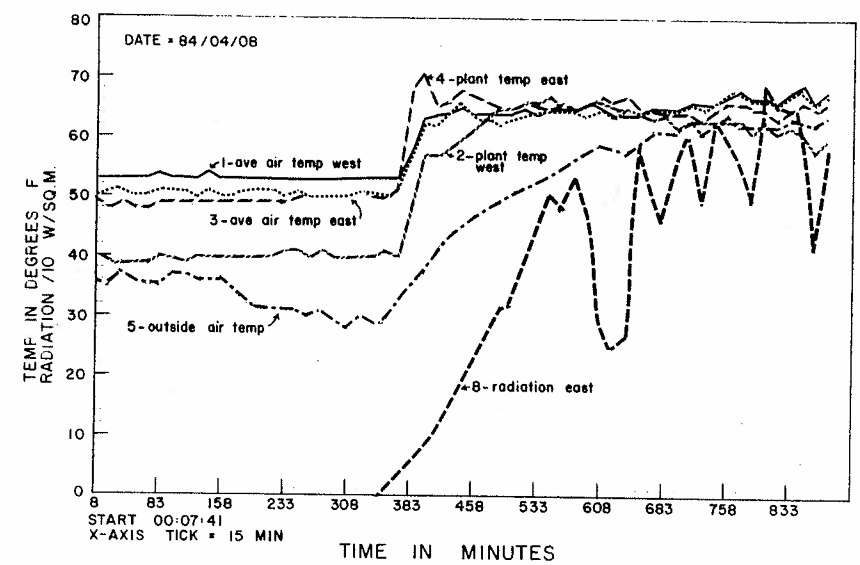
Fig. 5. Air temperature variation in a greenhouse heated with infrared units (top) and forced air Fan jet (bottom). Data recorded over a 15 hour period at 30 minute intervals. Note that air temperature variations from one location to another in the west house (infrared) were often within the accuracy limits of the measuring system. In the east house, air temperature under the unit heaters (No. 4), was usually below the other three air temperatures. Differences shown increase as the heating load increases. The higher plant vapor pressure under infrared heating (top) suggests that a portion of the radiant energy was being used to evaporate water. However, as the two houses were recorded on consecutive days (top March 10, bottom March 11) the differences were likely due to different outside air temperatures and radiation levels.



which we suggest is adequate to truthfully display conditions within commercial sized greenhouses without information loss. Ten minutes might be better, and we may institute that rate at a later date.

The data chosen for this article were selected to illustrate certain conditions that have become increasingly apparent as we continue to observe system operation. First, there is a consistent radiation difference between west and east houses, with the east house usually having a higher radiation level (Figs. 2, 3, 4). Under cloudy conditions, the differences are within the limits of accuracy, but under clear conditions the east house always has higher radiation levels even into the late afternoons. Although, in Colorado, it is common for the afternoon to become cloudy compared to the morning, it appears that the overhead infrared heaters significantly obstruct radiation reaching the sensors which are located in the center of each house at plant height. Although the difference is relatively small, it may be significant over the life of a crop.

The second observation was the consistently lower carnation foliage temperature as recorded by the system (Figs. 2, 3, 6) in the west house, and the fact that carnation temperature in the east house was often above the average air temperature, especially when the system switched over from night to day (Figs. 3, 4, 6). It was also noted that as the outside temperature dropped, plant temperatures tended to increase. It appears obvious that plant temperature in the center of the houses is directly dependent upon heating system operation. Heat transfer to and from a plant is a function of radiation, air movement (convection) and water loss (transpiration). The statement "heat the plants, not the air" is very misleading. Failure to maintain a reasonable air temperature with a crop such as carnations, is likely to result in significantly lower foliage temperatures. If the air is vigorously circulated (east house with Fan-jet system), convective heat transfer is likely to be more significant, especially in a tall crop. As the heating system operates more often (longer duty cycles and lower outside temperature), plant temperature will tend to increase either because of greater positive energy flow to the foliage by vigorous air circulation, or higher thermal radiation (infrared system, west house). Low growing, dense foliage, might not show the same situation. Spot foliage measurements in the west house with a portable infrared thermometer, under the hottest part of the infrared system, showed much higher foliage temperatures. The effect of heating system operation was particularly apparent as outside temperatures continued to increase, on the average, into the spring (Fig. 6). Under little or no air movement, and short operating periods of the heaters, the carnation foliage temperature sometimes



