QUEENSLAND DEPARTMENT OF PRIMARY INDUSTRIES

DIVISION OF PLANT INDUSTRY BULLETIN No. 783

INEXPENSIVE, SELF-CONTAINED FACILITY FOR RADIATION FROST STUDIES OF CROP OR PASTURE PLANTS

by D. A. Ivory, M.Agr.Sc., Ph.D.

SUMMARY

An inexpensive, self-contained facility was designed for radiation frost studies. Three separate freezing chambers can be independently controlled to reduce leaf temperatures to at least −10°C. A precision of ±0·13°C for individual leaves with 0·25 to 0·5°C variation in leaf temperature between plants over a 0·99 m² area can be maintained. An increasing gradient in air temperature of 0·6°C from the top to the base of the plant canopy approximates the conditions obtained with frosts in the field.

I. INTRODUCTION

The most common method of assessing the freezing resistance of crop and pasture plants is to simply measure their survival in the field over winter. If winter conditions are quite variable from year to year, however, testing would have to continue for a number of years to obtain a useful assessment for that locality. The limitations of this method appear to be (a) that it can be considerably time consuming and (b) that it does not allow easy extrapolation to survival assessment in other localities because variability in survival cannot be readily assigned to a single environmental or plant factor.

To overcome some of these deficiencies, particularly a saving in time, controlled laboratory freezing tests have been developed. Generally good correlations have been obtained between controlled freezing tests and field survival (Weibel and Quisenberry 1941; Amirshahi and Patterson 1956; Peake 1964; Marshall 1965; Single 1966; Smith and Boyd 1969). Controlled freezing has been used as either a standard screening technique (Single 1966; Smith and Boyd 1969; Hacker *et al.,* 1974) or in many cases as a means of studying factors which can affect the freezing resistance of individual plants. Most freezing chambers are designed to circulate refrigerated air from an external source. One of the greatest problems with such a design appears to be the large spatial variation in temperature that can occur (Bingham and Jenkins 1965; Paton 1972; Smith and Boyd 1969). An alternative design principle is to use radiative rather than convective cooling. This has the advantages of reducing spatial temperature variation within the freezing facility and of more closely simulating frosting under field conditions.

A controlled frosting facility was required for studies on the effect of environmental and plant factors on freezing resistance in tropical grasses (Ivory and Whiteman 1978a, 1978b). It was designed to use radiative cooling and meet the following requirements:

(1) a freezing chamber where the foliage of experimental plants should radiate to a cold absorber surface (i.e. heat sink) placed in the ceiling of the chamber.

(2) the temperature of the cold absorber surface should be capable of adjustment to produce any desired rate of leaf cooling and maintain a given leaf temperature indefinitely with a minimum of temperature fluctuation.

(3) three completely independent freezing chambers to be incorporated in the one facility so that studies could proceed simultaneously at different freezing temperatures.

(4) the whole facility should be completely self contained, moveable, reasonably inexpensive and easy to assemble.

Since the design and construction of this facility Aston and Paton (1973) and Ludlow and Taylor (1974) have used frost rooms designed to simulate radiation frosts but it is felt that this facility has some desirable design attributes not included in the frost rooms of Aston and Paton (1973) and Ludlow and Taylor (1974).

II. DESIGN AND CONSTRUCTION

Construction

A schematic drawing showing the essential design features is given in figure 1. In addition, a photograph showing the external appearance of the unit is given in figure 2 and an internal view of one frost chamber is given in figure 3.

The external shell of the whole unit was built of $1 \cdot 3$ cm thick marine plywood, the internal surface of which was painted with a black bitumastic sealer and the external surface with a high gloss vinyl paint. Polystyrene foam slabs 10 cm thick (density $0 \cdot 026$ g cm^{-3}) where glued to the inside of the plywood shell with polystyrene slabs of the same thickness and density used as dividing walls between frost chambers. A single $1 \cdot 3$ cm thick marine plywood sheet was glued to the internal surface of the polystyrene slab on the bottom of the unit to form the floor of the frost chambers. This created chambers 61 x 99 x 100 cm, internal measurement, giving a total air volume of $0 \cdot 604$ m^3 per chamber.

Once the unit was built up to this stage the doors for each chamber were cut out of the wall of the unit in the appropriate positions. A wooden flange was added to the perimeter of each door and a rubber sealer strip glued to the inside of this flange to provide a pressure seal for each chamber. The internal walls of each chamber were painted with a white water-based vinyl paint. Fifteen holes (5 x 3 rows), of 15 cm diameter, were cut out of $15 \cdot 5$ cm thick polystyrene slabs. These were placed on the floor of each chamber and provided an insulation barrier to the soil when pots of plants to be frosted were placed in them.

