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CONTROL OF TEMPERATURE, RELATIVE HUMIDITY AND CARBON DIOXIDE FOR REDUCED VENTILATION IN COMMERCIAL POTATO STORAGES

by

DOUGLAS A. IRVINE

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF BIOSYSTEMS ENGINEERING

UNIVERSITY OF MANITOBA

WINNIPEG, MANITOBA (CANADA)

SEPTEMBER, 1997

0-612-23352-9

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirements of the degree

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ABSTRACT

A microcomputer based monitoring and control system was designed, assembled, and field tested as a reduced ventilation controller in a commercial, multi-bin potato storage in southern Manitoba to reduce energy consumption during winter months. The system was integrated with an automatic temperature controller to control the fresh air inlet, and used CO_2 and temperature as parameters for control of the fan operation in one of two 650 t bins monitored. The CO_2, temperature, and relative humidity as well as the fan status, and fan energy consumption were monitored in two adjacent 650 t potato storage bins.

Potato storage facilities could reduce the demand for electrical power by turning ventilation off while emptying bins and grading potatoes for shipment during the months of December, January, and February. Monitored CO_2 concentrations increased quickly enough during any 8 to 10 h period, when all fans in the facility were simultaneously off, to warrant CO_2 set-point control to turn a fan on. Most times, the rapid removal of CO_2 from the test bin by the fan and continuous dilution from infiltration and exhaust with operation of fans in adjacent bins prevented the controlled fan from providing adequate ventilation when CO_2 was used as the only criterion for ventilation. The differential temperature between the upper and lower elevations of the potato piles were seen as a necessary criterion for ventilation when a bin ventilation fan remained off for an extended period and other fans were operating. A pre-set minimum differential temperature would also be the best criterion to turn fans off, rather than a lower CO_2 set point.

ACKNOWLEDGEMENTS

I sincerely thank Dr. D.S. Jayas for his encouragement and guidance from the very beginning to the very end of this study as my thesis advisor. His patience and faith in my ability to finish this work are greatly appreciated.

I thank Dr. W.E. Muir and Dr. M.K. Pritchard for their time and review of my work as members of my thesis committee.

I am very grateful to have had the assistance of J. Putnum, M. McDonald, and D. Watson as well as many students from time to time, especially B. Crerar.

I thank Dr. G. Mazza of Agriculture and Agri-Food Canada for initiating this work and providing the means for much of this project to take place. I also thank the staff at Agriculture Canada , Morden Research Station for their assistance.

Finally, I extend a big thank-you to my wife Lynn for her patience, support and understanding throughout this study. I also thank my two sons Benjamin and Raymond who often changed their plans for me, when I needed more time at the office.

This work was supported in part by Energy, Mines, and Natural Resources Canada; Manitoba Hydro; and Kroeker Farms Ltd.

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1.0 INTRODUCTION

Manitoba had 160 commercial potato producers in 1995, with 80% of the harvest being used for processed foods such as frozen fries and hash browns, instant mashed potatoes and potato chips. Four major potato and other vegetable processing plants produced these foods for an estimated combined sale of well over $200 million in 1994 (Manitoba Agriculture 1995).

Storage of potatoes in bulk commercial bins is necessary to make them available for consumption and processing from one harvest to the next. In Canada, producers must store some of their crop of processing potatoes for up to 10 mo. To remain viable and competitive, processors demand high quality potatoes from producers. Therefore, the producers must provide a storage atmosphere which can maintain high tuber quality throughout the storage period.

A potato storage manager must minimize the loss of mass resulting from dehydration (moisture loss) and respiration (dry matter loss). At the same time, a storage manager must minimize accumulation of reducing sugars in potatoes which can lead to non-enzymatic browning (an undesirable browning of the chip colour) when fried in cooking oil (Mazza 1983).

Numerous studies have been performed to determine optimum storage temperatures (Hyde and Morrison 1964, Zaehringer et al. 1966, Iritani and Weller 1977, Dwelle and Stallknecht 1978, Sherman and Ewing 1983, Schwobe and Parkin 1990) and preconditioning techniques (Pritchard and Adam 1992) for minimizing accumulation of reducing sugars. Reconditioning potatoes with the intention of burning off excess reducing sugars before removal from storage is also sometimes effective (Schaper and Preston 1989, Cargill et al. 1989).

In general, it is agreed that sugars accumulate more at storage temperatures ranging from 0 to 5 °C, than at temperatures ranging from 7 to 12 °C. The problem with storage at higher temperature is that there is greater water loss, stronger tendencies to sprout at earlier times, faster degradation of diseased tubers, and increased energy requirements from ventilation required to remove heat of respiration and maintain uniform temperatures in the bulk. Humidifying requirements are also greater at higher temperatures. To meet the storage objectives, a storage manager generally compromises between increased loss of mass to achieve low reducing sugar accumulation at high temperature or processing quality by lowering temperature to minimize moisture loss.

Potatoes should be stored in at least 90 to 95% relative humidity (ASAE 1991) to minimize the vapour pressure deficit between tubers and the air and consequently reduce the loss of tuber moisture. An exception is when potatoes are brought into storage wet, in which case they must be immediately dried to prevent soft rot (Rastovski et al. 1981). A reduction of relative humidity may be necessary if late blight (*Phytophthora intestans*), leak (*Pythium spp.*), or frozen potatoes are present (ASAE 1991). If high relative humidity is causing condensation in the storage, it must be reduced unless additional airflow or supplementary heating can be used to prevent it.

Concentrations of 0.2 to 0.3% CO_2 are common when potatoes are ventilated (ASAE 1991). After an application of the sprout inhibitor isopropyl-N-(3-chloro-phenyl) carbamate, commonly known as CIPC, CO_2 can accumulate to 3.2% in less than 48 h in a sealed Manitoba commercial storage (Mazza and Siemens 1990). Carbon dioxide can accumulate in a sealed potato storage to concentrations of 4% after 72 h of suberization without fresh air intake (Schaper and Varns 1978). Above normal rises in CO_2 are correlated to increased reducing sugar concentrations in potatoes (Mazza and Siemens 1990).

To maintain the recommended storage temperatures, relative humidities, and CO_2 concentrations, measurements of these parameters and the equipment to adjust and maintain the desired set points are needed.

Reliable, accurate, and inexpensive measurement of temperature in potato storage bins is not difficult. Sensors that are used include liquid in-glass thermometers, thermocouples, resistance temperature detectors (RTDs), and thermistors. It is the air temperature in the plenum that is maintained during ventilation. Normally the temperature of the upper potato bulk is measured once or twice per day to check for potential problems. Some temperature controllers have proven capable of maintaining temperatures in the plenum within $\pm$ 0.1 °C when cooling with outdoor air during ventilation.

Consistently high relative humidities in potato storage bins make reliable, accurate and inexpensive relative humidity measurement difficult. It is desirable to measure the relative humidity inside the potato bulk but there is no widely accepted, satisfactory method.

Carbon dioxide is not monitored continuously in potato bins, with the exception of some experimental bins such as at USDA-ARS (Schaper et al. 1987). Carbon dioxide measurement in the past has not been performed on a continuous basis in potato bins due to the complexity in operation and maintenance of equipment needed and the cost of instrumentation required. Today, infrared gas monitors are available for continuous industrial monitoring, are simple to operate and maintain, and can be purchased at a reasonable price.

Automatic temperature controllers for vegetable bins are designed to maintain a consistent plenum temperature by cooling recirculated air with cooler outside air. During cold winter months in Manitoba, infiltration, exhaust, convection and conduction heat losses often negate the requirement for additional cooling with outside air. Supplemental heat could often be advantageous to maintain desired temperatures but is not known to be a common practice in Manitoba bins. The capital cost of purchasing heaters and the energy cost of using supplemental heat is considered by many producers to be unjustified.

Some storage managers try to reduce the loss of respiratory heat generated by potatoes by minimizing ventilation and recirculation of air in a bin during cold months by operating fans intermittently (Cargill et al. 1989). Temperature controllers are often equipped with 24-h timers for intermittent ventilation management. Other storage managers do not use intermittent ventilation because while the fan is off, the plenum temperature is meaningless and there is no way to know if the bin has a uniform temperature, relative humidity, or adequate fresh air.

A large portion of a potato storage electric cost in Manitoba is attributed to the high demand for power to operate ventilation fans continuously through the cold winter months.

The objectives of this study were to:

1. evaluate the feasibility of using a computer based monitoring system with ventilation control capability to measure and control CO_2 concentrations within a bulk of stored potatoes in a commercial potato storage,
2. evaluate the feasibility of air sample retrieval for relative humidity measurement in remote locations within a commercial potato storage,
3. evaluate the monitoring and control requirements of a reduced ventilation controller for commercial potato bins to reduce energy consumption.

2. LITERATURE REVIEW

2.1 Carbon Dioxide Accumulation in Potato Bins

Carbon dioxide (CO_2) is a product of respiration of potatoes. Respiration involves the combustion of glucose ($C_6H_{12}O_6$) and uptake of oxygen (O_2) to produce water (H_2O), CO_2 and energy in the form of heat. Respiration of potatoes is continuous throughout all storage phases but not constant. Respiration rates have been reported from 1.0 mg CO_2/(kg tuber·h) for mature, dormant, tubers at 7.5 °C (Schippers 1977b) to 83 mg CO_2/(kg tuber·h) after harvest of immature, intact tubers (Shamaila 1985).

There are no recommended ranges for optimum concentrations of CO_2 in potato bins although studies have shown damaging and quality reducing effects on potatoes at various CO_2 concentrations. In ASAE (1991) standard, it is stated that a level of 1% CO_2 should be considered the upper allowable threshold and that ventilated bins commonly have a level of 0.2 to 0.3% CO_2. It is recommended that storage units in the Red River Valley potato growing areas are ventilated for 2 to 4 h with outside dampers closed at least every 24 h during suberization (Schaper and Varns 1978). This recommendation assumes the typical Red River Valley bins to have approximately 10 to 15% of the fan capacity as infiltration when dampers are closed.

A study on the effect of CO_2 concentrations on tuber quality in commercial bins (Mazza and Siemens 1990) found increases in reducing sugars and sucrose and darkening of chips made from these tubers, occurred immediately following rises in the CO_2 concentration. The range of CO_2 concentration measured in their monitored bins were 0.06 to 3.2% with peak concentrations during suberization, during and after application of the sprout inhibitor CIPC (isopropyl-N(3-chlorophenyl)-carbamate, active ingredient), and again as the senescent period progressed.

Both reduced O_2 and elevated CO_2 concentrations reduce suberin formation, prevent permiderm layers from forming (Wigginton 1974, Lipton 1975), break dormancy, stimulate sprouting (Burton 1958, Rastovski et al. 1981), and cause, influence, or correlate to disease incidence (Nielsen 1968, Tabak and Cooke 1968, Lund and Wyatt 1972).

Despite the reported accumulations of CO_2 in commercial potato bins and associated quality reducing effects they can have to potatoes, monitoring for CO_2 is not common in these facilities.

2.2 Relative Humidity in Potato Bins

Relative humidity is not always measured in potato bins. Instead the decision to humidify is often based on visual inspection of condensation on the walls or ceiling. Relative humidity should be kept at least 90-95% (ASAE 1991) unless there are diseased, or frozen potatoes, or wet potatoes which need to be dried. Accurate continuous measurement in potato bins can be difficult due to sensor contamination, loss of calibration, and accuracy in this high relative humidity range (Hunter and Rowe 1987). Electronic resistance type sensors are sometimes used in potato bins when incorporated as part of a control system package. Suppliers of vegetable-storage instrumentation and controls suggest electrical resistance relative humidity sensor/transmitter units be installed in the return air stream from the bin to the plenum. They claim this location provides a good average bin relative humidity measurement and condensation on the sensor is seldom a problem due to the rapid air movement.

The composition of potatoes vary with cultivar, growing conditions, and age but generally contain 63 to 80% water (Kadam et al. 1991). Water loss from tubers, including those intact, and disease free occur due to respiration and the vapour pressure deficit between the potato and the surrounding air. Vapour pressure difference as discussed here is the difference between the saturation pressure of the water at the average potato temperature and the vapour pressure of the air. To minimize the vapour pressure difference, the temperature of potatoes must be kept at a minimum and relative humidity of incoming air at a maximum.

An empirical equation (Eq. 1), for estimation of water loss from tubers is given in ASAE (1991) as:

$$L = (A + 0.1\ S)\ D \qquad (1)$$

where,

L = percent of original mass lost per week,

A = 0.7 for the first 2 weeks of storage,

= 0.2 for the remainder of storage,

S = percentage of sprouts per week, and

D = vapour pressure difference, mm Hg.

Studies have been performed to determine water loss as a function of temperature, relative humidity, and air velocity from ventilation (Butchbaker et al. 1973, Hunter 1985).

