Florida Reach-Ins: Environmental Chambers for Entomological Research

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ABSTRACT Controlled-environment chambers developed by University of Florida's Department of Entomology and Nematology differ from conventional reach-in chambers in that they depend on ambient air for cooling and dehumidification, allowing many chambers to be served by one remote, redundant cooling system. Furthermore, each group of eight chambers is controlled and logged by one XT-type computer, making these functions economical, precise, and flexible. Temperature and humidity can be controlled ±0.1°C and ±1% RH of setpoints. Setpoints can be constant, changed at user-specified intervals, or changed continually between user-specified inflection points. Lights and auxiliary outlet can be programmed to turn on and off at intervals of 1 s. Logged data can be viewed graphically without downloading.

IN 1987, when the University of Florida Department of Entomology and Nematology started to plan to equip a new building, a faculty committee decided that a new type of reach-in environmental chamber was needed and that 50 such units should be purchased. This decision was prompted by the need for multiple reach-in chambers and dissatisfaction with conventional ones (i.e., those built on a refrigerator chassis with heater, lights, appropriate controls, and [sometimes] other features added). Complaints about these reach-ins included the heat, vibration, and noise they generated, their lack of reliability and needed features, and their size and cost relative to their benefit. The committee drew up general specifications for reach-in environmental chambers that would be affordable and especially suited for entomological research. Included in their recommendations was that the chambers depend on ambient air for cooling and dehumidification.

Because of their interest in environmental chambers, J. J. Gaffney and Norm Leppla, then at the USDA Insect Attractants, Behavior, and Basic Biology Laboratory, agreed to supervise development of a prototype "Florida Reach-In," but development eventually fell to T. J. Walker (project manager), J. J. Gaffney (engineer; retired from USDA), A. W. Kidder (engineer and programmer), and A. B. Ziffer (programmer). The fourth and final prototype was completed in April 1990, and 56 chambers were built by November 1990, when the new Entomology and Nematology building was occupied. The initial multichamber, multiuser version of the controlling software was completed in May 1991, followed by an enhanced version in April 1992.

Description of Florida Reach-Ins

Each octet of chambers is controlled and logged by one IBM-XT computer or clone (Fig. 1). Each chamber consists of a main cabinet and three easily removable modules. In describing the cabinet, its modules, and the controlling hardware and software, we will be brief, but two detailed manuals thoroughly explain all aspects of the Florida Reach-Ins, including operating instructions, controlling software, and chamber and computer hardware (Walker 1992, Ziffer et al. 1992).

Main cabinet. The largest component of a Florida Reach-In is a stackable stainless steel cabinet (65 by 78 by 115 cm [w x d x h]) enclosing a 61 by 106 by 106 cm work space, illuminated through its rear, Plexiglas wall by a lights module (Fig. 2). The other interior walls and the ceiling of the work space are white-painted aluminum for light reflectance. The upper 18 cm of the cabinet houses the electronics tray, the humidifier module, a centrifugal blower, and a mixing chamber (Fig. 3). Air is pulled from the work space by the blower, heated with a 500-watt cartridge heater, humidified by steam injected at the blower outlet, blended in the mixing chamber, and returned to the work space via hollow chamber walls and a plenum under the perforated chamber floor. Other features of the main cabinet are a port (5 cm diameter) to the work space to accommodate electric cords or sensor leads (Fig. 2); air vents with controlled closures for regulating the amount of fresh air admitted; adjustable, epoxy-resin-coated shelves; removable, stainless perforated floor for uniform air flow and easy cleaning; card holder for displaying name of user and other information; and a lock in the chamber door handle.

Electronics Module. The electronic components of each Florida Reach-In are mounted in a tray (18 by 51 cm) attached to the control panel. They are easily accessed via a lift-off lid, and the tray can be removed by unfastening the control panel and unplugging the power and sensor cords that connect the module to the main cabinet. The control panel (Fig. 2) accommodates the main power switch, a computer-controlled auxiliary outlet, and a reset button. Green indicator lights show the status of relays that turn on and off the air heater, humidifier, lights, and auxiliary outlet; a red light shows that the power is on. A large red light warns that the safety thermostat has operated and remains on until the reset button is pushed. Electronic components (Fig. 3) include four solid-state relays, a fuse block, mechanical relays for emergency shutdown and controlling the safety thermostat's warning light, a DC power supply and transmitter for the temperature and humidity sensors, and a printed circuit board that receives the cable from the controlling computer.

