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GREENHOUSE ENVIRONMENTS AND CONTROL
PROGRESS REPORT I
CONTROLLING A GREENHOUSE ENVIRONMENT WITH A COMPUTER

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Computers offer great flexibility for controlling greenhouse environments, with the use of unambiguous setpoints and constants. However, good software requires good programming, good hardware, and a good knowledge of what is to be done in the greenhouse. Unfortunately, the inputs and implementation, upon which a program executes, may be the largest stumbling blocks in making full use of computers.

CGGA Bulletin 396 outlined the energy program planned for the CSU Bay Farm range (Fig. 1), using funds provided by the American Florists Endowment and the Colo. Agricultural Experiment Station, and equipment provided by Hewlett-Packard, Combustion Research Corp. and Raytek, Inc. The initial software for the HP-85 computer and two 3421A digital acquisition/control units, and the wiring, were completed in time to start the heating season in November, 1983 (Fig. 2). The program has undergone extensive revision throughout the winter, and it appears that we shall need another winter in order to provide adequate results.

Implementation systems

The major purpose of this study is to compare two different heating systems in identical greenhouses. The east, 30 × 100-foot, greenhouse (Fig. 1) is heated by two Modine, gas-fired unit heaters, located in the north end of the greenhouse, in conjunction with an Acme fan-jet and gable louver (Fig. 3). These two heaters provide a total of 600,000 BTU hr^{-1}, sea-level rated input, in two heating stages, with the fan-jet operating during heating cycles.

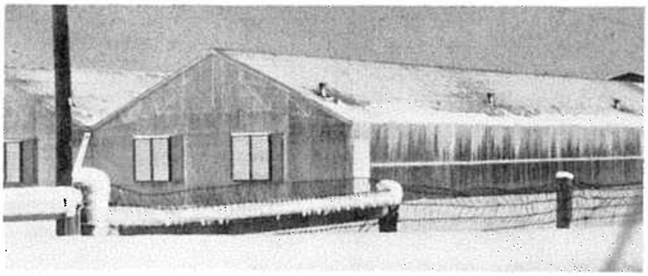

Fig. 1: The 6600 sq.ft. Bay Farm range, oriented north-south. This picture was taken prior to modification, and the exhaust stacks for the unit heaters may be noted. The computer control is located in a separate building out of the picture to the right.

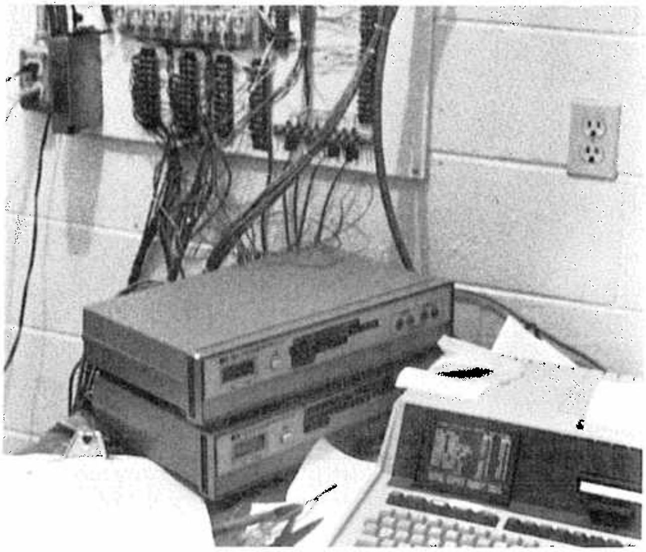

Fig. 2: Temperature control and data acquisition system for the Bay Farm range. To the right is an HP-85 desk computer with screen, printer and tape deck, controlling the two digital, data acquisition units in the center. These are connected to the implementation systems in the greenhouses via the terminal board on the wall.