Butchbaker et al. (1973) found that tuber age, closely followed by temperature were the most important variables affecting water loss. They determined that age correlates well to the rate of water loss due to sprouting which occurs at the end of the storage period. Temperature correlates well to water loss due to increased respiration accompanying the increased temperatures and due to the increase in vapour pressure deficit while relative humidity was held constant. Relative humidity and air velocity also correlate well with water loss but have less impact on overall water loss than age and temperature. It was hypothesised that low correlation coefficients were due to variations in relative humidity during the experiment. Air velocity was an important variable in loss of mass but had the least impact even though at high air velocities it was difficult to maintain high relative humidity.

Hunter (1985) developed a mathematical model to predict evaporative water loss. It was concluded that respiratory heat production was the primary force in evaporation of water from the tuber, especially at high relative humidities. At low airflow rates, evaporation was a direct function of respiration. It was concluded that at 97.8% relative humidity, the rate of water loss would be unaffected by airflow velocity. At this critical relative humidity, the percentage of respiratory heat which was latent heat decreased as temperature decreased.

Misener and Shove (1976) developed a mathematical model for prediction of cooling and moisture loss from potatoes. They found their model satisfactorily simulated the moisture loss of potatoes in an experiment using a 2.4 m column of potatoes. Their model did not consider air velocity.

2.3 Monitoring and Control in Potato Bins

Control of temperature in the air plenum of a commercial potato bin is considered by most storage managers to be the best method of maintaining bin temperatures (Gellert 1985). In the survey conducted by Gellert (1985), seven of eight respondents wanted no more than 0.28 °C variation in plenum temperature from a set point. Half of the respondents definitely wanted to control the differential pile temperature to within 0.56 °C during the holding period. Respondents were evenly divided on automatic differential control and semiautomatic outdoor control. The main difference between these two types of control is that with differential control, air warmer than a selected measured temperature in the bin minus a factory offset cannot be brought into the storage. In the semi-automatic outdoor air control, the maximum allowable temperature for ventilation using outdoor air is set by the operator. If the setting is exceeded, the fan shuts down.

Safety sensors are a must in any potato storage. For protection from ventilating with air that is warmer than the potatoes and for protection from delivering air which is too cold for the potatoes, electromechanical devices are used to disconnect power to the ventilation fan. A commonly used device to respond to these high or low temperatures, and trigger a mechanical switch when the set point is reached is a hydraulic pressure sensor in a bulb and capillary system (Gellert 1985).

Automatic temperature control in an air plenum is performed by measuring the plenum temperature and inducing proportionate signals to a proportioning damper motor or actuator ram. There are now more advanced controllers which use proportional integral (P.I.) and proportional integral derivative (P.I.D.) control.

Intermittent ventilation in potato bins is widely practiced. In the Red River Valley growing region including Manitoba, North Dakota, Minnesota and Saskatchewan, fans are either operated continuously with a low airflow or for only 6 to 12 h per day with higher airflow rates during the holding period (Schaper and Preston 1989).

Ashby et al. (1992) tested a variable speed drive on a main ventilation fan in a commercial potato storage and claimed some success in reducing pressure flattening and energy consumption compared to timed operation. Pressure flattening occurs when potatoes in the lower parts of a bin loose enough moisture to loose firmness needed to resist compression under the mass of potatoes above.

Yost (1984) used fan cycling schemes in apple bins to reduce energy consumption, preserve quality, maintain core temperatures within desired limits and maintain overall stack temperature differentials to within 0.55 °C. The results indicated that much of the cooling by refrigeration was simply removing the heat of the ventilation fan operation.

Humidity is normally added to the air either continuously when a ventilation fan is operated or intermittently. Some bins use commercial humidifiers with sensing elements to automatically control humidification. If humidistats are used to control humidification, set points should be periodically checked with a reliable psychrometer for accuracy (ASAE 1991).

2.4 Energy Consumption in Potato Bins

Energy is consumed in potato storage facilities by ventilation fans, refrigeration equipment, humidification equipment and lights in alleyways, grading areas and plenums. Pumps are used to supply water to bins for removal of potatoes from the bins with water fluming. In the grading area conveyor motors, bagging equipment, air dryers, and heaters use the bulk of the power.

Energy demand on the local electric utility is highest during the months of December, January and February. These are the same months that electric power is most expensive to produce. During these months many bins are emptied and potatoes are prepared for shipment while full bins are being ventilated 100% of the time. Energy consumption in the grading area cannot be reduced significantly. However, energy consumption from ventilation could be reduced while the work in grading areas take place. Energy consumed by a ventilation fan is in direct proportion to the time it is on. However energy demand during the months of December, January and February for medium and large users are subject to penalties if demand exceeds a certain amount. One storage facility at which a load research study took place increased their monthly peak demand in the winter months by approximately 75% by grading while ventilating all their bins simultaneously (Manitoba Hydro 1992).

3. METHODS AND MATERIALS

3.1 Storage Facility and Bins

A commercial, multiple-bin potato storage (Fig.1) in Winkler, Manitoba was the location for this study. This is a cooperative storage, operated by an experienced full time manager. Each of the 17 bins were filled with approximately 650 t of freshly harvested potatoes in the fall. Several bins in the facility contained table stock potatoes and were emptied as the storage season progressed between October 1992 and May 1993. Bins 12 and 13 monitored for this study contained 'Russet Burbank' potatoes, a cultivar used for potato fry processing. These bins were usually kept full until June or July due to the availability of refrigeration for spring and summer holding.

The layout of the facility is shown in Fig.1 with the location of the monitoring system and bins 12 and 13, which were monitored in this study. The facility was wood framed, insulated, and had wood sheeting and galvanized steel paneling on the outside. Partitioning walls in the facility were wood studded with horizontal 25 mm (1") thick grooved wall board and tin sheeting on both sides. Air plenums were located immediately inside of the east and west outer walls. Walls were constructed with insulation between studs and covered with a vapour barrier and painted wood sheeting. Each bin had a set of swing type plywood sheeted and insulated doors, dimensioned approximately 4.88 m wide by 4.88 m high overall on its outside plenum wall. Engineering details of the facility

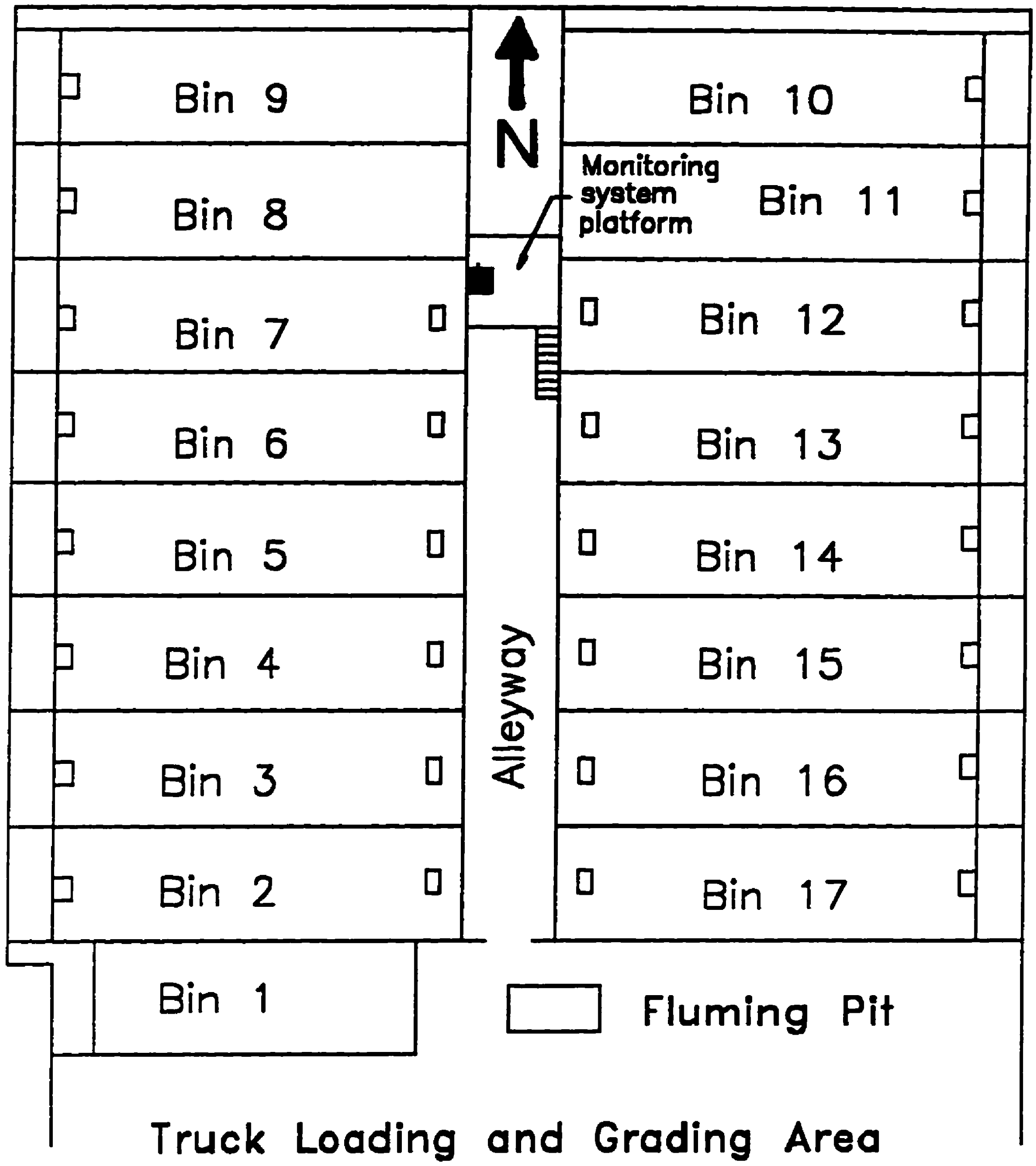

Figure 1. Layout of the potato storage facility showing locations of monitored bins.

construction were not available and therefore the insulation values for the ceiling, walls and exterior bin doors are not known for certain.

Due to the high humidity in the bins and outside temperatures often dropping below -20 °C in winter, insulation must be capable of preventing condensation on the inside walls. Heat transfer coefficients for potato bins in the Red River Valley growing regions of Manitoba and North Dakota are given by Schaper and Preston (1989) as 0.14 to 0.29 W/m^2K for walls and 0.14 to 0.19 W/m^2K for ceilings.

Dimensions, ventilation ducts and sampling locations of the monitored bins are illustrated in Fig. 2. The two monitored bins had identical dimensions, fans, and distribution ducts. Ventilation was provided by a 3.7 kW, two-speed axial fan in each bin. The fans were always operated on low setting, using between 1.8 and 2.0 kW.

Floors were concrete with cast-in-place water flumes connected to a central water flume that led to a central collection pit. The central collection pit serviced a large and regularly active grading and loading area. The water flumes were covered by wooden slats with unguarded slots and were also used for a portion of the potato bin ventilation. The primary ventilation to the bins was distributed by two round, corrugated and galvanized steel ducts with 32 mm perforations spaced at 200 mm centre to centre on each side in a row located 45° down from the horizontal centre line of the duct.

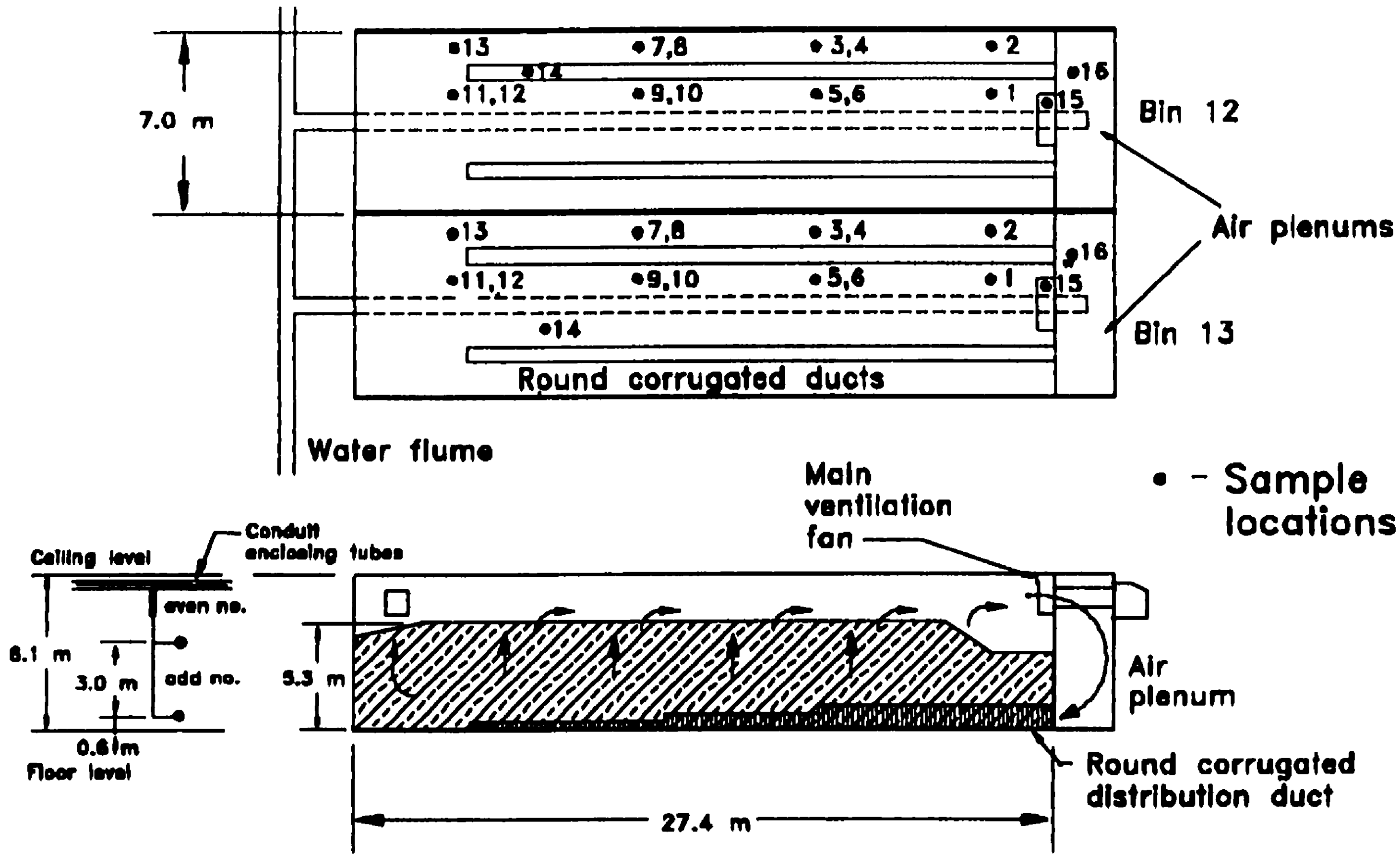

Figure 2. Test bin details showing sampling locations and flow of recirculating air. Odd numbered locations were in lower portion of the bin and even numbered locations were in the upper portion of the bin.