Humidifier Module. This module has an insulated stainless steel boiler powered by a 200-watt cartridge heater and protected by a safety thermostat (Fig. 3). Tap water is supplied to a reservoir via a tube that can be quickly disconnected. A float-activated valve maintains a constant water level in the reservoir, which feeds the boiler by gravity flow. Steam passes to the cabinet's mixing

Fig. 1. Eight Florida Reach-Ins. Control and logging are by computer at left.

chamber through an insulated stainless steel tube. Humidifier components are mounted in a tray that slips into a recess in the upper rear of the main cabinet.

Lights Module. Two 20-watt fluorescent fixtures with individual ballasts are mounted on an aluminum housing (50 by 8 by 75 cm) that couples to the rear of the cabinet. When the lights are on, a muffin fan ventilates the module through light traps that prevent outside light from entering the chamber work space.

Controlling Hardware. The controlling computer has two analog-to-digital (A/D) boards and a digital input/output board. These boards are connected by cables to two break-out boxes that each connect, via 15-conductor cables, with four Florida Reach-Ins. The A/D boards digitize signals from temperature and humidity sensors. The digital board receives input from light sensors and sends controlling outputs to the 32 solid state relays.

Software. Developing the software for Florida Reach-Ins proved as difficult and time-consuming as developing the chambers themselves. The source code, in Turbo Pascal, is 1.2 Mbytes and 37,000 lines, with about 20% licensed from second parties. Executable files that control and log eight chambers are 300 kbytes.

Every 5 s the computer monitors temperature and humidity in eight chambers and compares the values with the setpoints. Using current and past differences between setpoints and actual temperatures and humidities, it determines what duty cycle (percentage time on) is appropriate during each of the next 5 s for each of the 16 air and steam heaters. In calculating percentage time on, the computer adds three components: *P*roportional, *I*ntegral, and *D*erivative (i.e., it uses P.I.D. control, which enables it to prevent overshoots, to seek the setpoint on the basis of past errors, and to adjust the rate of change [Johnson 1988]). The computer turns lights and auxiliary outlets on or off within 1 s of the time specified. At user-specified intervals, the computer logs, for each chamber, the current temperature and relative humidity and whether the lights and auxiliary outlet should be on or off. If the light sensor has detected a deviation from the specified light regime (as from a lights failure or from someone opening the chamber door when the lights are off), a lights error is logged for that interval. Every 15 min, logged data are written from RAM to the hard disk. If the power to the computer fails, program execution stops and all chamber relays open (cutting off heat sources other than the blower motor). When its power is restored, the computer restarts itself, logs the interruption, and resumes control. Because the computer's clock continues to run during the outage, subsequent control events and data logging occur at the correct real time.

The main screen of the user interface displays important information about the status of each chamber (Fig. 4A). Entering the number of a chamber causes a six-choice menu to overlay the main screen, as shown in the figure. Users must specify their username and password to edit control parameters or chamber information and to erase a data file, but no restrictions are placed on viewing or copying logged data. Some features of the control program are accessible only to "superusers." For example, a superuser can set the computer's clock and add or delete usernames when chambers are reassigned.

Choice 2 on the main menu brings up a screen that directs the user to specify the mode of control. If *time-varying* control is selected, the user is prompted to upload a file with the required instructions (see below). If *constant* control is selected, the user can specify setpoints for temperature, humidity, photoperiod, logging interval, and control of auxiliary outlet. By accessing other screens, the user can change P.I.D. parameters and sensor calibration constants.