The cold absorber surface in each chamber consisted of a 96 x 58 cm perforated $0 \cdot 056$ cm stainless steel plate which was suspended 3 cm below the ceiling of the chamber by bolts which passed through to the outside of the top surface of the unit. In preliminary tests colder air was found to accumulate in the bottom of the freezing chambers and therefore a black polyvinyl plastic sheet was placed $2 \cdot 5$ cm below the cold plate and sealed to the walls of the chamber by masking tape. This effectively sealed off the cold plate from the rest of the chamber and reduced the build-up of colder air at the base of the

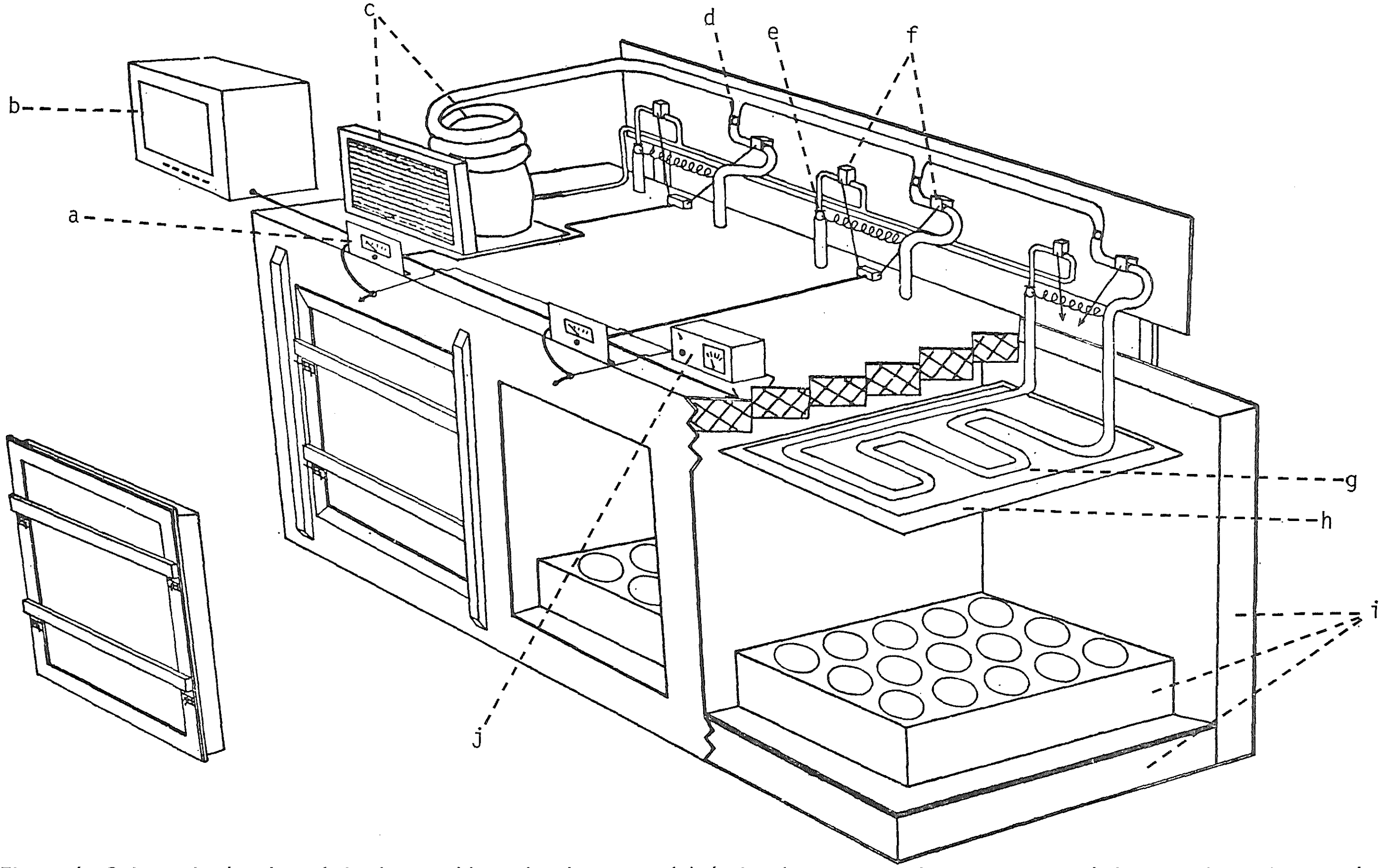

Figure 1. Schematic drawing of the frost cabinet showing essential design features: a, thermostat control; b, potentiometric recorder; c, refrigeration unit; d, one-way valve (in suction line); e, TX valve (in refrigerant line) with temperature sensor to suction line; f, solenoid valves; g, stainless steel refrigerated plate; h, polyvinyl chloride sheet which separates the refrigerated plate from the frost chamber; i, polystyrene insulation; j, relative humidity sensor.