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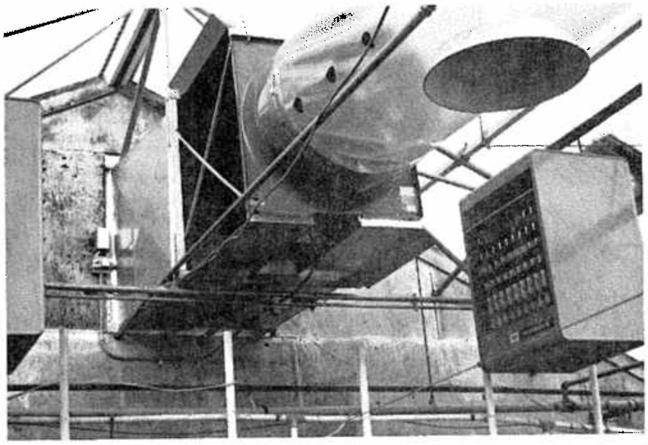


Fig. 3: Fan-jet system with two Modine, gas-fired unit heaters in the east house, giving two heating stages, with fan-jet operating when first stage heating comes on. Sea level BTU hr^{-1} input 600,000.

The west, 30 × 100-foot, house is heated by two lines of Combustion Research Engineering infrared units with four burners located at opposite ends of the house. The system was modified with additional piping in January, 1984, as shown in Fig. 4. Two stages of heating are provided with a total 520,000 BTU hr^{-1} input at sea-level.

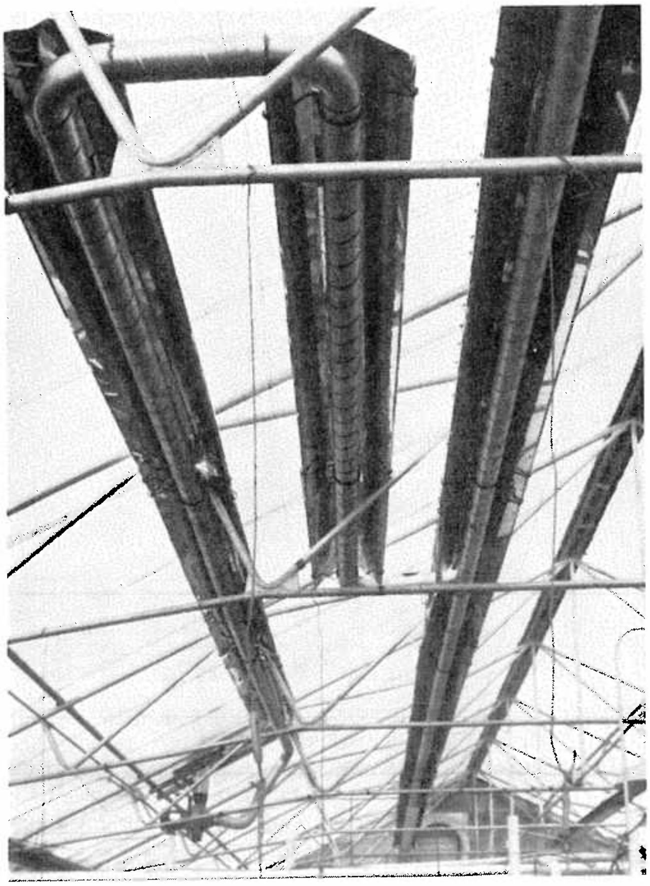


Fig. 4: Combustion Research Engineering infrared heating system in the west house. There are two independent systems, each with two burners, giving two heating stages. Total sea level input is 520,000 BTU hr^{-1}.

Other than the heating systems, the remainder of the temperature control system is identical with three cooling stages, automatic louver and ventilator operation. Evaporative pads and CO_2 injection (Johnson burners) are controlled by the computer system. CO_2 concentration is not measured.

Inputs to control system

Each house has four air temperature sensors, using thermocouples in aspirated housings (Figures 5 and 6). One wet bulb thermocouple is at station No. 2 in each house. These aspirator shelters have deliberately high air movement (900 fpm) in order to ensure adequate wet bulb measurements and fast temperature response. Response time for 24 gage, bare wire thermocouples, at 56 fpm air flow, is less than 2 seconds (time required to reach 63.2% of final temperature). Recommendations for adequate aspiration in psychrometric (wet bulb) measurements range from 590 to 985 fpm. One aspirated thermocouple is located outdoors.