3.2 Ventilation Rate

The volumetric flow rate provided by the fan in bin 12, while the bin was full of potatoes was measured by a crude airflow test at the fan inlet to be approximately 15 $(m^3/h)/t$. For this test a 0.37 m^2 and 3.05 m long duct was constructed in place for airflow measurement with a pitot tube in front of the fan chamber inlet. However, due to the entrance losses added by the test to the fan chamber, the actual fan capacity will be higher than measured.

Small and Hodgkinson (1989) provided the relationship in Eq. (2) for plenum static pressure (P_p) to average static pressure (P) in round corrugated steel ducts and the velocity pressure (P_v) at the duct entrance.

$$P_p = P + n \cdot P_v \tag{2}$$

where: n = duct pressure loss coefficient (1.805), dimensionless

Static pressure measurements were made in the plenum and throughout the length of one round corrugated duct per bin and applied to Eq. (2) to estimate the velocity pressure at the duct entrance. The volume flow rate was then calculated from the velocity pressure, the duct cross-sectional area, and the number of ducts (two), in the bin. It was not possible to obtain a good static pressure profile inside the water flume which also served as an air duct, because it was half full of water, but since the cross-sectional area was small relative to the round ducts, airflow was assumed negligible. Using the results from the static pressure measurements, calculated P_v from Eq. (2), duct velocity and total airflow per tonne were calculated and are given in Table 3.1. The diameter of the entrance duct was 0.915 m.

Recommended airflow rates for potato storage ventilation in the Red River Valley growing region of Manitoba and North Dakota are given by Schaper and Preston (1989) as 26 to 38 (m^3/h)/t for storage temperatures under 10 °C. Airflow calculated with Eq. (2) using the measured static pressures imply this facility fit these criteria.

Table 3.1 Calculated bin ventilation airflow using velocity pressure determined by applying Eq. (2) to measured static pressures.

	P_p (Pa)	P (Pa)	P_v (Pa)	Velocity (m/s)	Bin Airflow (m^3/h)/t
Bin 12	35	23	6.65	3.33	24.25
Bin 13	44	29	8.31	3.72	27.10

3.3 Monitoring System and Sampling Locations

A micro-computer based monitoring system was installed for two consecutive storage seasons. During the first season, 1991/92, the system was only used to monitor the bins and evaluate the equipment for monitoring in the commercial storage environment. During the second season, 1992/93 the system monitored bin environments and fan status and controlled the fan in one bin periodically. A commercial temperature controller for automatic blending of fresh and recirculated air was installed in the same bin in which the fan could be operated intermittently by the computer system. Only data monitored during the 1992/93 season are presented and discussed in this thesis.

The micro-computer based monitoring and control system was located on a platform in the alleyway (Fig. 1). The micro-computer was an IBM compatible 286 AT with a 1.0 Mb RAM. Data acquisition and control were performed using two analog cards with 16 bit resolution, "Analog Connection ACPC-16-16" (Strawberry Tree Inc., Sunnyvale, CA). Four compatible 'T11' terminal panels, each having eight analog input, digital input and digital output terminals provided connection for all instruments, sensors and controlled equipment (Fig.3). The analog cards came with associated software which could be custom programmed with calibration factors, timed or set point control settings, data logging options and other various input or output options. The two analog cards provided the system with 32 analog and 32 digital channels. All analog input terminals were on aluminum isothermal plates and had built-in cold junction compensation for thermocouples.

3.4 Air Sample Retrieval

Air samples were withdrawn by 115 VAC vibratory type pumps built into each "Nova model 421P" CO_2 monitor (Nova Analytical Systems Inc., Hamilton, ON). Flow rates of samples varied slightly between CO_2 monitor pumps but were always between 1.5 and 4

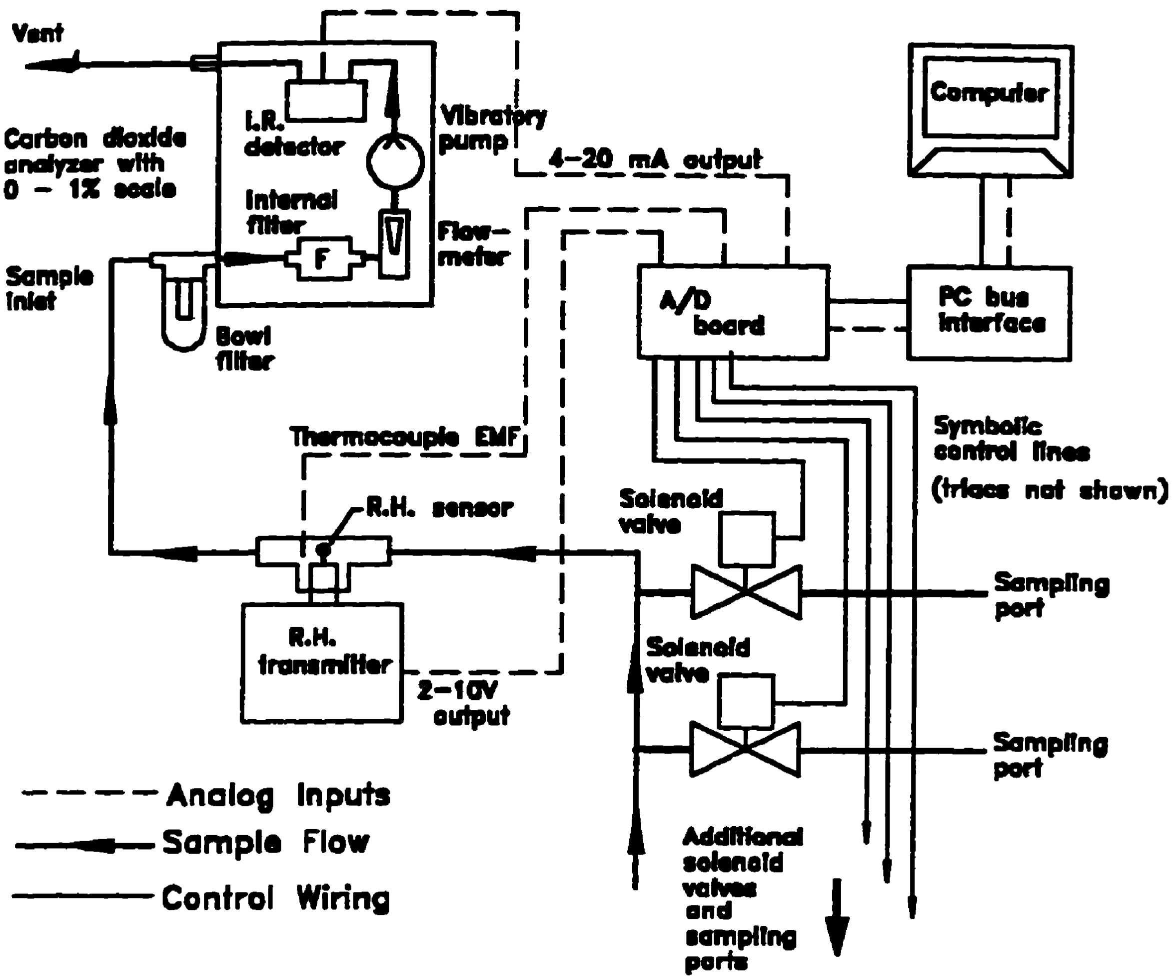

Figure 3. Schematic of partial monitoring system.

L/min. A sample was withdrawn from a location (Fig.2) through sampling tubes (Nylo-Seal 44-SN, Imperial Eastman, Chicago, IL) having an inner diameter of 4.67 mm, when a corresponding, normally closed, 2-way electric solenoid valve (Deltrol Fluid Products, Bellwood, IL) was turned on (Fig.3). The air samples were drawn through the tubing, the solenoid valve, past an encapsulated relative humidity sensor and then through a CO_2 monitor for 5 min before switching to another location.

3.5 Temperature Measurement and Calibration

Temperatures were measured with 24 gauge, type T, copper-constantan thermocouples (Thermo Electric (Canada) Ltd., Brampton, ON). Calibration of the data acquisition system, cold junction compensation, and aluminum isothermal plates for thermocouples was performed by immersing the ends of short thermocouple lengths (made only for the calibration) into ice water, boiling water, and water at a range of temperatures between 0.0°C and 100.0°C. Precision glass calibration thermometers with 0.1°C scale divisions were used as the standard for calibration. Scale and offset factors were determined for each individual thermocouple channel and programmed into the data acquisition software.

All thermocouples used in calibration or the bin had their tips coated with clear nail polish to protect them from corrosion. In the bins, thermocouples were protected from direct contact with potatoes by securing their tips inside a hollow 40 mm diameter, plastic, spherical ball with 6 mm diameter perforations around its surface (practice golf ball).

Thermocouple wires were taped securely to the tubing used for retrieving air samples to prevent stretching or breaking in the potato pile.

3.6 Relative Humidity Measurement and Calibration

Relative humidity was measured in withdrawn air streams (Fig.3) with a relative humidity sensor/transmitter unit model "RH-2" which uses a bulk polymer resistance sensor (General Eastern Instruments Ltd., Watertown, MA).

The relative humidity measured at the sensor was not the true relative humidity in the bin. It was assumed sensible heating occurred between the origin of the air samples and the sensor itself. Air temperatures were measured at each sample tube inlet in the bin using the thermocouples as previously described. A representative relative humidity of the sample origin was calculated using psychrometric equations (ASHRAE 1985) which incorporated the bin temperature at tube inlet, the temperature at the sensor and measured relative humidity.

To aid sensible heating, and avoid moisture condensation, the sample tubes were enclosed in PVC conduit from the monitoring system cabinet to points where tubing branched into the potato bulk. Conduit was insulated with 25 mm thick fiberglass pipe insulation. A 1.5 kW air heater was placed in a small enclosure with a blower connected to the PVC conduit to provide warm forced air through it. The heater and blower were run continuously, except during sprout inhibition.

The relative humidity sensor/transmitter units were factory calibrated to $\pm2\%$ and generated 4-20 mA output linearly proportional to 0-100% relative humidity. In total, four full calibrations were performed on the first sensor/transmitter unit purchased in early 1991, and three on the second unit. During the second test on the second sensor/transmitter unit, it failed and required repair. The first calibration was performed on a unit prior to a trial installation of half the monitoring system in a potato bin in May 1991. The second calibration on the same unit was performed after dismantling the system at the end of July 1991, along with a new sensor/transmitter purchased for another installation during the 1991/92 season. The next calibration was done on both sensor/transmitter units toward the end of the storage season in May 1992 when one unit was found to be erratic, and later failed completely while being calibrated. Additional calibrations of both units were made prior to the 1992/93 storage season installation.

The standard used for the relative humidity calibrations was a General Eastern Hygro-M1 Optical Dew Point Monitor and 1111H sensor (General Eastern Instruments, Watertown, MA). All full calibrations were completed in the electronics laboratory of the Agricultural Engineering Building, University of Manitoba. One partial calibration check was made at the storage during the 1992/93 season in February 1993 using the Optical Dew Point Monitor and 1111H sensor. Other random checks were made by switching tubes from one bin stream to another and comparing outputs between the two sensor/transmitter units while sampling the same location.