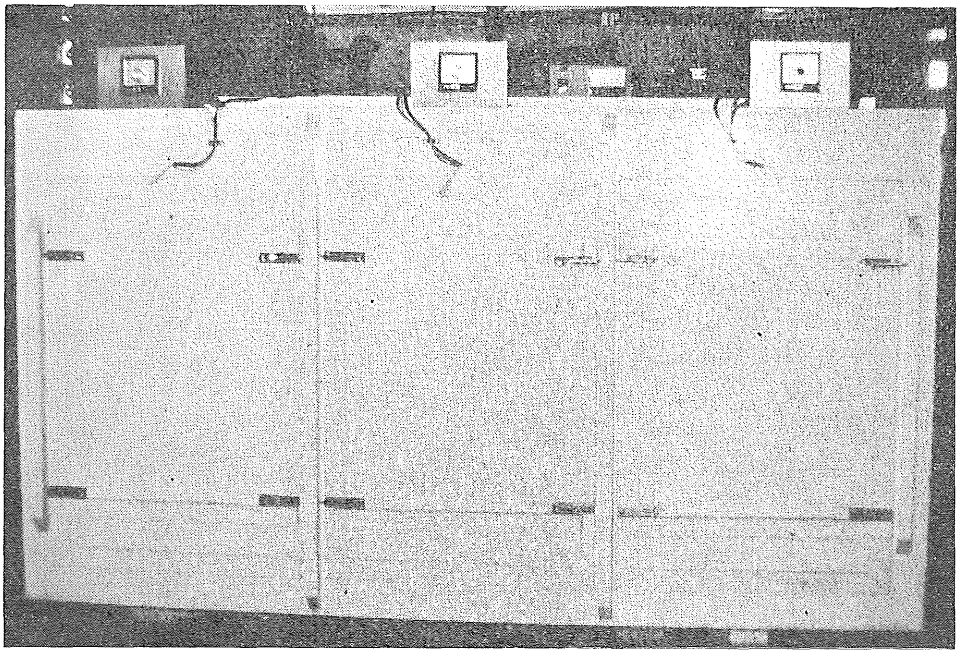

Figure 2. External view of the frost cabinet facility. (Particular features can be identified from figure 1.)

chamber. The presence of this polyvinyl sheet and the polystyrene slab in the base of the chamber reduced the internal dimensions of the frosting chamber to 61 x 99 x 80 cm, giving a total air volume of 0·483 m^3 per chamber.

Temperature regulation

A $\frac{3}{4}$ H.P. Kirby "Tecumseh" condensing unit, using R12 refrigerant, was used to refrigerate the cold absorber surfaces in each freezing chamber. The three chambers were connected in parallel. The liquid line was constructed of 0·95 cm ($\frac{3}{8}$") diameter copper tubing with 0·63 cm ($\frac{1}{4}$") diameter copper tubing branching off this line to each cold plate. The refrigerant line was bracket riveted to the upper surface of the cold plate as shown in figure 1. Two solenoid valves were placed in line at the inlet and outlet to each cold plate, with a TX valve also placed on the inlet line. The amount of refrigerant allowed through each TX valve was determined by the outlet temperature on the suction line. The solenoid valves open and close simultaneously and are operated electrically from the individual thermostat for each freezing chamber.

The thermostats used were FCJ Fenwall thermistor bead thermostats with a temperature control range of —50° to +40°C and a cycling range of 1·5°C. This type of thermostat was found to have the considerable advantage over a pressure-bulb sensor thermostat of a much more rapid response to change in air temperature. This characteristic is essential in minimizing the amplitude in leaf or air temperature when attempting to maintain constant temperature conditions (table 1).