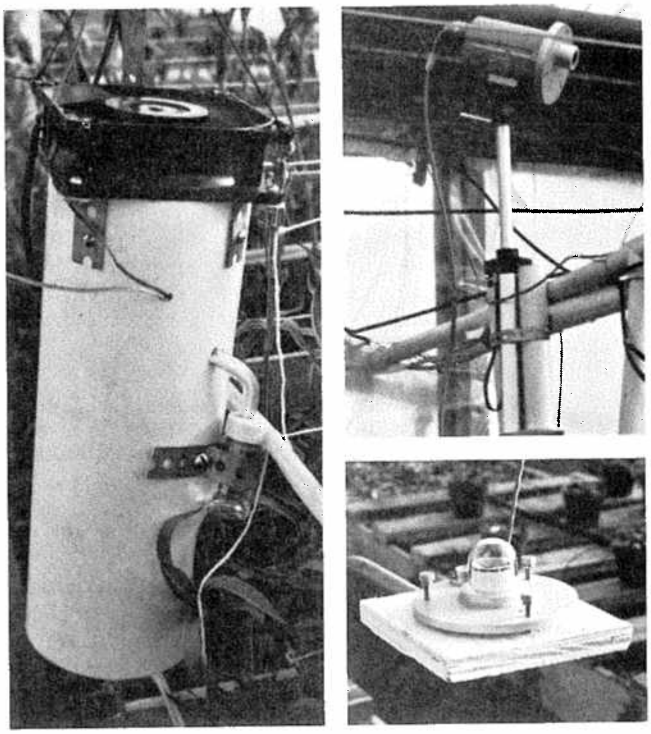


Fig. 5: Input installation. The aspirated unit in the left picture contains a wet and a dry bulb thermocouple. Wind speed in these units ranges from 900 to nearly 1000 fpm which assures adequate ventilation of the wet bulb and decreases dry bulb response time to an estimated 1 second or less. The top, right picture is one of two remote sensing, infrared thermometers, mounted to provide an integrated carnation plant temperature in each house. The bottom, right picture is a silicon cell pyranometer for measuring total, short wave, global solar radiation at approximate plant height.

Two remote sensing, infrared thermometers (Raytek, Inc.) are located as shown in Figures 5 and 6. These have a 20° field-of-view so that at 10 ft from the optical plane of the sensor, the systems will "see" an area of about 9.5 sq.ft., or a circle with a 1.8 ft radius. These were set in the particular locations to provide a maximum carnation foliage area without interference from structure, walks or supports.

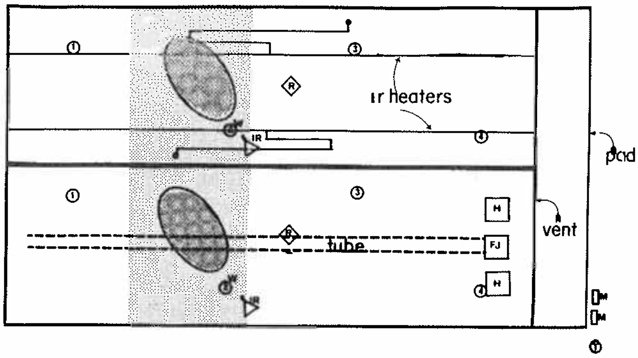


Fig. 6: Floor plan of the Bay Farm greenhouse. The two houses are separated by two layers of polyethylene film.

W = wet bulb temperature sensors. Numbers 1 through 4 are locations of the aspirated dry bulb sensors.
M = gas meters
R = solar radiation sensors
IR = infrared thermometers
T = outside temperature sensor
FJ = fan-jet
H = Modine heater

The shaded area is planted to single pinched, standard and miniature carnations. The dark, ellipsoid area is the approximate vegetational region "seen" by the infrared thermometers.