Time-varying control allows setpoints to be changed continually or at user-specified intervals. The user decides what the chamber should do, uses a utility program to prepare a table of instructions in a prescribed ASCII format, and uploads the table

Fig. 2. Open Florida Reach-In, showing control panel with indicator lights and auxiliary outlet, adjustable shelves, lights behind Plexiglas in back, and perforated floor. Sensors for temperature and humidity are in cylinder in air return at center of work space ceiling. Access port, sealed with neoprene stopper, is at upper front of right wall.

onto the controlling computer. The computer then uses the table to produce a chronology of changes and formulas. *Changes* turn the lights or auxiliary outlet on or off or change P.I.D. parameters. *Formulas* are determined by user-specified *inflection points* for temperature and humidity. A formula remains in effect from one inflection point to the next, and during that time, the control program uses it to calculate a new setpoint every 5 s. The user may specify either of two formula-calculating algorithms. If *ramp* is specified, the formulas describe straight lines between inflection points. If *curve* is specified, the formula between any two inflection points describes the parabola that would pass through those two and the next inflection point (Fig. 5).

The logging system provides for versatile on-screen graphing (Fig. 4), making it easy to keep current on chamber performance. Logged data can be downloaded for archiving, for making numerical analyses, or for making graphs for presentations (cf. Fig. 6).

Performance of Florida Reach-Ins

With constant-mode control, temperatures and humidities can be maintained ±0.1°C and ±1% RH of the programmed setpoints (Fig. 4C), unless the ambient temperature has large, short-term oscillations. For example, in a room with 5°C fluctuations every 3 min, chamber temperature and humidity varied ±0.2°C and ±2% RH about the setpoints. Place-to-place variation in temperature within a chamber is generally <0.5°C unless the chamber is operating at 10° above ambient. Lights being on or off has no effect on the stability of control of temperature or humidity. The excellent humidity control results, in part, from the stable temperature control and from the lack of a cold coil that cycles in temperature. The range within which control of temperature and humidity is possible depends on ambient conditions. The minimum temperature that can be maintained is 1 to 3°C above ambient, with the lower value requiring good air flow on the exterior chamber walls. Maximum temperature is 15 to 20°C above ambient. Florida Reach-Ins presently operate between 11 and 40°C because some are in rooms held at 10°C and others are in rooms at 20°C. Chambers in these rooms, which are dehumidified only by the room cooling systems, maintain humidities as low as 40% and as high as 95%. The range available within a particular chamber depends to a large degree on the difference between chamber and ambient temperatures. With chamber temperatures 3°C above ambient, most chambers can maintain relative humidity constant at 50 to 95%. At 15°C above ambient, the range is 40 to 85% RH.

With time-varying control, many types of environmental regimes can be produced (Figs. 4D, 6A–D). During steps from one temperature or humidity to another, as in Fig. 6C, the maximum rate of increase is 1°C and 20% RH min^{-1}. Rates of decrease may be as great but are more dependent on differences between setpoints and ambient conditions. For example, as chamber temperatures drop from 15 to 5°C above ambient, maximum rate of cooling drops from 0.9 to 0.1°C min^{-1}. With the weather simulation in Fig. 6D, the maximum absolute difference between the hourly setpoints and the actual chamber temperature was 0.29°C (mean = 0.09).

In the first 50+ chamber-years of operation the only component of the Florida Reach-In that has given substantial trouble has been the steam generator. After 6 to 12 mo of service, sediments sometimes obstruct the gravity water flow to the boiler and reduce or stop steam production. Normal operation is restored by removing the humidity module and flushing the sediments from the boiler. This problem could be eliminated by improving the