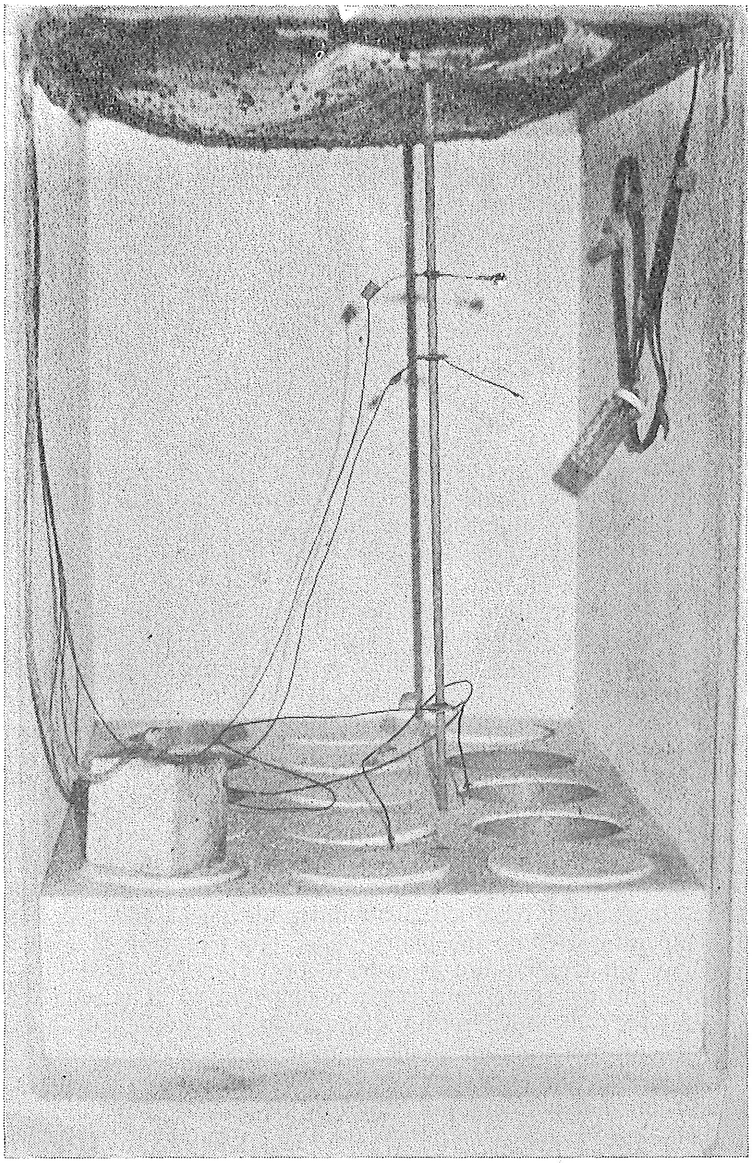

Figure 3. Internal view of a single frost chamber showing the possible placement of thermocouples and relative humidity sensor.

After considerable testing it was found that the thermostat sensor was best placed in contact with the bottom side of the cold plate. This position minimized the amplitude of the leaf temperature when attempting to maintain a constant leaf temperature and additionally minimized the lag in response between the leaf temperature and the temperature of the cold plate (table 1).

TABLE 1

AMPLITUDE IN AIR TEMPERATURE WITHIN FREEZING CHAMBERS WITH DIFFERENTIAL PLACEMENT OF THE SENSORS OF TWO DIFFERENT TYPES OF THERMOSTATS, UNDER CONDITIONS OF "CONSTANT" TEMPERATURE

Sensor Position	Amplitude in Air Temperature (°C)	Thermostat Type
1. Placed in air below PV sheet	2·5	Pressure-bulb
2. Placed in air above PV sheet	1·5	Pressure-bulb
3. Placed in contact with cold plate above PV sheet ..	0·5	Pressure-bulb
4. Placed in contact with cold plate above PV sheet ..	0·13	Bead-thermistor

III. PERFORMANCE

In preliminary testing of the refrigeration performance and temperature control of individual freezing chambers it was found necessary to place one-way valves in the suction line after each of the outlet solenoid valves, to allow completely independent temperature control for each chamber.

Four 0·031 5 cm constantan-copper thermocouples were placed in each chamber for monitoring temperature. These were connected to a Phillips 12-channel potentiometric recorder which was set to give a readout from every thermocouple every 24 s. The recorder was adjusted to 1·5 mV full scale deflection, which was equal to 25°C, so that each division on the chart was equal to 0·25°C. The thermocouples which measured air temperature were shielded by small pieces of aluminium foil.

The normal procedure prior to frosting plants was to attach (with adhesive tape) one thermocouple to the undersurface of a recently emerged leaf positioned near the top of the plant (approximately 50 to 60 cm above the soil surface). The other thermocouples recorded air temperature near the top of the plant foliage; air temperature within the plant foliage approximately 2·5 cm above the soil surface; and soil temperature at a depth of 1 cm. A typical time course of events during a frosting experiment is given in figure 4. It is seen that the soil temperature remains well above freezing-point and that the gradient in air temperature between the top and bottom of the plant canopy is 0·6°C with the air temperature at the base of the plant warmer than at the top of the plant foliage. This compares with an air temperature gradient of 0·2 to 0·3°C and 0·75 to 0·9°C between the 80 and 20 cm and 60 and 20 cm heights, respectively, in the canopy of a wheat crop under radiative frost conditions (Burrage 1972).