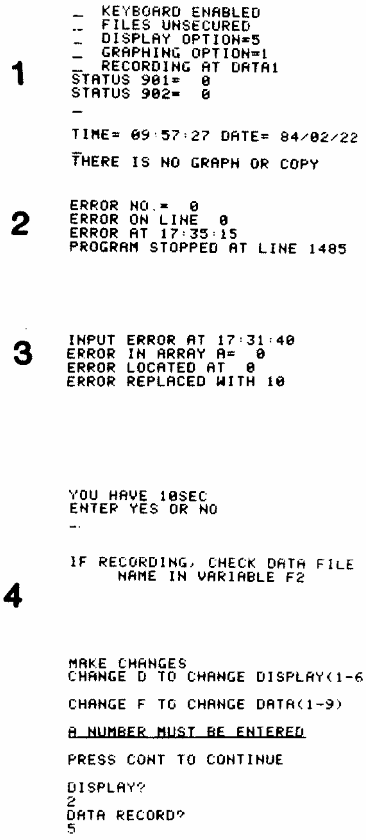
Radiation is measured in each house with a silicon cell pyranometer (Figures 5 and 6) which measures total, short wave global solar radiation. These are calibrated with the standard Weather Bureau, Eppley pyranometer.

The system was originally set up to use an infrared thermometer as the primary control sensor in the west house. We quickly found that this seriously confounded the information we sought, especially as the differences we are measuring are often within the limits of accuracy of the system as originally specified. At this time, the system reads the four air temperatures in each house and determines the average. This average air temperature is used by the computer software to compare with the set-points for temperature control. The system assures that we are measuring only air temperature, and there is no interference from radiation in either house.

The controlling program

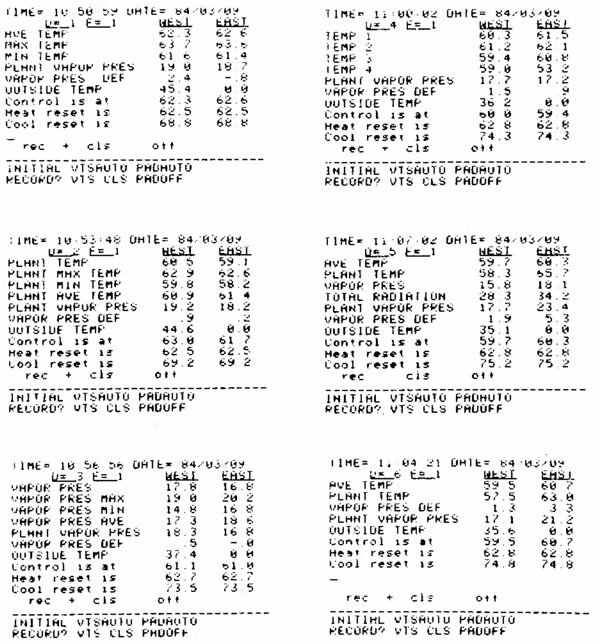
The system executes a control cycle at a rate set by the operator. The minimum execution time is about 40 to 50 seconds, depending upon the system status. At start-up, the computer prints time and status (Fig. 7), reads all inputs and checks inputs for errors. If there is an error in any input (e.g. broken wire) a reasonable number is substituted so that execution can continue without the system "crashing". Any other error will cause a halt with an alarm (Fig. 7). After error checking, the program performs the necessary calculations, stores the results, checks for night or day operation, CO_2 generation, pad operation and goes into a subroutine for actual temperature control. The control temperature is compared to recomputed set-points, and the implementation equipment set accordingly to return the controlled air temperature to equality with the set-points. At this point, the operator may manually halt execution if any changes are desired (Fig. 7), otherwise execution continues. Halting execution will set off an alarm. After this, the display is up-dated (Fig. 8) and the system "idles" until another control execution is initiated. A 90 second execution interval has been found satisfactory.

A separate program is provided for entering the required constants, set-points, etc. The operator may return to the initialization program at any time by pressing an appropriate "immediate execution" key. In the event of power failure, computer memory is lost, but there is an automatic start program. At power up, the system will automatically call the programs to re-establish computer control. The operator must re-set the system clock, however.



```
_   KEYBOARD ENABLED
..  FILES UNSECURED
_   DISPLAY OPTION=5
_   GRAPHING OPTION=1
_   RECORDING AT DATA1
STATUS 901=  0
STATUS 902=  0
_

TIME= 09:57:27 DATE= 84/02/22

THERE IS NO GRAPH OR COPY


ERROR NO.=  0
ERROR ON LINE  0
ERROR AT 17:35:15
PROGRAM STOPPED AT LINE 1485


INPUT ERROR AT 17:31:40
ERROR IN ARRAY A=  0
ERROR LOCATED AT  0
ERROR REPLACED WITH 10


YOU HAVE 10SEC
ENTER YES OR NO
_

IF RECORDING, CHECK DATA FILE
     NAME IN VARIABLE F2


MAKE CHANGES
CHANGE D TO CHANGE DISPLAY(1-6)

CHANGE F TO CHANGE DATA(1-9)

A NUMBER MUST BE ENTERED

PRESS CONT TO CONTINUE

DISPLAY?
2
DATA RECORD?
5
```