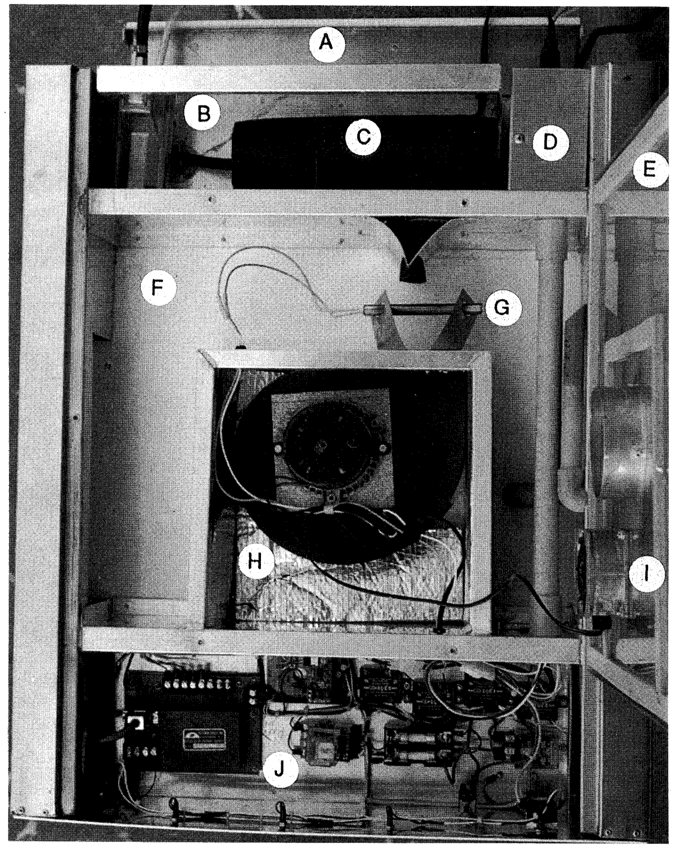

Fig. 3. View of Florida Reach-In from above. Lights module (A) attaches to rear of cabinet. Lids have been removed from humidifier module (B) and electronics module (J). Main lid (E) seals mixing chamber (F) and closes blower compartment (H). Muffin fan (I) ventilates blower compartment. The insulated boiler (C) discharges steam into the blower air stream. Air from blower passes over 500-watt cartridge heater (G), is humidified, and directed right and left to hollow walls that feed the conditioned air to a plenum beneath the perforated floor of the work space. Rear power center (D) connects with electronics module via PVC conduit. Smaller PVC pipes (to right of and beneath conduit) are air ducts from mixing chamber to outside and from outside to work space.

water supply. Because each generator uses a maximum of 0.3 liter of water per hour, a water treatment unit of modest capacity would suffice.

Time-varying control of temperature and humidity is well illustrated in Fig. 6, but the similar versatility in control of lights and auxiliary outlet is not. For example, any number of light and dark periods can be scheduled each day, or the photoperiod can be made to change gradually from one day to the next. The auxiliary outlet allows programming of any device that is plugged into it (e.g., a strobe can be activated once or at intervals during a dark period, or a light source of intermediate intensity can be switched on at the beginning and end of dark periods to simulate evening and morning twilights).

The fluorescent light used in Florida Reach-Ins differs from natural light in its intensity (1000 lux), spectrum (little near-UV), and flicker frequency (120 cycles per s^{-1}). Such light seems to work well in studies of insect development, but more nearly natural light could be obtained by modifying the lights modules of Florida Reach-Ins in ways suggested by Shields (1989).

Accuracy of the temperature and humidity signals is maintained by easy-to-use, software-supported calibration procedures.