In all frost experiments, leaf temperature was invariably about 0.15 to 0.2°C lower than the adjacent air temperature, which is considerably less than the temperature depression of 0.3 to 0.55°C and 1.23 to 1.45°C at the 60 and 80 cm heights, respectively, in the canopy of a wheat crop under radiative frost conditions (Burrage 1972).

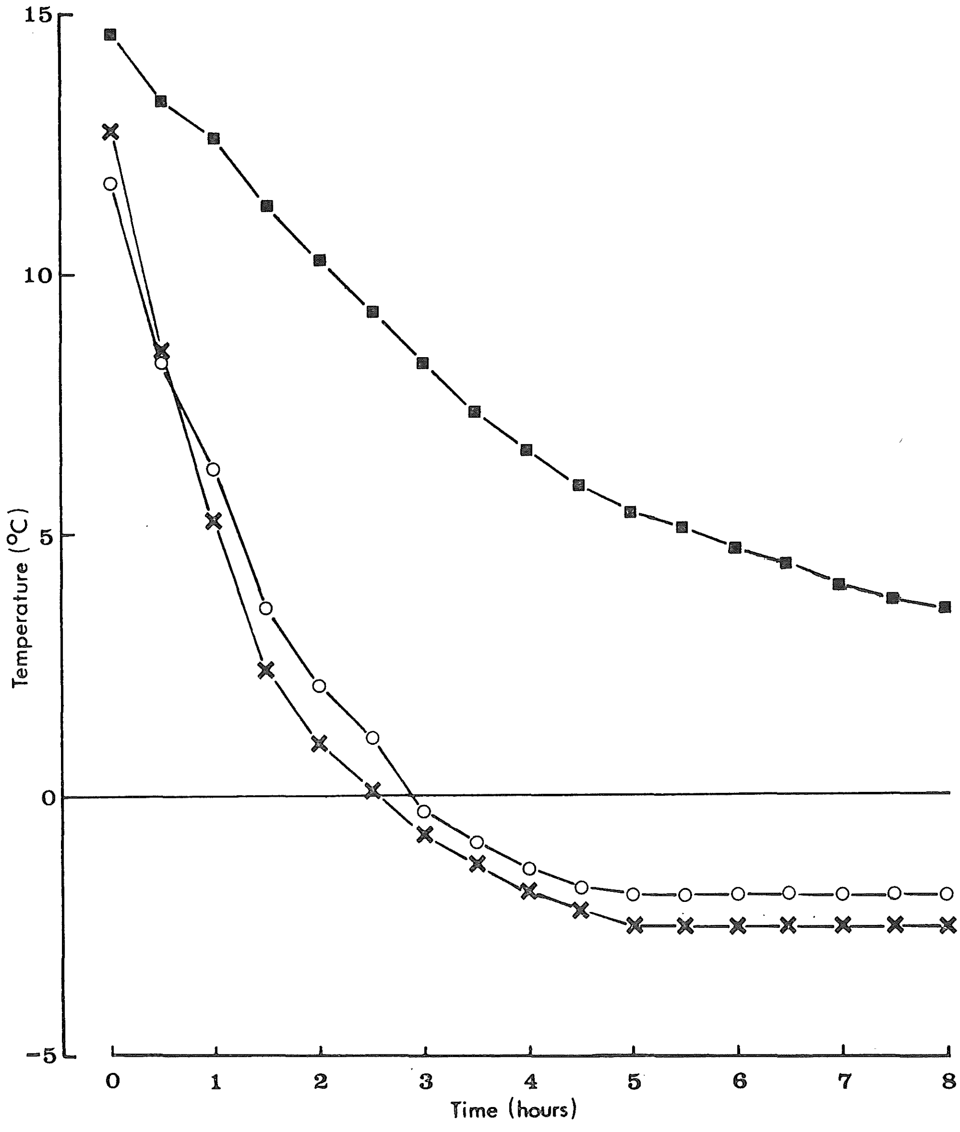

Figure 4. Typical time-course of events for air temperature at the top (x) and bottom (o) of the plant canopy and soil temperature (■) at a depth of 1 cm where plants were frosted at —2·5°C for 3 h.

Under equilibrium freezing conditions, the horizontal spatial variation in leaf temperature near the top of the plant canopy was found to be 0.25 to 0.5°C. This variation was primarily due to a graduation in temperature from the door to the rear of each chamber but superimposed on this was a more random variation which presumably depended on the density of foliage below and adjacent to the leaf to which the thermocouples were attached. In all freezing experiments therefore replicates were blocked from the front to the rear of each compartment.