Fig. 7: Program status and operation displays. No. 1 is printed when the computer starts a program for the first time or is reset. In this example, pressing any key will halt program execution. Files may be duplicated and edited. In a program under modification, this reduces time in changing software — as long as unauthorized individuals are not likely to tamper with the machines. No. 2 is the standard error notification which turns on the alarm and halts execution. No. 3 specifically notifies the operator of an input error. However, the error is replaced with a ballpark value which allows execution to continue until the operator can correct the condition (i.e. a broken wire). No. 4 is a means to exit the main program in order to make changes. The top part is displayed at each execution. If "YES" is entered, the computer beeps, turns on the alarm and exits to the bottom part of No. 4 at which time the operator must enter required values for display and recording options, reset the computer clock and make any other changes. With a keyboard disabled, this would be the only place where execution could be permanently halted for changes.



```
TIME= 10:50:59 DATE= 84/03/09
      D= 1 F= 1           WEST   EAST
AVE TEMP                  62.3   62.6
MAX TEMP                  63.7   63.5
MIN TEMP                  61.6   61.4
PLANT VAPOR PRES          19.0   18.7
VAPOR PRES  DEF            2.4    -.8
OUTSIDE TEMP              45.4    0.0
Control is at             62.3   62.6
Heat reset is             62.5   62.5
Cool reset is             68.8   68.8
_
  rec  +  cls      off
----------------------------------
INITIAL VTSAUTO PADAUTO
RECORD? VTS CLS PADOFF
```

```
TIME= 11:00:02 DATE= 84/03/09
      D= 4 F= 1           WEST   EAST
TEMP 1                    60.3   61.5
TEMP 2                    61.2   62.1
TEMP 3                    59.4   60.8
TEMP 4                    59.0   53.2
PLANT VAPOR PRES          17.7   17.2
VAPOR PRES DEF             1.5     .9
OUTSIDE TEMP              36.2    0.0
Control is at             60.0   59.4
Heat reset is             62.8   62.8
Cool reset is             74.3   74.3
  rec  +  cls      off
----------------------------------
INITIAL VTSAUTO PADAUTO
RECORD? VTS CLS PADOFF
```

```
TIME= 10:53:48 DATE= 84/03/09
      D= 2 F= 1           WEST   EAST
PLANT TEMP                60.5   59.1
PLANT MAX TEMP            62.9   62.6
PLANT MIN TEMP            59.8   58.2
PLANT AVE TEMP            60.9   61.4
PLANT VAPOR PRES          19.2   18.2
VAPOR PRES DEF              .9     .2
OUTSIDE TEMP              44.6    0.0
Control is at             63.0   61.7
Heat reset is             62.5   62.5
Cool reset is             69.2   69.2
  rec  +  cls      off
----------------------------------
INITIAL VTSAUTO PADAUTO
RECORD? VTS CLS PADOFF
```

```
TIME= 11:07:02 DATE= 84/03/09
      D= 5 F= 1           WEST   EAST
AVE TEMP                  59.7   60.3
PLANT TEMP                58.3   65.7
VAPOR PRES                15.8   18.1
TOTAL RADIATION           28.3   34.2
PLANT VAPOR PRES          17.7   23.4
VAPOR PRES DEF             1.9    5.3
OUTSIDE TEMP              35.1    0.0
Control is at             59.7   60.3
Heat reset is             62.8   62.8
Cool reset is             75.2   75.2
  rec     cls      off
----------------------------------
INITIAL VTSAUTO PADAUTO
RECORD? VTS CLS PADOFF
```