3.7 Carbon Dioxide Measurement and Calibration

Carbon dioxide (CO_2), in bins, were measured with the "non-dispersive infra-red method" by Nova model 421P CO_2 monitors (Nova Analytical Systems Inc., Hamilton, ON). These monitors give continuous 4-20 mA output proportionate to CO_2 content of an air stream. One monitor was a non-linear output type, the other was a linear output type. Vibratory pumps, built in to the monitors, pulled a continuous air stream from sample points in the bin, through the tubing and the sensor. Both units were wall mounted, had a visible meter on the front panel for direct reading and were equipped with water and dust traps at their inlets.

The non-linear monitor was calibrated in May 1991, when it was first obtained. Calibrations of both monitors were done when the systems were put together in September 1991 and again in July 1992. Calibrations of the CO_2 monitors were made using a Beckman Infrared Gas Analyzer (Model 865, Beckman Instruments Inc., CA) as the standard. Calibrations of these monitors were completed at the Agriculture Canada Research Station in Morden, Manitoba.

During use at the storage facility, throughout the two 10 mo studies, the monitors were periodically checked for minimum output (zero) with a CO_2 scrubber tube provided with the monitors. Monitor outputs were also compared to each other by switching sampling tubes.

3.8 Data Logging, Display and Analysis

Data logged to disk included average and present values of CO_2 from each monitor, relative humidity from both sensor/transmitter units, temperature at each of the two relative humidity sensors within the air stream (Fig.3), temperature at 32 bin locations, the status of each solenoid output, the fans in the two monitored bins, each programmed set point status and the time and date of each reading. The data in the bin were logged every 5 min throughout the 1992/93 storage season (October 1992 to July 1993). Periodic interruptions to data logging for equipment servicing and power outages occurred. Data from January 21, 1993 through February 11, 1993 was accidentally deleted though some was retrieved uncorrupted and is therefore presented. In this thesis, data collected between October 1992 to March 30, 1993 are discussed.

Data were logged to a user named, comma and delimited ASCII file that was in a compatible format for spreadsheets and other data analysis programs.

Since more analog inputs were required to handle all the measurements than were available, double pole, double throw relays were used to enable temperature measurement at two locations with the same analog input. The time sequencing was arranged in such a way that a temperature measurement from a location always coincided with the time that a solenoid corresponding to that location for gas sampling was on.

Power consumptions by ventilation fans were also monitored in bins 12 and 13 separately from the computer system using pulse energy meters obtained from Manitoba Hydro. Manitoba Hydro also had special energy monitoring equipment installed in this facility to gather energy and demand information since 1991 for the main facility.

3.9 Ventilation Control System

The function of the control system (Fig. 4) was to maintain either temperature or CO_2 within a preset range in the bin by turning on the ventilation fan at the upper set point and off at a lower set point. When the fan did run, a fresh/return air blending door was operated by a H970R Series, Gellert Raw Product Ventilation Control Panel (The Gellert Company, Boise, ID), to maintain a uniform temperature in the plenum. All the normal safety limits were built into the control panel, such as low temperature limit in the plenum and high outside air temperature limit.

Wiring was such that the storage manager could turn off the computer control with a manual toggle switch placed in the H970R control panel (Fig. 4). Panel lights were installed to indicate if the computer had shut the fan off and whether the computer system had control of the fan or not. The H970R panel provided the storage manager with all other indicator lights required to know the status of the system.

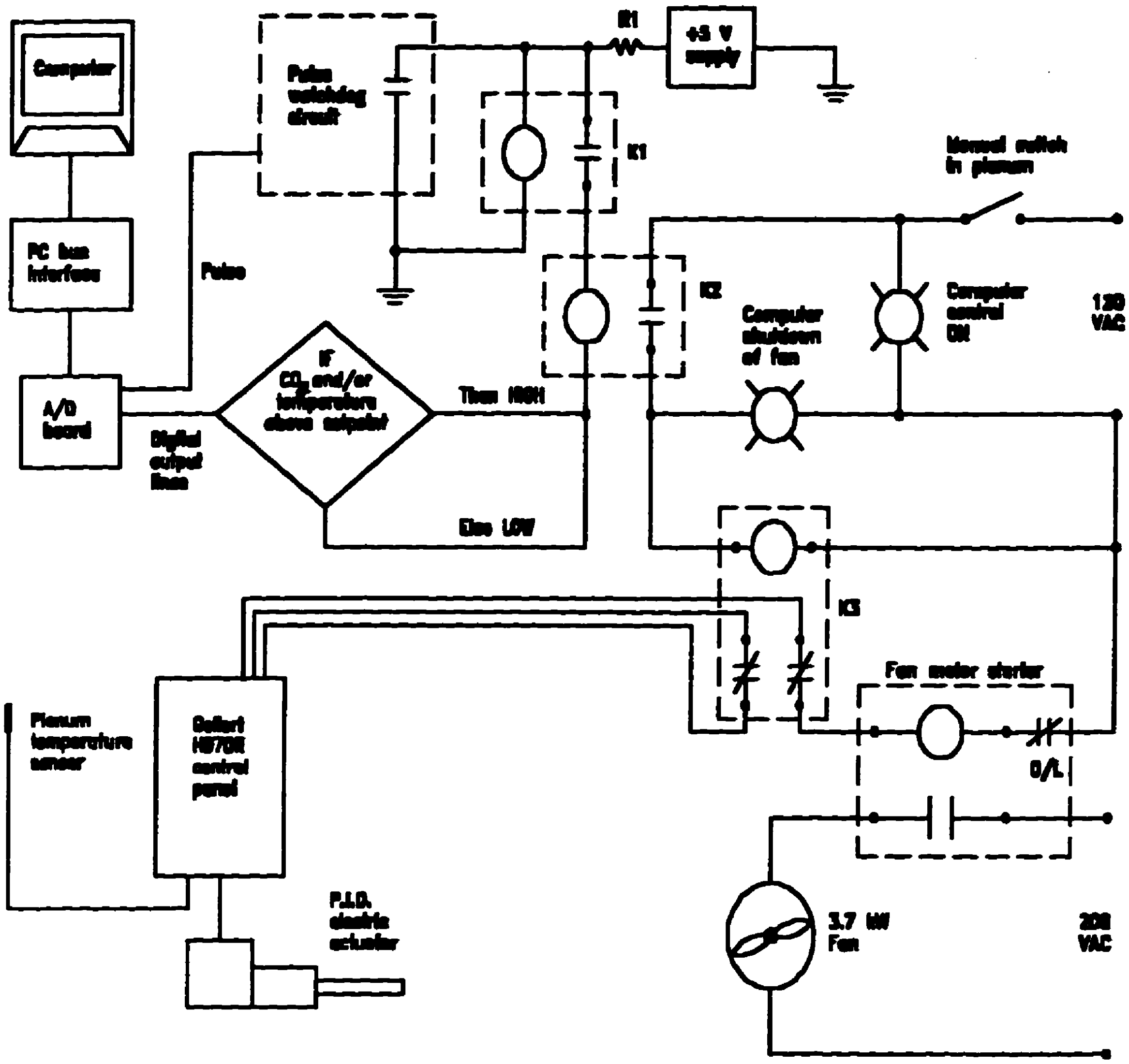

Figure 4. Schematic of the integrated microcomputer based control system and conventional control system, used in bin 12.

The H970R control panel was operated in continuous ventilation mode for the duration of the experiment. Without intervention, the control panel could only shut off the fan if the air in the plenum was too cold.

Setup for computer control was such that a digital output from the computer system would allow the fan to turn on or off only if a set point was exceeded. Once the fan was running, a lower set point would turn it off.

A pulse watchdog circuit (Fig. 4) was constructed to prevent the computer from turning the fan off if the program did not or could not maintain a regular digital output pulse. Irregular output could be caused by program malfunction, an exit from the program control mode or an exit from the program itself. Digital outputs remained in their initial states when the control mode for the program was off, therefore leaving the possibility of extended, undesirable fan shutdown. The watchdog circuit could prevent K1 relay from energizing and supplying K2 with the +5 V power source required to energize it and stop the fan (Fig.4).

4. RESULTS AND DISCUSSION

4.1 Carbon Dioxide Measurement and Control

4.1.1 Carbon Dioxide Measurement and Calibration

Carbon dioxide (CO_2) monitors worked well throughout all tests and installations in the potato bins. There were no malfunctions, no loss in response time and they held their calibration fairly well. Three calibration curves showing CO_2 sample measurements by the calibration standard equipment against the nonlinear CO_2 monitor output are shown in Fig. 5 along with the respective trend lines for each calibration. Calibrations performed before and after a two month trial installation in 1991 provided confidence in the equipment's ability to hold its calibration after continuous use in a potato storage atmosphere. The regression equations used in all cases fit data very well using either second order polynomial or power equations ($R^2 > 0.9$). The regression equations used were obtained using SAS NLIN procedure (SAS 1985).

The output from the nonlinear monitor varied from one calibration to the next (Fig.5). Between May 1991 and September 1991, the change in output resulted from an adjustment to the span potentiometer which was made to slightly increase the maximum obtainable reading. The apparent shift of the curve between September 1991 and July 1992, after 10 mo of continuous monitoring, was due to some drift. Drift from zero on each monitor was checked at two to four week intervals during both storage seasons, by attaching a CO_2 scrubber tube, supplied with the monitors, to the air inlet. Drift from zero

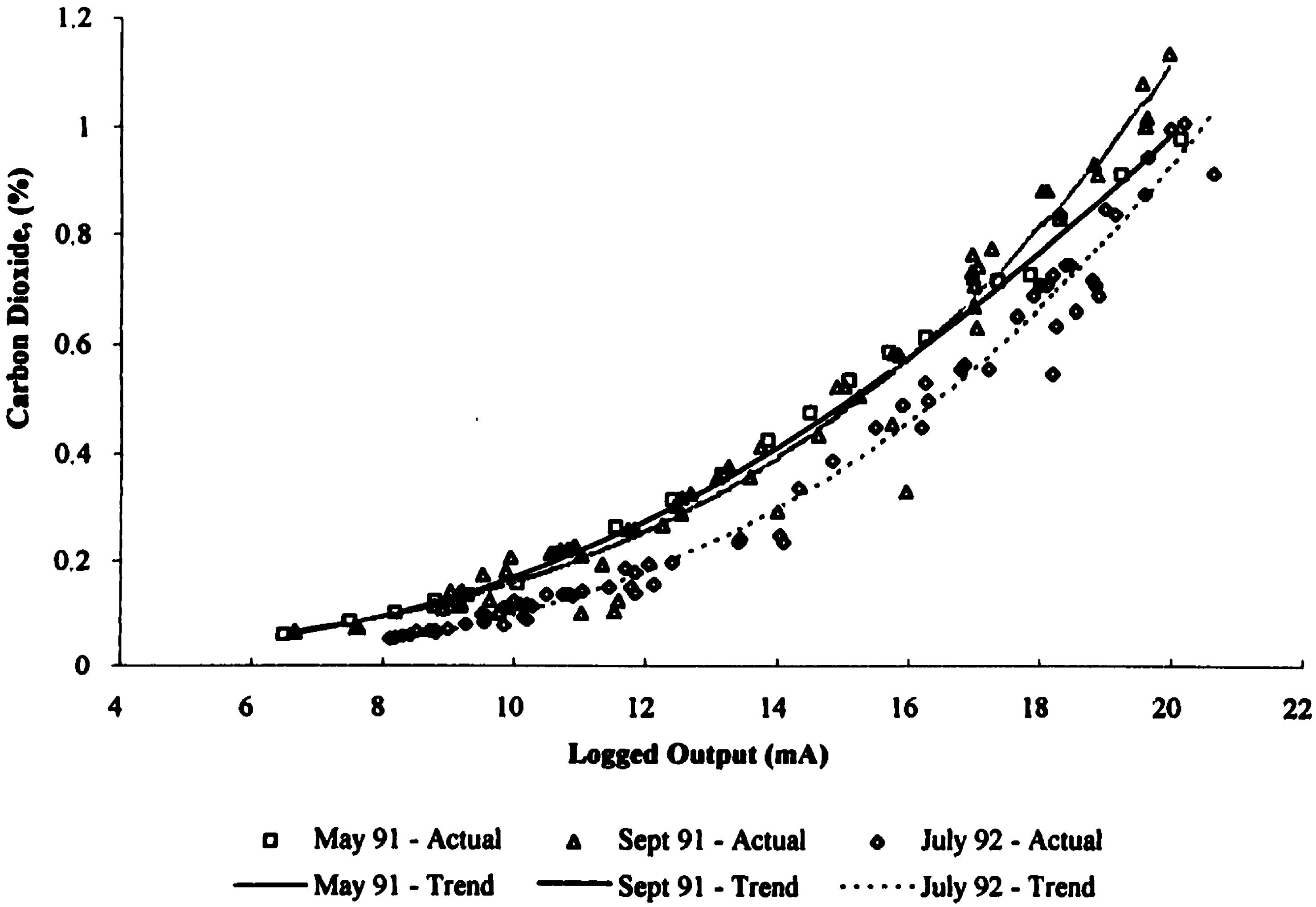

Figure 5. Calibration data and regression curve for nonlinear CO_2 monitor.

never exceeded $\pm$ 0.05% CO_2 on either monitor and was not adjusted while the monitors were being used in the storage.