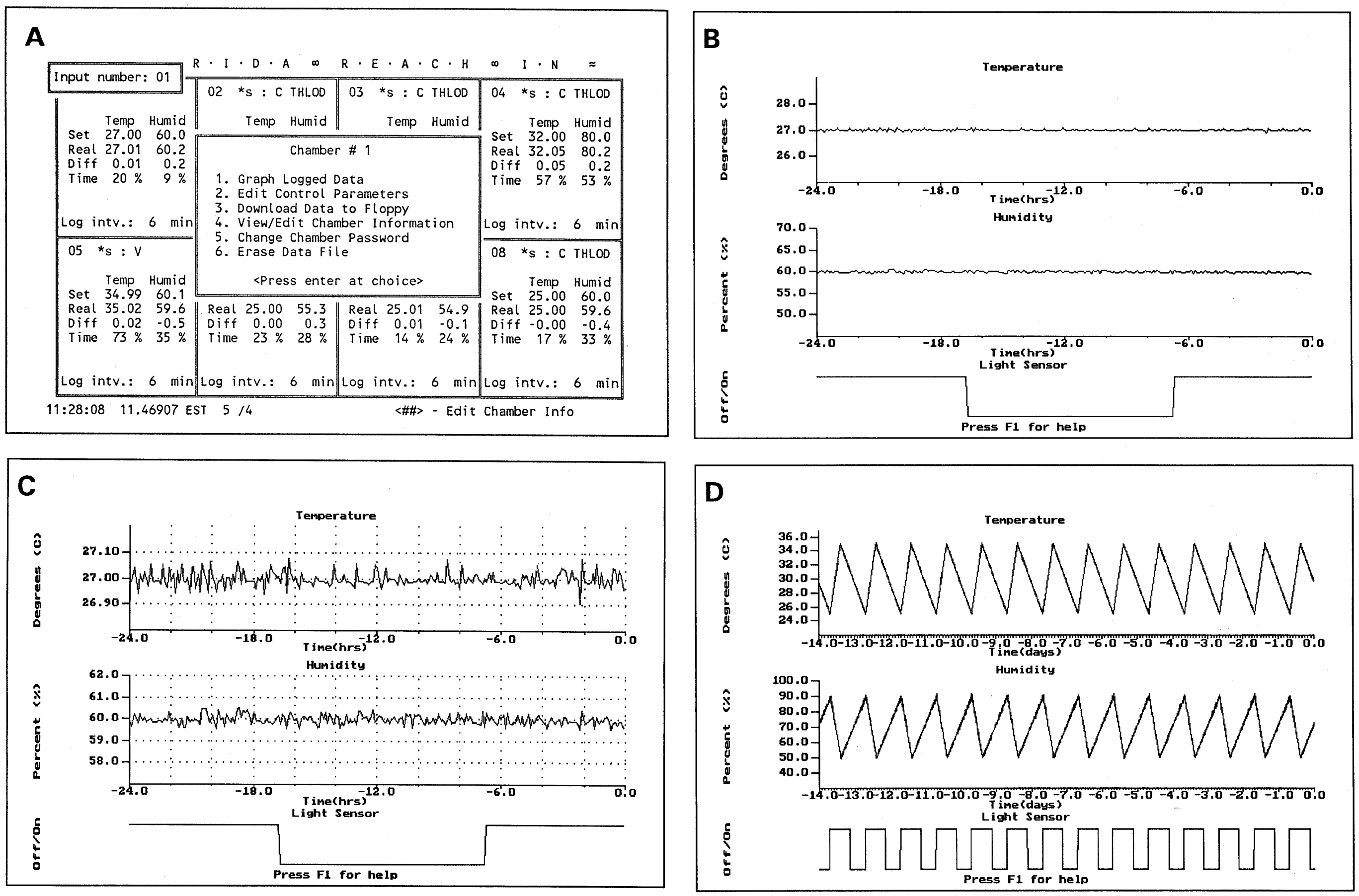

Fig. 4. Screens captured from the monitor of the computer controlling eight Florida Reach-Ins. (A) Main screen, which displays status of chambers, overlaid with menu for Chamber 1. (B) Graph of last 24 h of logged data for a chamber set at 25°C and 60% RH. (C) Same graph with *y* axes zoomed and grid added. (D) Fourteen-day graph of ramped temperature and humidity.

Conclusions

Others have used ambient air to cool and dehumidify reach-in environmental chambers. For example, Nicholls & Grills (1968) and Ashley & Greany (1978) described such chambers and reported satisfactory control of temperature and humidity in the ranges that are generally used for rearing insects. They did not discuss using cooled and dehumidified ambient air to get lower temperatures and humidities in the chambers, but that idea is implicit to their chamber designs.

Use of ambient air for cooling has advantages and limitations. A remote, redundant cooling system can serve evaporator coils in many rooms of chambers, and it isolates the chambers from the heat, noise, and vibration associated with compressors and condensers. Alternatively, a pair of room air conditioners in each room can provide economical, failsafe cooling. Using several rooms, set at different temperatures, permits chambers to operate at a wider array of constant temperatures and can save energy by allowing all chambers to operate within a few degrees of ambient. With time-varying control (e.g., Fig. 6), the range of temperatures that can be achieved in a single chamber is limited to 17°C.