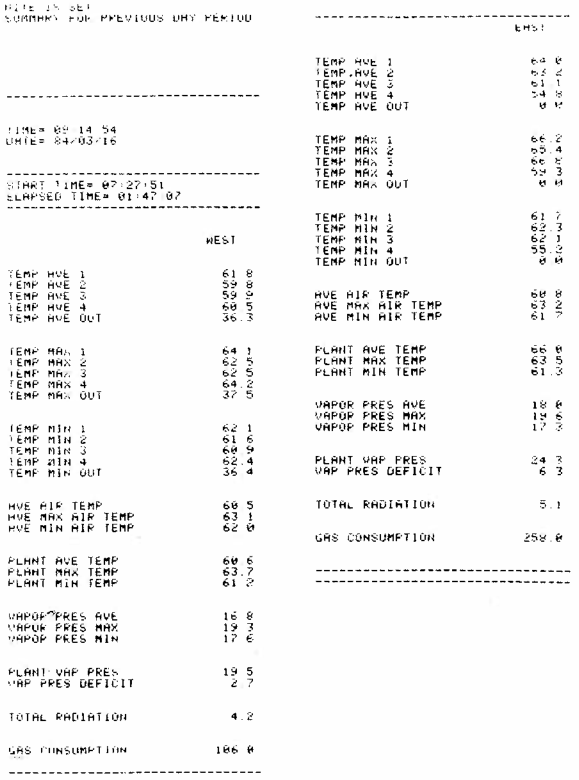
```
TIME= 10:56:56 DATE= 84/03/09
      D= 3 F= 1           WEST   EAST
VAPOR PRES                17.8   16.8
VAPOR PRES MAX            19.0   20.2
VAPOR PRES MIN            14.8   16.8
VAPOR PRES AVE            17.3   18.6
PLANT VAPOR PRES          18.3   16.8
VAPOR PRES DEF              .5    -.0
OUTSIDE TEMP              37.4    0.0
Control is at             61.1   61.0
Heat reset is             62.7   62.7
Cool reset is             73.5   73.5
  rec  +  cls      off
----------------------------------
INITIAL VTSAUTO PADAUTO
RECORD? VTS CLS PADOFF
```

```
TIME= 11:04:21 DATE= 84/03/09
      D= 6 F= 1           WEST   EAST
AVE TEMP                  59.5   60.7
PLANT TEMP                57.5   63.0
VAPOR PRES DEF             1.3    3.3
PLANT VAPOR PRES          17.1   21.2
OUTSIDE TEMP              35.6    0.0
Control is at             59.5   60.7
Heat reset is             62.8   62.8
Cool reset is             74.8   74.8
_

  rec  +  cls      off
----------------------------------
INITIAL VTSAUTO PADAUTO
RECORD? VTS CLS PADOFF
```

Fig. 8: Various display options for the HP-85. The displays are updated at each control execution. The underlined D= and F= are the display and recording options now in the system. These are replaced by *EXECUTING* when the system is controlling. All displays show the temperature being used by the system to control (Control is at), and the recalculated heat (Heat reset is) and cooling (Cool reset is) setpoints. The ventilators may be permanently closed, the pads may be turned off permanently, the system will record, and the system can be reinitialized by pressing appropriate keys below the mnemonics at the bottom of the screen. The "+" sign flashes when the system is idling.

At day-to-night switchover, as determined by an operator-set level, the system automatically prints a summary for the previous period (Fig. 9). This gives the average, maximum and minimum inputs for each temperature, total radiation, total gas consumption, and hours of elapsed time since the last switchover. At night, the cooling system is disabled if outdoor temperature is below the set-points. We deliberately avoid the use of "relative humidity". This moisture measurement requires the dry bulb temperature for intelligent use. The program calculates humidity from the wet bulb temperature reading in millibars vapor pressure which is an absolute humidity value, using a standard psychrometric formula. We assume that well-watered carnations will have an internal leaf relative humidity of 100%. If leaf temperature is known (infrared thermometers), plant vapor pressure can be determined from standard tables. If the difference between plant and air vapor pressure is zero, or less, then conditions are suitable for condensation. A dehumidification cycle is not included in this program.