Output from the linear monitor with the scrubber applied consistently read approximately -0.03 to -0.05% CO_2. The non linear monitor drifted from +0.05% to -0.01% CO_2 and back over the course of the 1992/93 storage season. Ambient temperature changes at the monitor may have affected the noted drift. Monitor output checks, made by switching sampling tubes from one monitor to the other to compare readings proved there was a small difference, with the linear monitor for bin 12, reading approximately 0.05% CO_2 lower than the nonlinear monitor. These comparisons were only valid for the concentration measured in the bins at the time and not over a wide range.

Carbon dioxide concentrations measured by the analyzer stabilized at a consistent output from sample points at all bin locations within approximately 30 s. The 5 min sampling period from each location was more than enough time to obtain a reliable reading from a location.

4.1.2 Carbon Dioxide Accumulation and Decay

A plot of CO_2 accumulation at all sampling locations in bin 12 while all fans in the facility were off (Fig. 6), illustrates the resulting variation within a bin. The rate of change in CO_2 concentration was approximately equal at all locations throughout the bin while all

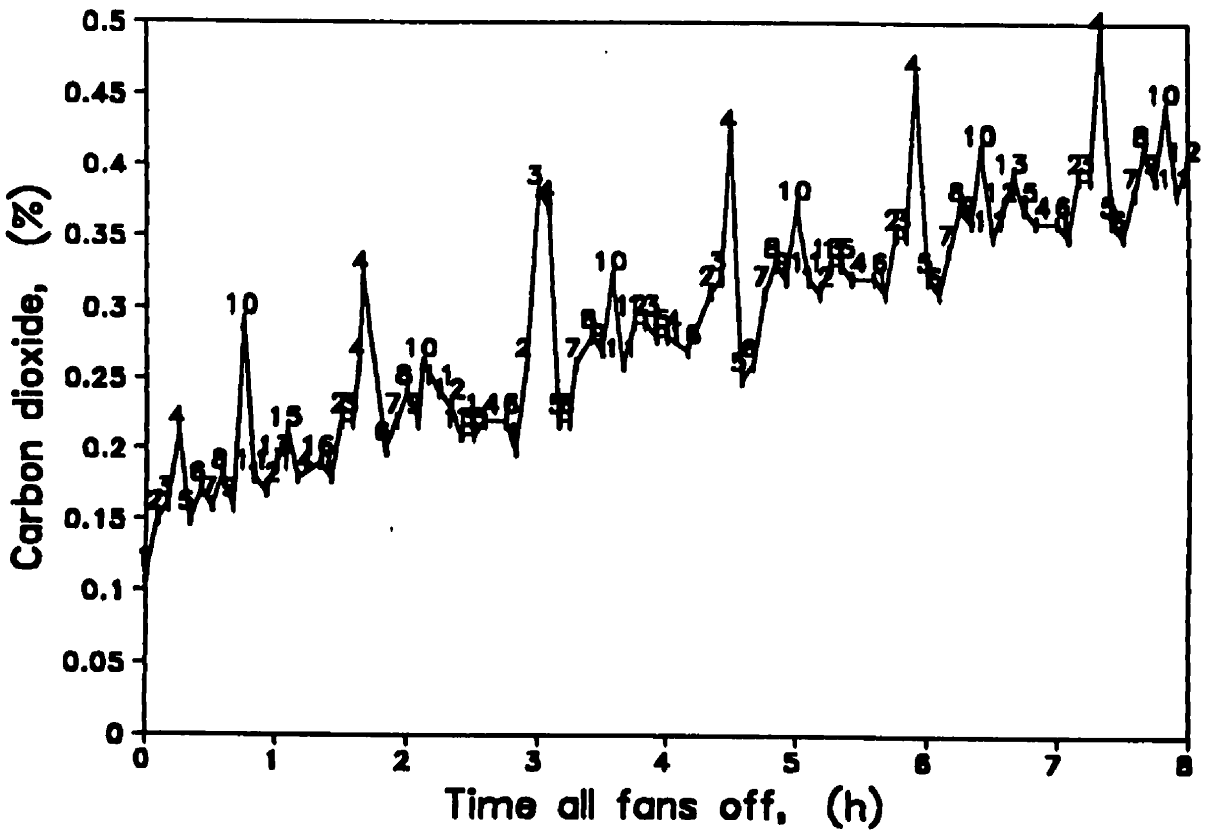

Figure 6. Accumulation of CO_2 at locations 1 to 16 of bin 12 (where numbers in figure represent location of sample in bin) while all fans in the facility were off.

fans in the facility were off. However, the rates of increase in CO_2 observed during fan-off periods were not consistent from one period to another.

A closer look at data for periods when the fan in bin 12 was under computer control and the fan was off revealed that although the recorded fan status indicated the fan was off, it had to have come on very briefly. This was evident because the data were logged to disk at times other than the pre-programmed logging sequence which would only occur if the fan status changed. It is not known why the data did not show the fan status as being on but a safe assumption would be that the status change was so brief that only the returning state was logged. Low and inconsistent accumulation rates of CO_2 can be attributed in part to this fan activity.

Concentrations of CO_2 (Fig. 6), while all fans were off, were lower at locations 1, 3, 7, 9 than at 2, 4, 8, and 10, respectively. It is known for certain that fan status did not change even briefly during the time these data were logged because these were recorded while the fan control was off. Higher concentrations at higher bin elevations was also common when fan control was causing the fan in bin 12 to come on in brief bursts, though no change of the fan status was recorded.

The trend of higher concentrations at upper locations of a bin with all fans off contradicts findings of Schaper and Varns (1978), whose study found higher concentrations close to the floor toward the centre and rear of their bin away from the fan chamber. They suggested wind had a diluting effect on the CO_2 concentrations closer to the fan chamber. Away from the fan chamber, they suggested the higher mass of CO_2 molecules relative to other molecules in air caused them to settle near the floor. When all fans were off in the present study, wind may have helped dilute and push the CO_2 upward. Wind pressure and thermal buoyancy are driving mechanisms for natural ventilation and infiltration (ASHRAE 1985). This study was conducted primarily while outdoor temperatures were much cooler than the indoor temperatures. Thermal buoyancy in buildings warmer than the outside cause an internal building pressure to be equal to outside pressure against the building at some elevation above the floor while infiltration enters from below this level and exhausts above this level. This phenomenon causing air to flow upward through the building may have been partially responsible for a larger CO_2 concentration observed at higher elevations in the bins. The occasional short burst of air from the controlled fan would have added to this effect. The tendency for higher concentrations in these bins to be in the upper locations of the potato bulk suggests that air sampling could be made near the top of other bins for control purposes. This would make tubing installation easier since it could be installed after the bins are filled rather than during filling.

Average concentrations of CO_2 between November 30, 1992 and January 21, 1993 at all locations of bin 12 for each fan status are shown in Table 4.1 and likewise for bin 13 in Table 4.2. The data show that when test bin fan was off but fans for adjacent bins were on, CO_2 was almost as low as when all fans were on. The difference between average concentration of CO_2 in bin 12, when the fan is off but fans in adjacent bins are on, and the

Table 4.1 Means and standard deviations of CO_2 concentrations (%) at sampling locations for four fan ventilation conditions in bin 12, between Nov. 30, 1992 and Jan.21, 1993.

Bin 12	All fans in facility ON			Fan in bin 12 - ON others OFF			Fan in bin 12 - OFF others ON			All fans in facility OFF		
Location	Mean	S.D.	n	Mean	S.D.	n	Mean	S.D.	n	Mean	S.D.	n
1 *	—	—	—	—	—	—	—	—	—	—	—	—
2	0.09	0.09	459	0.11	0.10	58	0.18	0.09	700	0.24	0.12	262
3	0.09	0.08	450	0.11	0.09	59	0.17	0.09	705	0.25	0.12	258
4	0.10	0.10	471	0.14	0.12	69	0.19	0.09	675	0.27	0.11	257
5	0.10	0.09	458	0.12	0.10	64	0.18	0.10	703	0.25	0.13	253
6	0.10	0.09	456	0.11	0.10	56	0.22	0.10	697	0.29	0.13	238
7	0.10	0.09	462	0.10	0.08	60	0.17	0.09	691	0.25	0.12	244
8	0.14	0.11	579	0.18	0.11	105	0.17	0.09	545	0.26	0.12	188
9	0.13	0.11	568	0.17	0.12	106	0.15	0.09	556	0.24	0.13	190
10	0.13	0.11	567	0.16	0.10	97	0.20	0.09	567	0.29	0.12	209
11	0.13	0.11	543	0.16	0.10	96	0.17	0.09	591	0.24	0.11	210
12	0.13	0.11	542	0.17	0.10	96	0.19	0.11	578	0.28	0.10	208
13	0.12	0.11	526	0.16	0.10	91	0.20	0.11	558	0.28	0.13	196
14	0.11	0.10	498	0.13	0.08	88	0.16	0.09	627	0.24	0.12	217
15	0.12	0.11	512	0.13	0.08	90	0.18	0.09	612	0.25	0.12	232
16	0.10	0.09	460	0.14	0.14	67	0.17	0.09	704	0.24	0.12	282

S.D. = Standard Deviation,
n = sample size
* Data missing due to failed solenoid in sample stream.

Table 4.2 Means and standard deviations of CO_2 concentrations (%) at sampling locations for four fan ventilation conditions in bin 13, between Nov. 30, 1992 and Jan. 21, 1993.

Bin 13	All fans in facility ON			Fan in bin 12 - ON, others OFF			Fan in bin 12 - OFF, others ON			All fans in facility OFF		
Location	Mean	S.D.	n	Mean	S.D.	n	Mean	S.D.	n	Mean	S.D.	n
1	0.15	0.08	457	0.19	0.15	64	0.25	0.11	690	0.28	0.12	266
2	0.14	0.07	459	0.18	0.10	58	0.25	0.11	700	0.30	0.12	262
3 *	---	---	---	---	---	---	---	---	---	---	---	---
4	0.15	0.08	471	0.26	0.14	69	0.25	0.11	675	0.34	0.11	257
5	0.15	0.08	458	0.18	0.11	64	0.26	0.11	703	0.32	0.13	253
6	0.15	0.08	456	0.21	0.11	56	0.25	0.11	697	0.36	0.13	238
7	0.15	0.08	462	0.17	0.10	60	0.25	0.11	691	0.29	0.12	244
8	0.18	0.09	579	0.25	0.11	105	0.24	0.12	545	0.32	0.12	188
9	0.17	0.09	568	0.25	0.13	106	0.24	0.12	556	0.33	0.13	190
10 *	---	---	---	---	---	---	---	---	---	---	---	---
11	0.17	0.09	543	0.22	0.11	96	0.24	0.11	591	0.29	0.11	210
12	0.17	0.09	542	0.26	0.12	96	0.24	0.11	578	0.31	0.10	208
13	0.17	0.09	526	0.25	0.11	91	0.24	0.11	558	0.35	0.13	196
14	0.16	0.09	498	0.31	0.11	88	0.25	0.11	627	0.38	0.12	217
15	0.17	0.09	512	0.26	0.11	90	0.24	0.10	612	0.37	0.12	232
16	0.15	0.08	460	0.20	0.14	67	0.25	0.11	704	0.32	0.12	282

S.D. = Standard deviation,
n = sample size
* Data missing due to failed solenoids in sample stream.

average concentration with the fan on continuously are small for CO_2 set point and dead-band control. If set points are made too high, a risk of too little ventilation is possible, and if dead-bands are made too narrow, undesirable fan cycling can occur. Both of these reactions occurred causing the controlled fan to remain off for extended periods of time, or to cycle on and off too frequently.

Data were used for linear regressions to estimate the rate of CO_2 accumulation at each location for times that all fans were off for an extended time during the holding period between November 1, 1992 and January 21, 1993 (Table 4.3). The CO_2 data for each period and location were adjusted by subtracting the initial concentration to eliminate the offset and make data compatible for the regression. The accumulation rates are shown as $\%CO_2/h$ which represents the rate of increase in concentration of CO_2 in the bins.

Rates of CO_2 accumulation and the difference from one location to another were lower than expected. Accumulation rate data for periods recorded as having all fans off were more consistent at all locations in bin 13 than bin 12 as is reflected by the better R^2 values at every location (Table 4.3). The low averages in bin 12 and possibly bin 13 resulted from occasions where there were almost no increases for long periods of time due to the short but frequent switching on and off of the fan in bin 12 under set point control. The average accumulation rates in Table 4.3 exclude the two periods during which the most rapid accumulations were noted, namely suberization and following the sprout inhibition of the tubers with CIPC.

Table 4.3 Average linear CO_2 accumulation rate at sampling locations in the monitored bins while all fans were off, between Nov. 1, 1992 and Jan. 21, 1993.