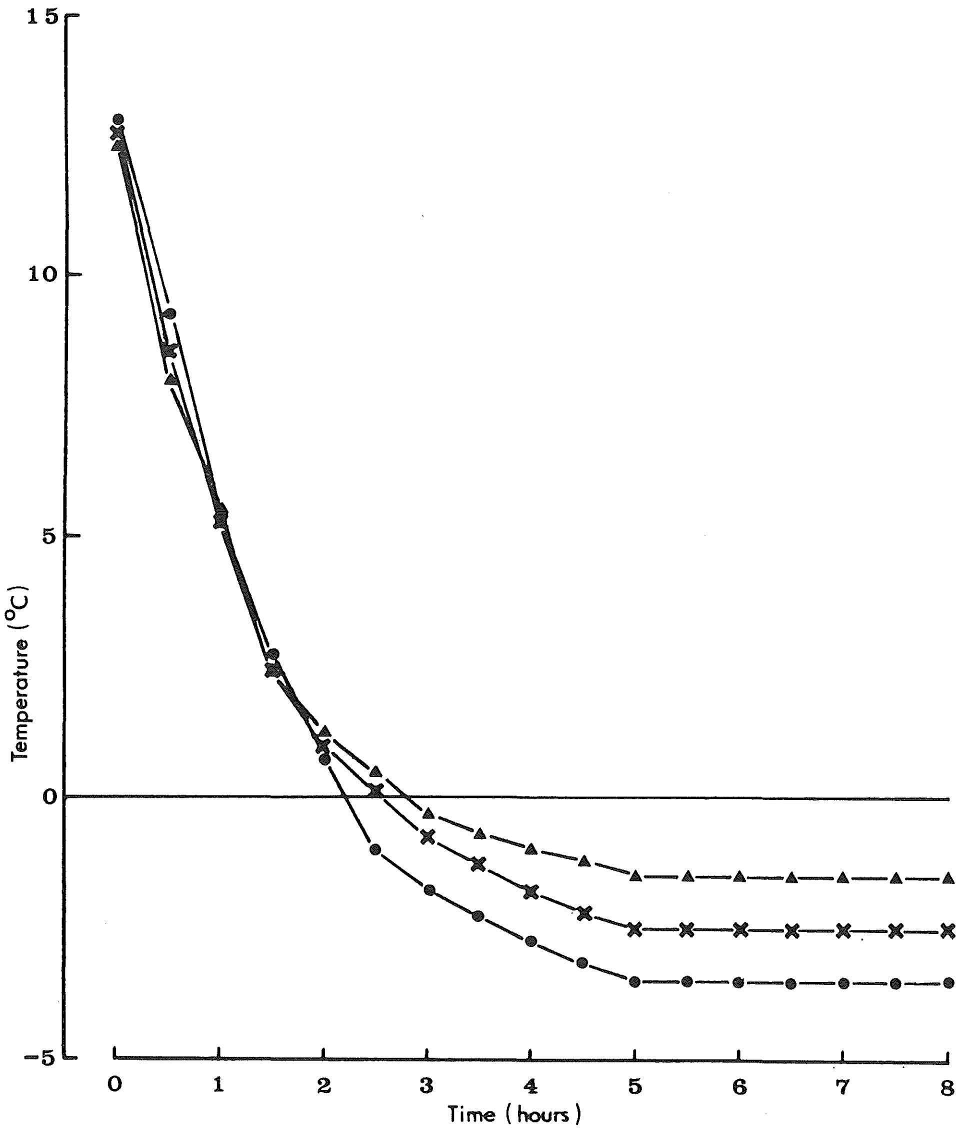

Figure 5. Typical time-course of events for leaf temperature where plants were frosted at —1·5 (▲), —2·5 (×) and —3·5 (●) °C for 3 h.

Typical patterns of leaf, air and soil temperature reduction are shown in figures 4 and 5. The normal procedure used was to manually set the thermostat to produce a cold plate temperature of 5° to 10°C colder than the leaf temperature. Subsequently the cold plate temperature was further reduced by manual adjustment of the thermostat to produce the desired rate of reduction in leaf temperature. If a faster rate of leaf cooling was required than shown in figures 4 and 5, a larger differential was needed between the cold plate temperature and the leaf temperature than given before. A cooling rate for leaves of up to 8°C h^{-1} could normally be achieved with faster rates possible when the heat loading from outside the unit was less (i.e. during winter). When the desired equilibrium leaf temperature was achieved (usually 5 h after commencement of refrigeration) the plate temperature was 2° to 10°C colder than the chamber air temperature, depending on the equilibrium leaf temperature and the level of heat loading from outside the chamber. During the equilibrium phase of freezing some further small adjustments have to be made to the temperature of the freezing plate to maintain an equilibrium leaf temperature as heat is gradually removed from the walls of the chamber. With such manual adjustment of the thermostat the equilibrium temperature of an individual leaf can be maintained within $\pm$ 0·13°C for prolonged periods of time.