Information presented digitally, while unambiguous, requires more interpretation by the operator, and one seldom remembers digital information from one moment to the next. To overcome this deficiency, another sub-routine allows automatic data storage and recording. The rate of data storage can be at each execution (i.e. once every 90 seconds), or at whatever multiple of the execution rate the operator desires. One must be careful not to become overburdened with data. The data, on tape, can be plotted so a grower can visually assess environmental control.



```
[illegible] IS SET
SUMMARY FOR PREVIOUS DAY PERIOD



----------------------------------

TIME= 09:14:54
DATE= 84/03/16

----------------------------------
START TIME= 07:27:51
ELAPSED TIME= 01:47:07
----------------------------------

                           WEST


TEMP AVE 1                 61.8
TEMP AVE 2                 59.8
TEMP AVE 3                 59.9
TEMP AVE 4                 60.5
TEMP AVE OUT               36.3


TEMP MAX 1                 64.1
TEMP MAX 2                 62.5
TEMP MAX 3                 62.5
TEMP MAX 4                 64.2
TEMP MAX OUT               37.5


TEMP MIN 1                 62.1
TEMP MIN 2                 61.6
TEMP MIN 3                 60.9
TEMP MIN 4                 62.4
TEMP MIN OUT               36.4


AVE AIR TEMP               60.5
AVE MAX AIR TEMP           63.1
AVE MIN AIR TEMP           62.0


PLANT AVE TEMP             60.6
PLANT MAX TEMP             63.7
PLANT MIN TEMP             61.2


VAPOR PRES AVE             16.8
VAPOR PRES MAX             19.3
VAPOR PRES MIN             17.6


PLANT VAP PRES             19.5
VAP PRES DEFICIT            2.7


TOTAL RADIATION             4.2


GAS CONSUMPTION           106.0

----------------------------------
```

```
----------------------------------
                           EAST


TEMP AVE 1                 64.0
TEMP.AVE 2                 63.2
TEMP AVE 3                 61.1
TEMP AVE 4                 54.8
TEMP AVE OUT                0.0


TEMP MAX 1                 66.2
TEMP MAX 2                 65.4
TEMP MAX 3                 66.8
TEMP MAX 4                 59.3
TEMP MAX OUT                0.0


TEMP MIN 1                 61.7
TEMP MIN 2                 62.3
TEMP MIN 3                 62.1
TEMP MIN 4                 55.2
TEMP MIN OUT                0.0


AVE AIR TEMP               60.8
AVE MAX AIR TEMP           63.2
AVE MIN AIR TEMP           61.7


PLANT AVE TEMP             66.0
PLANT MAX TEMP             63.5
PLANT MIN TEMP             61.3


VAPOR PRES AVE             18.0
VAPOR PRES MAX             19.6
VAPOR PRES MIN             17.3


PLANT VAP PRES             24.3
VAP PRES DEFICIT            6.3


TOTAL RADIATION             5.1


GAS CONSUMPTION           258.0


----------------------------------
----------------------------------
```

Fig. 9: System status printout for the previous night or day period. The time and date for switchover to night or day is given, together with the previous switchover and elapsed time. The average, maximum and minimums for inputs are given in °F, vapor pressures in millibars, total radiation in gram-calories per sq.cm. and gas consumption in ±400 × counts = cubic feet of gas. Maximums and minimums are replaced with current values one hour after switchover in order to avoid the previous night or day values.

Summary

Computerization of the greenhouse environment requires: 1) a computer with adequate central memory storage, 2) appropriate acquisition/control peripherals, 3) sensors which are calibrated and installed properly, 4) an operator who knows what he's doing (some training), 5) good software, and 6) a good implementation system. Retrofitting a greenhouse with an existing implementation system will not be desirable if that implementation system (fans, heaters, ventilators, etc.) is inadequate. Furthermore, retrofitting will increase cost since the software will have to be customized for the particular application. We are beginning to find that full use of computers in greenhouse environmental control will require changing heating and cooling systems in many greenhouses, especially if precise and accurate environmental regulation is to be achieved.

Progress Report II will deal with environmental measurements we have been able to make at the Bay Farm during the 1983-84 heating season, and Progress Report III will cover general plant responses.