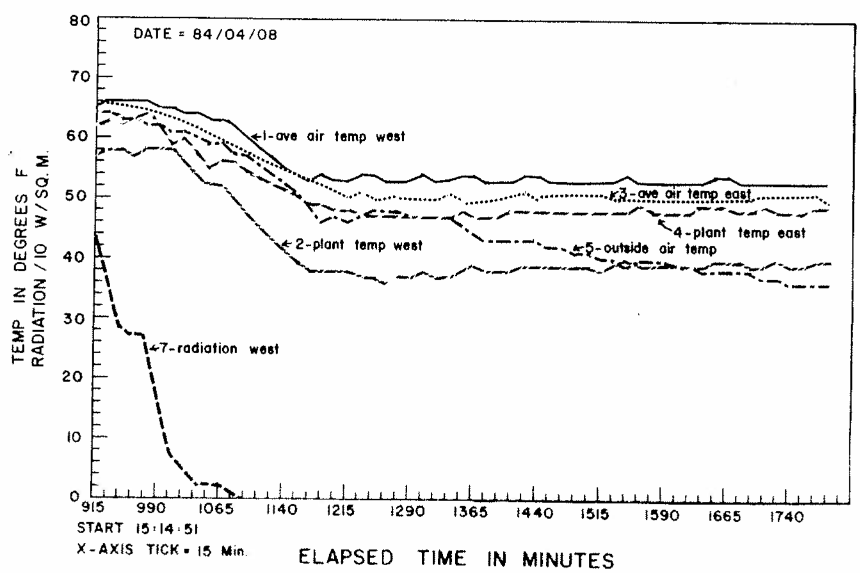


Fig. 6. Data recorded over a 30 hour period at 15 minute intervals, beginning at midnight on April 8 and continuing the following night. Setpoints were deliberately changed so that the infrared system (west house) was controlled at an average air temperature of 53 night, versus an average air temperature of 50 for the forced air (east) house. The day setpoints were 63 and 60. Despite raising the infrared setpoints, carnation foliage temperature was significantly lower than the average air temperature under the infrared system. Note that outside air temperature was relatively high. Note also, that with low duty cycles of the forced air system, carnation foliage temperature also tended to be lower than the outside air temperature.

dropped *below* the outside air temperature. We have, this spring, observed carnation temperatures close to freezing within the greenhouse when the outside air temperature is at or slightly below the average air temperature setpoint.

A third, preliminary observation this past spring, was the much higher air temperature variation in the east house with considerable air circulation, versus the west house with its natural convection pattern (Fig. 5). Air temperature under the Modine heaters (north end of east greenhouse), has almost always been significantly cooler than average air temperature, and the south end almost always higher than the average air temperature. These differences have not been apparent in the west house, and the small variations noted have been usually within the accuracy of the measuring system. Plant response has been in accordance with these observations (see Progress Report III).

Summary

We have at least three major observations to report:

1. Energy transfer to foliage by convection remains one of the more important processes in controlling temperature. If there is no radiation to the foliage, and no energy transfer by convection processes, then the foliage will radiate energy to cold surfaces and the plant temperature will drop.
2. Forced circulation of air inside a commercial sized greenhouse is likely to set up large temperature variations, depending upon the system. Cool temperatures are almost invariably below and behind unit heaters, especially as the heating load requirement increases. In our estimation, forced air heating increases problems of crop uniformity even though that system may be cheaper.
3. Large plant temperature variations can also be experienced with infrared systems since the thermal radiation at the burner is higher than at the exhaust end.

In order to adequately prepare for next winter, we are beginning to believe we will have to alter the computer software in order to partially correct for the temperature differences and plant responses observed. Until this is done, we will be unable to truly determine energy consumption between the two systems. At present, data tends to indicate a significantly lower gas consumption under infrared heating. However, as will be pointed out in Progress Report III, carnation response follows that found with lower air temperatures, and is consistent with plant temperature measurements.

TEAM FINISHES TENTH IN TIGHT CONTEST

The Colorado State University flower judging team traveled to Penn State March 28-31 to attend the 43rd Annual Intercollegiate Contest. David Lang, Renee Moses, Regina Lang and Jayne Reeves represented CSU along with Karen Kampman and Will Healy as coaches. In a very close contest, CSU finished 10th — only 160 points behind first place North Carolina State. In the professional design contest Renee Moses won the second place plaque for her European design.

From left to right: Renee Moses, David Lang, Dr. W.E. Healy, Coach, Regina Lang and Jayne Reeves.

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