Use of ambient air for dehumidification takes advantage of the fact that the ambient air is automatically dehumidified by condensation on the coils of the room's cooling system. The minimum humidity that can be maintained in a chamber depends on chamber ventilation, moisture sources within the chamber, ambient dewpoint, and the temperature of the chamber. If lower humidities are desired, ambient dewpoint can be lowered by using smaller, thus colder, evaporator coils to cool the rooms. Room dehumidifiers can achieve the same result, but they increase the heat load of the room. The maximum humidity that can be maintained is limited by condensation on the coldest surfaces within the chamber. When higher humidities are desired, the coldest surfaces within a chamber (usually the ceiling of the work space beneath the electronics and humidifier modules) can be warmed by thinly insulating them.

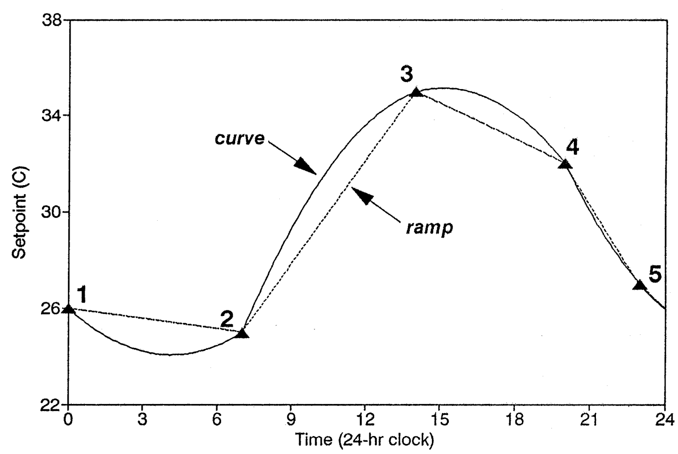

Fig. 5. Continuously varying setpoints calculated from five inflection points by curve and ramp algorithms of the program for time-varying control. Each curve between inflection points is based on three points (e.g., the curve between points 1 and 2 is from a parabola fit to points 1, 2, and 3; the curve between points 4 and 5 is from a parabola fit to points 4, 5, and 1). Each ramp is simply the straight line between inflection points.