In preliminary experiments it was found that the atmosphere within the frost chambers was not saturated when temperatures were below 0°C. This resulted in little or no formation of ice crystals on the leaf surface which caused substantial supercooling to occur before leaf tissues began to freeze (Ivory 1975). An atomized water spray was therefore placed in the chamber prior to freezing and operated externally by compressed air to maintain a saturated atmosphere within the chamber during freezing experiments. The relative humidity of the atmosphere in each chamber could be continuously monitored through an electrical resistance type humidity sensor (Carseldine 1973a, 1973b) (figure 6). Carseldine's (1973b) humidity meter circuitry was modified to provide a much wider range of relative humidity measurements by the introduction of two measurement ranges, *viz.* 40 to 70% R.H. and 70 to 100% R.H.

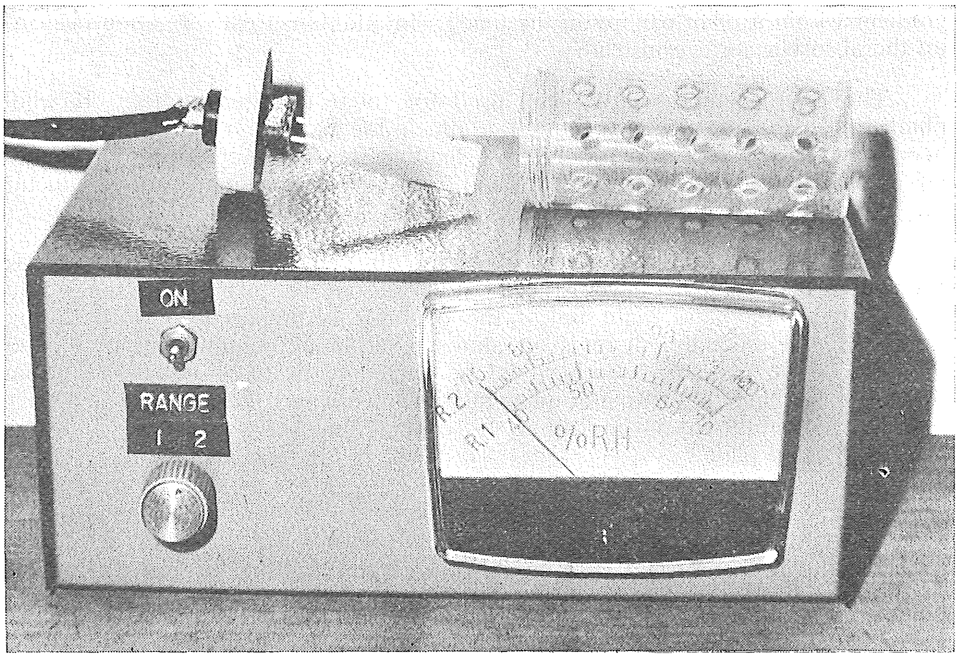

Figure 6. Electrical-resistance relative humidity sensor with measurement ranges of 40 to 70% R.H. and 70 to 100% R.H. (Sensor and protective cover are placed on top.)

The normal procedure during frosting experiments was to bring the atmospheric relative humidity to 100% when the leaf temperature was reduced to $+2°$ or $+3°C$. A fine misting at this stage in the freezing cycle ensured a reasonable level of very small water droplets on plant tissue surfaces, increased the relative humidity to 100% and usually only temporarily increased the chamber temperature by 1° to 1·5°C.

IV. DISCUSSION

The degree of precision in temperature control in the frost chambers proved invaluable in separating the effects of plant and environmental parameters on foliar freezing resistance in tropical grasses as induced differences between treatments (1° to 1·5°C) and species (2·5C) were usually small (Ivory and Whiteman 1978a, 1978b). The ability to simultaneously impose three different freezing regimes also ensures that pre-treatment conditions can be identical.

The dimensions of each cabinet allowed frosting of plants up to 55 cm in height. Where it is desired to examine freezing resistance in taller crop or pasture plants the building of a facility with greater height within the frost chambers should only require the use of a larger refrigeration capacity.

Aston and Paton (1973) also initially used a plastic sheet to isolate the absorber surface from the surrounding air but discontinued its use because frost formation on the sheet considerably reduced transmission of infrared radiation essential for radiation cooling of the leaf surfaces. Frost formation also occurred on the lower surface of the PVC sheet in these frost cabinets. However, where the sheet was removed, the temperature gradient within the cabinet was inversely changed from an increasing temperature from the sheet to the floor (the natural gradient within a plant canopy in the field). In addition, frost formation occurred on the absorber surface instead.