Bin 12				Bin 13			
Location	Accumulation rate (% CO_2/h)	R^2	n	Location	Accumulation rate (% CO_2/h)	R^2	n
1	—	—	—	1	0.015	0.42	131
2	0.020	0.21	131	2	0.019	0.49	131
3	0.018	0.14	113	3	—	—	—
4	0.021	0.28	109	4	0.016	0.56	109
5	0.016	0.24	112	5	0.020	0.53	112
6	0.014	0.34	100	6	0.018	0.61	100
7	0.019	0.29	104	7	0.016	0.44	104
8	0.014	0.17	88	8	0.015	0.52	88
9	0.017	0.21	92	9	0.018	0.69	92
10	0.015	0.22	98	10	—	—	—
11	0.009	0.13	100	11	0.013	0.53	100
12	0.011	0.11	110	12	0.009	0.44	110
13	0.014	0.00	94	13	0.019	0.54	94
14	0.018	0.28	113	14	0.018	0.62	113
15	0.016	0.20	122	15	0.020	0.59	122
16	0.020	0.27	143	16	0.022	0.49	143

Bin 12 Mean	Bin 12 S.D.	Bin 13 Mean	Bin 13 S.D.
0.016	0.003	0.017	0.003

R^2 = dimensionless, correlation coefficient squared, for linear regression % CO_2 vs. time (h),
n = sample size,
S.D. = standard deviation.

Using Eq. (3), and an estimated 27,000 moles of air in either bin 12 or bin 13 each containing approximately 650 t of potatoes, rates in Table 4.3 can be converted and compared to values of respiration which may be expressed as g $CO_2/(t \cdot h)$.

$$g\ CO_2/(t \cdot h) = ((\%CO_2/h)/100) \cdot (Moles/Bin) \cdot (44\ g/Mole\ of\ CO_2) / t \qquad (3)$$

Applying Eq. 3 to the average $\%CO_2/h$ accumulation rate for both bins in Table 4.3, the average accumulation rate was only 0.3 g $CO_2/(t \cdot h)$. This accumulation rate is lower than reported respiration rates in the literature for any condition to which tubers of any cultivar are exposed. As an example, the lowest respiration rate reported by Schippers (1977a, 1977b) for potatoes was 1.0 g $CO_2/(t \cdot h)$. The problem with comparing these numbers from a commercial storage as opposed to a laboratory apparatus, is in estimation of air exchange to and from outside and from other bins during all ventilation conditions.

4.2 Relative Humidity Measurement By Air Sample Retrieval

4.2.1 Relative Humidity Measurement and Calibration

Results from calibration of one of the two relative humidity sensor/transmitter units (Table 4.4) show that the sensor held its calibration well while installed from May 1991 to July 1991. During the 1991/92 storage season there was a slight drift. Under normal circumstances the sensor was, due to sensible heating, measuring relative humidities between 50 and 85%. At 50% relative humidity the difference between the September 1991 and May 1992 calibrations was only 0.23% relative humidity and at 85% the difference was 1.65% relative humidity. The calibration in July 1992, revealed another slight drift in the same direction, causing the offset to become more negative and the slope of the new calibration line to be slightly greater. This shows that over time, even if not always measuring high humidity, these sensors will slowly drift from calibration. One sensor failed in the 1991/92 season after approximately seven months of use in the storage. It is very likely that condensation problems at about that time caused the sensor to fail.

Table 4.4 Regression results for relative humidity sensor/transmitter unit calibrations.

Calibration Date	Bin 12	R^2	Bin 13	R^2
May 1991	$Y = 0.989X + 0.77$	0.997	----------------	-------
September 1991	$Y = 0.971X + 0.73$	0.998	$Y = 0.813X + 10.04$	0.996
May 1992	$Y = 1.014X - 1.19$	0.995	Failed Sensor	-------
July 1992	$Y = 1.056X - 6.57$	0.990	$Y = 0.729X + 19.76$	0.990

Where: Y = Calibrated relative humidity (%),

X = Measured relative humidity (%).

4.2.2 Air Sampling and Sensible Heating Assumption

During the 1991/92 storage season it was determined that a minimum of 4 min continuous sampling time was needed for the sensor to equilibrate to the sample stream relative humidity. In the 1992/93 storage season, the sample time was increased to 5 min. An exception to the equilibration time was if the air was changing while being drawn past the sensor, as occurred when water was condensing out of the sample in the sample tube or being vapourized.

The method used in this study to measure relative humidity within the potato bulks was unique compared with other methods in the literature. Sensible heating is a well known psychrometric process in which an air-water vapour mixture is heated without adding or removing moisture. The advantages of measuring the relative humidity of sensibly heated air withdrawn from the potato bulks as recognized by this study were:

1. A single relative humidity sensor was used to measure the relative humidity from numerous locations.
2. The sensor was accessible for calibration or replacement.
3. Air samples measured by the sensor, when sensible heating was successful, had a lower relative humidity than the origin of the samples thus problems associated with measuring relative humidities in the range of 90-100% were eliminated.
4. The air in the sample stream did not appear to be as dirty as air in the bin.

The disadvantages or difficulties encountered from using this method were:

1. Sensible heating must be assured and required a difficult installation of sample tubing through conduit and continuous heating, in this case using heated forced air.

2. The accuracy of each measurement depended upon the accuracy of three measurements; two temperatures and the relative humidity. The calibration error of the sensor/transmitter units or error in temperature measurement could result in a large calculated error in relative humidity. The magnitude of the error was dependent upon all three measurements.

3. A leak proof sampling system was necessary with a reliable pump, though for this study, it was a prerequisite for CO_2 sampling anyway.

4. Calculations had to be performed to determine the relative humidity at the sample origin.

5. A continuous output was not possible because each time a sample location was switched, a period of time was needed for the sensor to equilibrate to the new air stream relative humidity.

All of the above advantages to using the technique for measuring relative humidity were recognized in this study. The first advantage is two fold. First, the cost of measuring several locations is reduced and secondly all measurements are relative to each other in the sense one does not have calibration differences between different relative humidity sensors. The only calibration difference is that of temperature at the location of sample origin.

Of the above disadvantages, only one is seen as a major difficulty and that is assuring the validity of the sensible heating assumption in the sample tubes. During the 1991/92 storage season, the sensor temperatures occasionally dropped below those in the bin because of very cold alleyway temperatures. The undesired temperature differential resulted in sensible cooling and condensation instead of sensible heating. During that season attempts to warm sample tubing from the bins were unsuccessful. In the 1992/93 storage season the sensors were installed in an insulated cabinet and kept warm with the help of a 1.5 kW heater placed in another enclosure to one side of the sensor cabinet. Heated air was forced into rigid, insulated conduit around sample tubing. Conduit was extended through the storage to all points above the potatoes. This effort improved the results considerably but did not entirely solve the problem.

Measured and calculated relative humidities for locations 5 and 6 in bin 12 are shown in Fig. 7. Condensation occurred in several sample tubes on two occasions during the 1992/93 storage season. Almost immediately after the potatoes were placed in storage, during suberization, water condensed in the sampling tubes. The calculated relative humidity of samples soon became greater than 100% as the moisture left in the tubing was absorbed by further samples. Sample tubes were blown out with dry compressed air in an attempt to speed up the drying of the inside of the tubes.

The second time condensation was found in sample tubes, the calculated relative humidity exceeded 100% for a period of approximately one week starting Jan. 5, 1993. The relative humidity calculated for bin 12 the week before and perhaps two weeks after the first calculated relative humidity greater than 100% are probably inaccurate

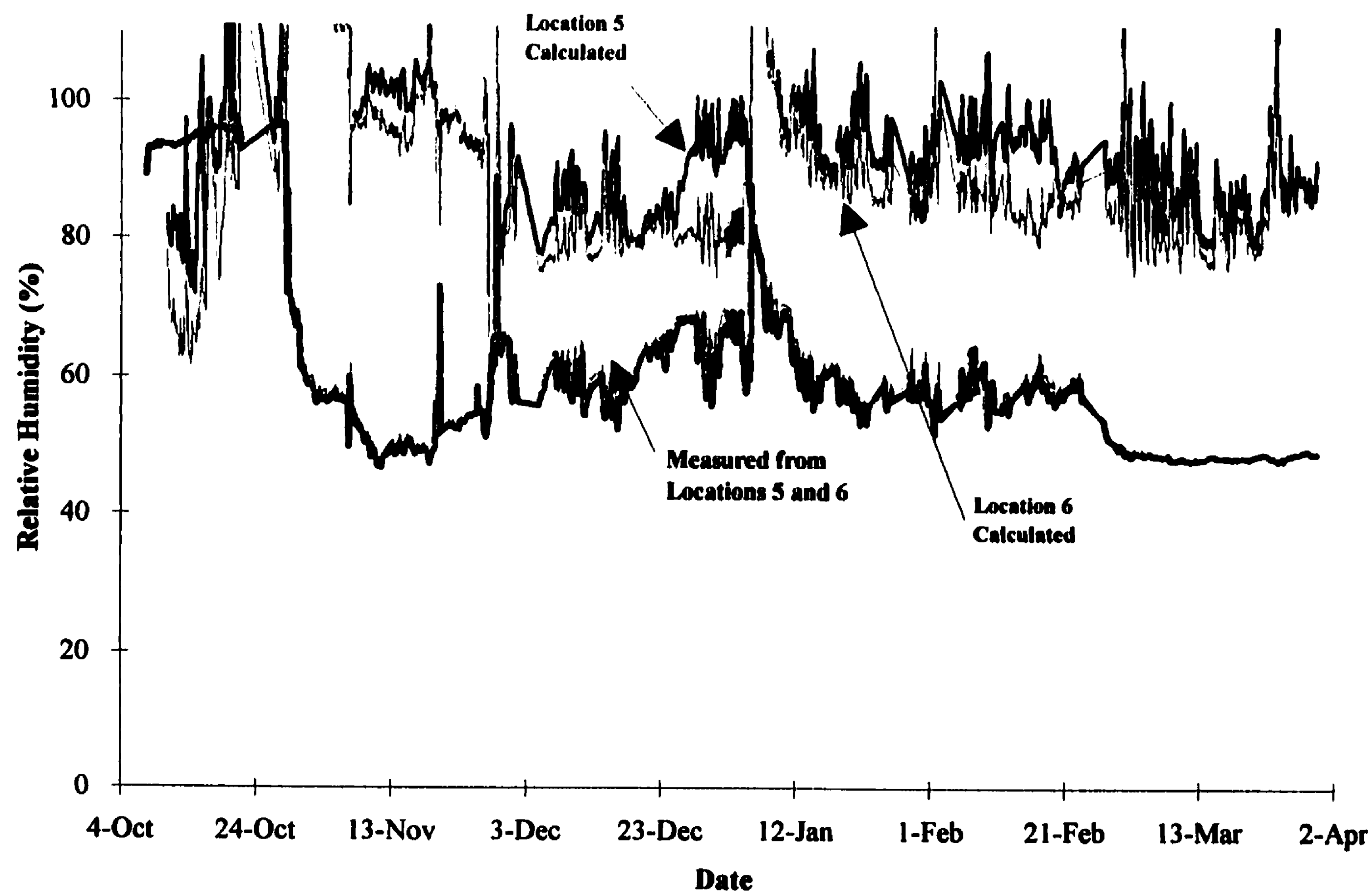

Figure 7. Bin 12 relative humidity at locations 5 and 6 (1992/93), calculated assuming sensible heating of the sample before measurement.

representations of the bin relative humidity (Fig. 7). As a result of these periods when it was known from visual inspection that condensation had occurred in the tubing and at the sensor, it is impossible to know how much or how well the relative humidity data calculated represents actual conditions. When the calculated relative humidity is well below 100% for the majority of a time period, a moving average relative humidity may be more accurate, due to cycles of humidifying the air and condensing the moisture in the tubes.

4.3 Intermittent Ventilation Experiment

During the 1992/93 storage season the management for this facility manually shut off fans for potato bin ventilation while emptying bins and grading to reduce their peak electric power demand during the months of December, January and February. It was anticipated that by doing this, CO_2 could accumulate to concentrations approaching 1%. The computer based monitoring system was set-up to control the status of the ventilation fan in bin 12 by either a CO_2 set point and dead-band or a temperature set point and dead-band or both simultaneously.

Automatic intermittent ventilation began Oct. 19, 1992 but was frequently turned off by the storage manager until Nov. 1. Prior to this date fans were turned on and off manually by the storage manager to allow suberization and then to cool potatoes slowly by drawing outside air at night when outside temperatures were cooler. When computer control by set point CO_2 was allowed by the storage manager and the producer, they desired to lower temperatures further in bin 12. Therefore, the computer was set to control CO_2 but with a second criteria that for the fan to stop, temperature in location 1 of the bin was to be below an agreed set point temperature. Although bin temperature decreased during the week, the lower set point temperature was not reached and the fan remained on.