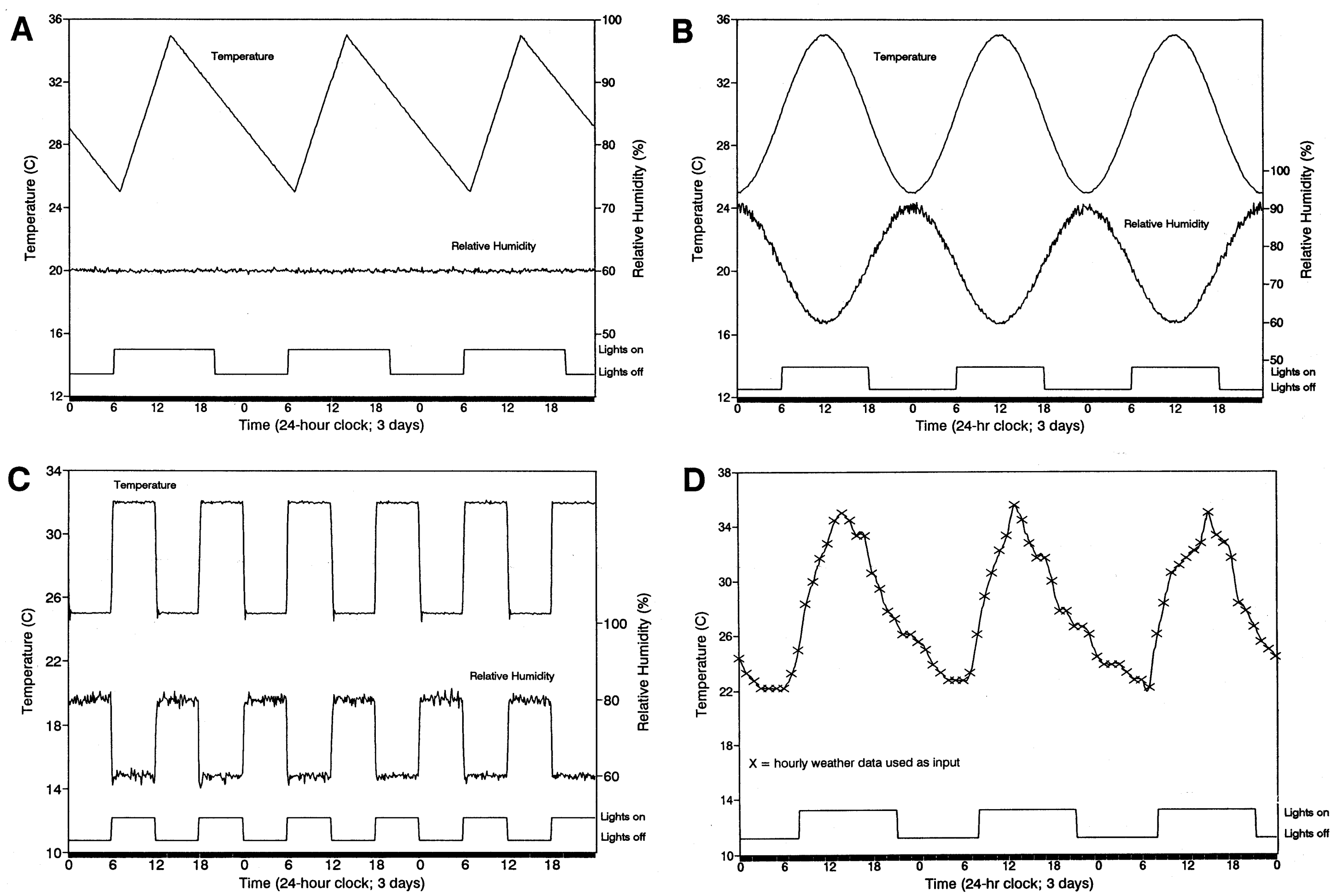

Fig. 6. Three-day records of time-varying control by Florida Reach-Ins. (A) Temperature ramped between 25 and 35°C with RH at 60%. (B) Sinusoidal cycles of temperature and RH. (C) Twice-per-day stepped cycles of temperature and RH; light and dark alternated every 6 h. (D) Weather simulation (hourly temperature data from the Gainesville airport used as input).

Others have also used computers to control multiple chambers. In the early 1970s, researchers at New Mexico State University used a programmable calculator and extended memory unit to accomplish time-varying control of temperature and humidity in two to five chambers (Atmar & Ellington 1973, Atmar et al. 1978). More recently, and with the same computer we used, Taylor & Shields (1990), at Cornell University, produced smooth daily thermoperiods in eight modified low-temperature incubators. Their chambers were cooled by individual compressors that were run continuously to give better temperature control. Humidity was not controlled.

Our 56 chambers and their controlling hardware and software cost $140,000 ($2,500 each), not including the cooling system for the rooms that house the chambers nor the labor required to develop the chambers and to test the chambers and their controlling software. Our greatest economy was to use one low-cost computer to control and log multiple chambers. The Taylor & Shields (1990) system and two commercial systems are superficially similar to ours in that each uses one computer to log data from multiple chambers; however, the routine control calculations are done by controllers in each chamber that each cost from one to three times the cost of an XT. Our more economical solution allowed us to develop and purchase chambers of noteworthy quality and durability and to include many special features (e.g., humidity control, programmable auxiliary outlet, light error detection, and easy-access port). We were also able to put the parts likely to require service in three easily removed and replaced modules, permitting chambers to be kept in service by substituting modules during repairs.

There was some initial anxiety that using a single computer to control eight chambers might cause reliability problems, because a computer breakdown can cause eight chambers to fail simultaneously. More than 1 yr experience with 56 chambers and seven computers has shown otherwise. In fact, the passive refrigeration system in combination with computer control has proven more reliable and provides more precise control than conventional commercially available chambers. We do have a backup computer with backup A/D and digital boards available for rapid replacement in the event of a failure.

Environmental chambers that are as reliable, versatile, and affordable as Florida Reach-Ins are needed for experimental studies of many problems in insect ecology and physiology. Too often in the past, available chambers have broken down or proved incapable of precise control. Too often in the past, available chambers could only maintain constant conditions or make stepwise changes rather than make graded changes or closely simulate the natural environment. Too often in the past, true replication has been foregone because chambers were too few (because they were too costly) to permit producing a given environment in more than one chamber.

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