The frost chambers have been used for foliar freezing studies. If whole plant freezing studies were required a much longer period of time would be needed to reduce soil temperature to a suitable freezing range due to the much larger heat load to be removed from soil. In such studies temperature reduction may be hastened by the removal of the plastic sheet within the chamber.

The manual control of cabinet temperature has two main disadvantages. Firstly, freezing studies have to be conducted out of phase with the normal periodicity of day and night unless the operator is prepared to work through the night and secondly, there is an almost continuous commitment of time on the part of the operator. Both would be overcome by the installation of some form of programmable temperature regulation involving a feed-back arrangement between temperature sensors within the cabinet and the thermostat control of the refrigerated plate.

V. ACKNOWLEDGEMENTS

I would like to thank Lindner and May Pty. Ltd. for the design and construction of the refrigeration unit, Mr J. Tester for the general construction of the frosting facility, Mr G. Kirven for design and construction of the humidity meter and technical assistance and Messrs. D. Page-Hanify and F. Holmwood for technical assistance. Financial support from an Australian Wool Board Senior Postgraduate scholarship and the Queensland Department of Primary Industries is also gratefully acknowledged.

REFERENCES

AMIRSHAHI, M. C., and PATTERSON, F. L. (1956).—Development of a standard artificial freezing technique for evaluating cold resistance of oats. *Agronomy Journal* 48:181-6.

ASTON, M. J., and PATON, D. M. (1973).—Frost room design for radiation frost studies in *Eucalyptus*. *Australian Journal of Botany* 21:193-9.

BINGHAM, J., and JENKINS, G. (1965).—Techniques for assessing the cold resistance of cereals in the selection of hybrid material. *Journal of Agricultural Science* 65:201-5.

BURRAGE, S. W. (1972).—Dew on wheat. *Agricultural Meteorology* 10:3-12.

CARSELDINE, A. J. (1973a).—A relative humidity sensor for work at low temperatures and high humidity levels. *C.S.I.R.O. Food Research Quarterly* 33:86-8.

CARSELDINE, A. J. (1973b).—Development of relative humidity sensors for use at low temperatures and high humidities. C.S.I.R.O. Food Research Report No. 56:1-15.

HACKER, J. B., FORDE, B. J., and GOW, JOCELYN M. (1974).—Simulated frosting of tropical grasses. *Australian Journal of Agricultural Research* 25:45-57.

IVORY, D. A. (1975).—The effects of temperature on the growth of tropical pasture grasses. Ph.D. thesis, University of Queensland.

IVORY, D. A., and WHITEMAN, P. C. (1978a).—Effects of environmental and plant factors on foliar freezing resistance in tropical grasses. I. Precondition factors and conditions during freezing. *Australian Journal of Agricultural Research* 29:243-59.

IVORY, D. A., and WHITEMAN, P. C. (1978b).—Effects of environmental and plant factors on foliar freezing resistance in tropical grasses. II. Comparison of frost resistance between cultivars of *Cenchrus ciliaris, Chloris gayana* and *Setaria anceps*. *Australian Journal of Agricultural Research* 29:261-66.

LUDLOW, M. M., and TAYLOR, A. O. (1974).—Effect of sub-zero temperatures on the gas exchange of buffel grass. *In* Bieleski R. L., Ferguson A. R., and Cresswell M. M. (eds.), 'Mechanisms of regulation of plant growth'. Bulletin 12, The Royal Society, N.Z., Wellington, pp. 513-8.

MARSHALL, H. G. (1965).—A technique of freezing plant crowns to determine the cold resistance of winter oats. *Crop Science* 5:83-6.

PATON, D. M. (1972).—Frost resistance in *Eucalyptus*: A new method for assessment of frost injury in altitudinal provenances of *E. viminalis*. *Australian Journal of Botany* 20:127-39.

PEAKE, R. W. (1964).—Evaluation of cold hardiness by controlled freezing of field hardened forage crops. *Canadian Journal of Plant Science* 44:538-43.

SINGLE, W. V. (1966).—Studies on frost injury to wheat. 3. Screening of varieties for resistance to ear and stem frosting. *Australian Journal of Agricultural Research* 17:601-10.

SMITH, R. L., and BOYD, F. T. (1969).—A laboratory method for cold resistance evaluation of *Chloris* and other tropical grasses. *Proceedings of the Soil and Crop Society of Florida* 29:175-80.

WEIBEL, R. O., and QUISENBERRY, K. S. (1941).—Field vs. controlled freezing as a measure of cold resistance of winter wheat varieties. *Journal of the American Society of Agronomy* 33:336-43.

(Received for publication 21 June 1977.)

The author is an officer of Agriculture Branch, Queensland Department of Primary Industries, and is stationed at the Queensland Wheat Research Institute, Toowoomba, Q. 4350.