The storage manager was satisfied with the temperatures by Nov. 6 and allowed fan control to be based on CO_2 concentration with a slightly more flexible temperature. By this time, only small amounts of fresh air were being allowed by the commercial temperature controller. The upper CO_2 set point was set at 0.25% and the lower at 0.20%. The resulting fan operation in bin 12 can be seen in Fig. 8, where the fan in bin 12 did not come on until Nov. 11. The fan did not come on because the fans operating in other bins reduced CO_2 in this bin while its fan was off. This occurred often, as is evident by the low means for CO_2 in Table 4.1 and 4.2 for times when a bin fan is off while adjacent bin fans are on. The fan power consumption for bin 13, which is adjacent to bin 12, is shown in Fig. 9. Fan activity in bin 13 was always the same as the activity in all bins other than bin 12. Therefore, Fig. 9 can be assumed to show fan power use for all other bins in the facility.

Figure 8 and 9 show power used by the fans times a fraction of a 15 min interval that the fan was on as recorded with the energy meter installed by Manitoba Hydro. Since the fans in bins 12 and 13 were run on low speed, operation for a continuous 15 min pulse recorder cycle showed an energy consumption of approximately 2.0 kW·15 min. When the fan was run for less than the full 15 min pulse cycle, it recorded energy consumption (kW·15 min), of 2.0 kW times the fraction of the 15 min pulse cycle the fan was on.

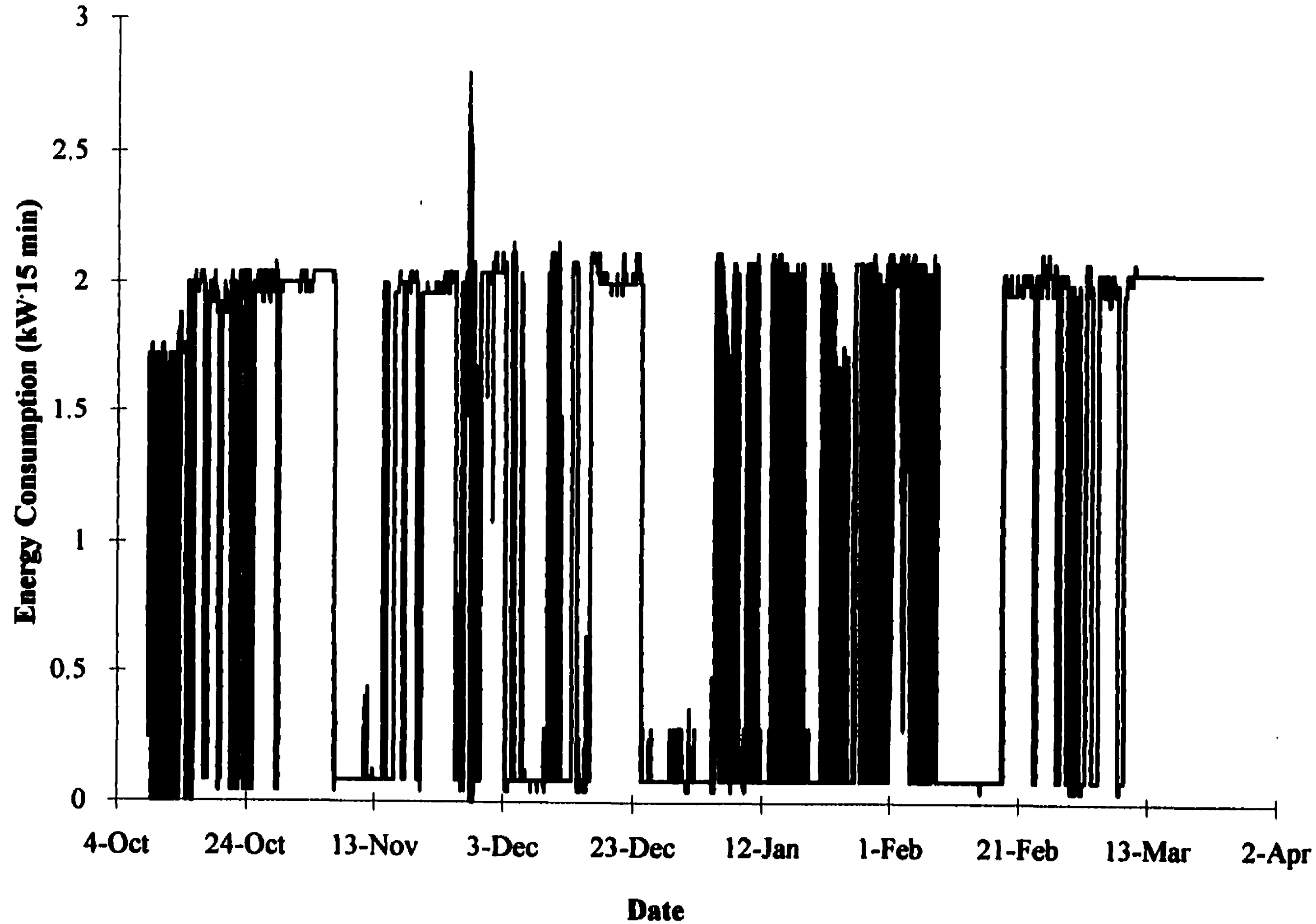

Figure 8. Bin 12 energy consumption (kW·15 min) of the fan, 1992/93.

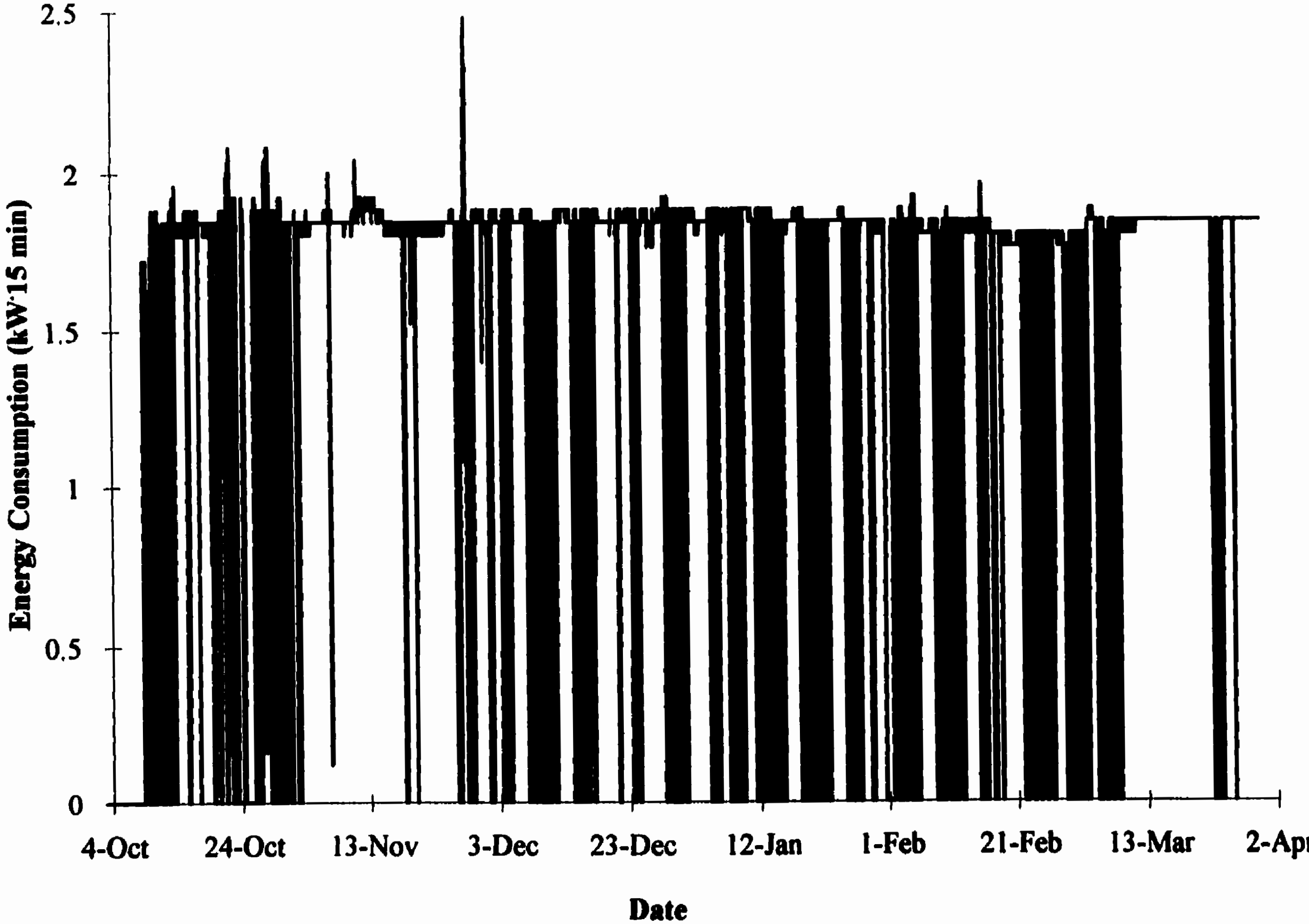

Figure 9. Bin 13 energy consumption (kW·15 min) of the fan, 1992/93.

Energy use recorded for the fan in bin 12 (Fig. 8), showed an above zero base consumption when the fan was not running. This is showing the power used by the Gellert controller which consumed power to operate relays, a small processor for P.I.D. control of the louvre for fresh air blending as well as the actuator itself and heat tape on the louvre door for protection from freezing up in the winter.

On Nov. 11 the fan in bin 12 ran for approximately 3 min at a time to keep the CO_2 within the set point range. In Fig. 8, fan activity is shown as an energy consumption of approximately 0.4 kW·15 min, which represents the fact that the fan was on for approximately 20% of the 15 min pulse recorder cycle, which is 3 min. The rise in CO_2 in bin 12 (Fig. 10) and bin 13 (Fig. 11) on this date occured during an application of the sprout inhibitor CIPC to bins 14 and 15. Since the distribution of CO_2 was not as uniform as usual, it appeared to be an external source of CO_2 entering into these monitored bins. Frequent on and off status of the fan resulted from switching sampling locations every 5 min, each having quite different concentrations, the higher of which would allow the fan to come on and lower of which would turn it off.

If average concentrations of CO_2 over a period of time were used as a fan start criterion, the fan would be less likely to start as often. One potential problem with using averages could arise if an area subjected to high concentrations of CO_2, but only represented as one of several samples, was not ventilated because the set point was not reached. A complex analysis system that could keep track of the average CO_2 concentration from any individual location as well as

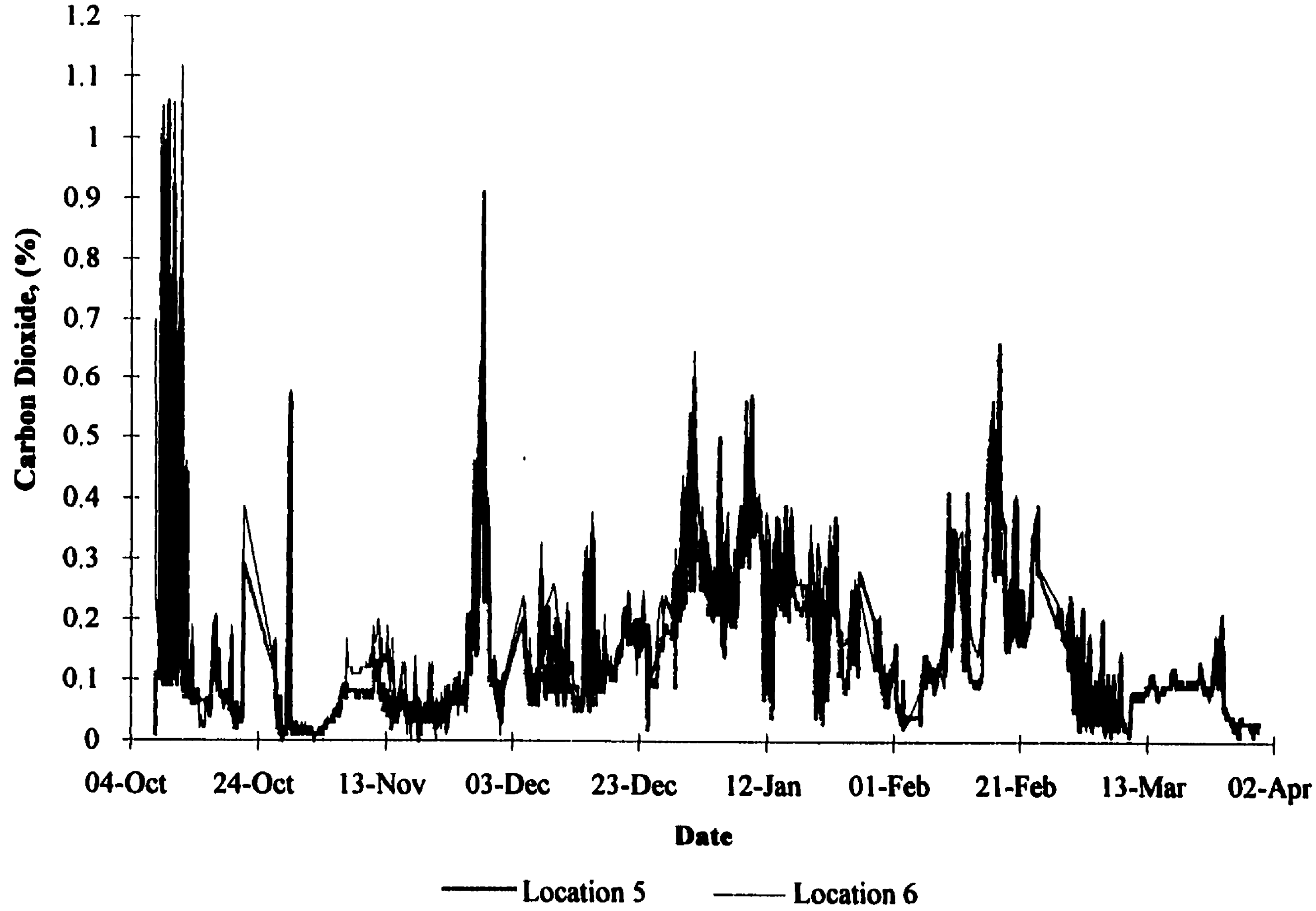

Figure 10. Bin 12 carbon dioxide concentrations at locations 5 and 6, 1992/93.

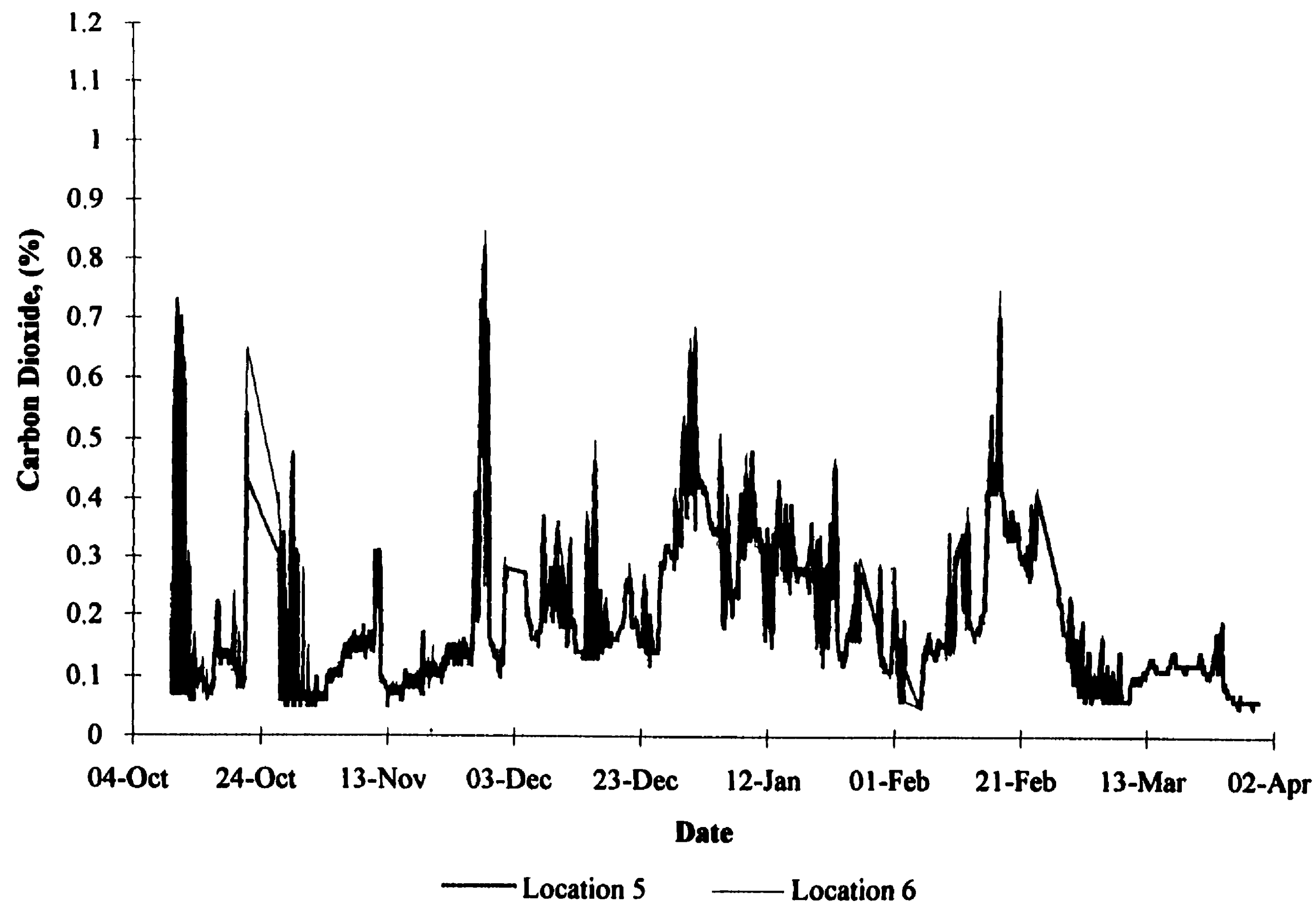

Figure 11. Bin 13 carbon dioxide concentrations at locations 5 and 6, 1992/93.

all locations combined, may reduce the risk of not ventilating one location frequently enough when it needs more than an average amount of ventilation.

Temperatures in the lower levels of bin 12 (represented by location 5, Fig. 12) initially continued to decrease or remain unchanged while the fan was off between Nov. 6 and Nov. 11. In the upper locations of bin 12 the temperature increased (represented by location 6, Fig 12). This shows that cooler air moved upward through the pile while the fan was off and other bin fans were on, but too low an airflow to maintain a temperature differential within recommended or preferred limits. Most respondents to a survey by Gellert (1985) wanted the maximum differential in their potato bulk to be no greater than approximately 0.55 °C after the potatoes had been lowered to holding temperature. The combination of low CO_2 accumulation and inadequate airflow observed indicate that a minimum ventilation strategy using CO_2 accumulation as the only criterion for ventilation is not feasible in a multi-bin facility when fan status of an adjacent bin is not the same.

On Nov. 14 the computer control settings were adjusted to include a temperature set point once again, to cool the bin and equilibrate pile temperatures. Maximum allowable concentration of CO_2 before the fan would come on, after temperature set points turned it off, was set at 0.25%. It took less than one full day for the lower temperature set point (7.7 °C) to be reached because in the lower (odd numbered) locations the temperatures were almost identical to what they had been before the fan had turned off on Nov. 6. The difference between the upper and lower temperature set points (set point dead-band) was 0.6 °C.

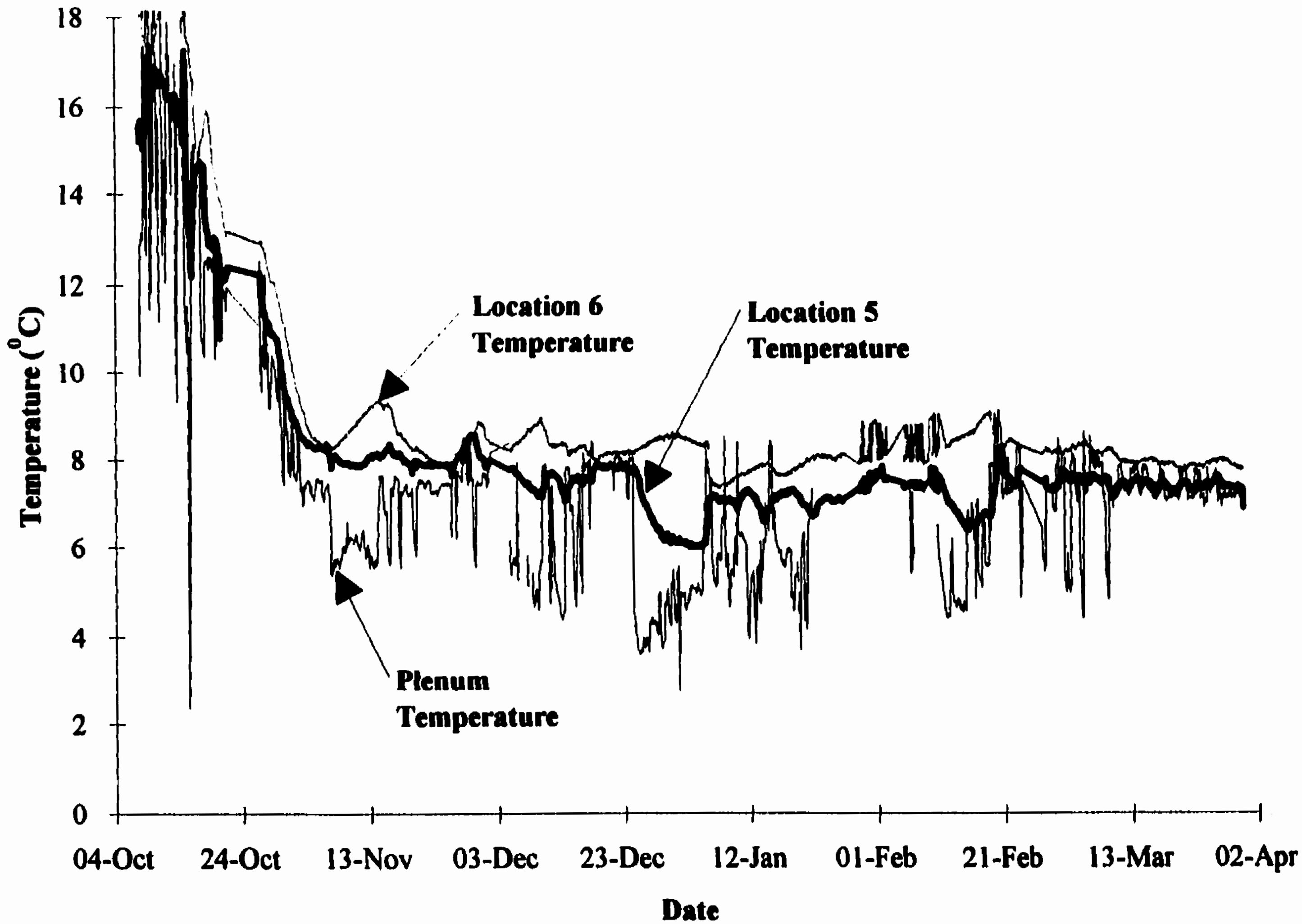

Figure 12. Bin 12 temperatures in the plenum and locations 5 and 6, 1992/93 .

Afterward, the fan status was only changed by the temperature set point until the control settings were changed on Nov. 25. An increase of 0.6 °C occurred at location 1 in bin 12 while the fan was off though CO_2 failed to reach a level of 0.25% in any location. In most locations there was no increase of CO_2 at all.

On Nov. 25 the CO_2 set point was readjusted to activate the fan when it reached an upper level of 0.20% and shut it off when it dropped to 0.15%. As a result, the set point was exceeded several times during the one day trial, turning the fan on for 2-5 min each time. The next day (Nov. 26) all fans in the facility were turned off for sealing before CIPC treatment to follow the next day. During this short period on Nov. 26, in which all fans in the facility were off, the first major rise in CO_2 was recorded (Fig. 10 for bin 12, Fig. 11 for bin 13). Since the fans were shutdown manually, the computer could not turn the fan on. In addition to the large accumulation of CO_2 while all fans were off, there was a large rise in measured relative humidity from approximately 90% to 100% in bin 12 (Fig. 7). Relative humidity in bin 13 increased only slightly from 90% to an approximate maximum of 93%.

After sprout inhibition with CIPC and an overnight manual shutdown of the fans, CO_2 based control was resumed in bin 12. Fans other than bin 12 were kept off for another few hours after a brief flushing. The set point, in expectations of higher levels, was increased to 0.4% as the upper limit and 0.35% as the lower limit. It did not take long for the new upper set point to be reached. The lower set point limit was reached after approximately 15 min of fan operation the first time CO_2 was flushed out but less time was required in subsequent fan starts.

The fan turned on and off several times for approximately 12 h until other fans were turned back on. As soon as the other fans were turned on, the CO_2 dropped below its set point and held the fan off until it was turned on manually after 12 h. The fan was then left to run continuously until Dec. 4.

Relative humidity appears to have taken a large drop during the application of CIPC. It is possible this is not a true measurement since the heater and blower for warming sampling tubes had to be shut down during the application of CIPC. Furthermore the rise to 100% the next day coincides with the heater and blower being turned back on. Therefore, condensation may have occurred in the sampling tubes, making the sensible heating assumption used for calculation of relative humidity invalid until the water finished evaporating. On the other hand there is some evidence to suggest relative humidity did decrease during the application of CIPC, though quite probably not as much as seen in these data since some condensation must have occurred (Fig. 7 for bin 12). The drop in relative humidity coincided exactly with the start of CIPC application and ended exactly with the fans being turned on to flush the bins. After a brief rise to 100% relative humidity, during which it is likely water from previous condensation was being added to the air samples, the humidity dropped down again to a level lower than that prior to sprout inhibition. This new lower level remained stable for approximately one month in both bins (Fig. 7 for bin 12, Fig. 13 for bin 13).

On Dec. 4 computer control was resumed. Only a small temperature differential between top and bottom levels of the bin existed at this time. The computer shut off the fan since the CO_2

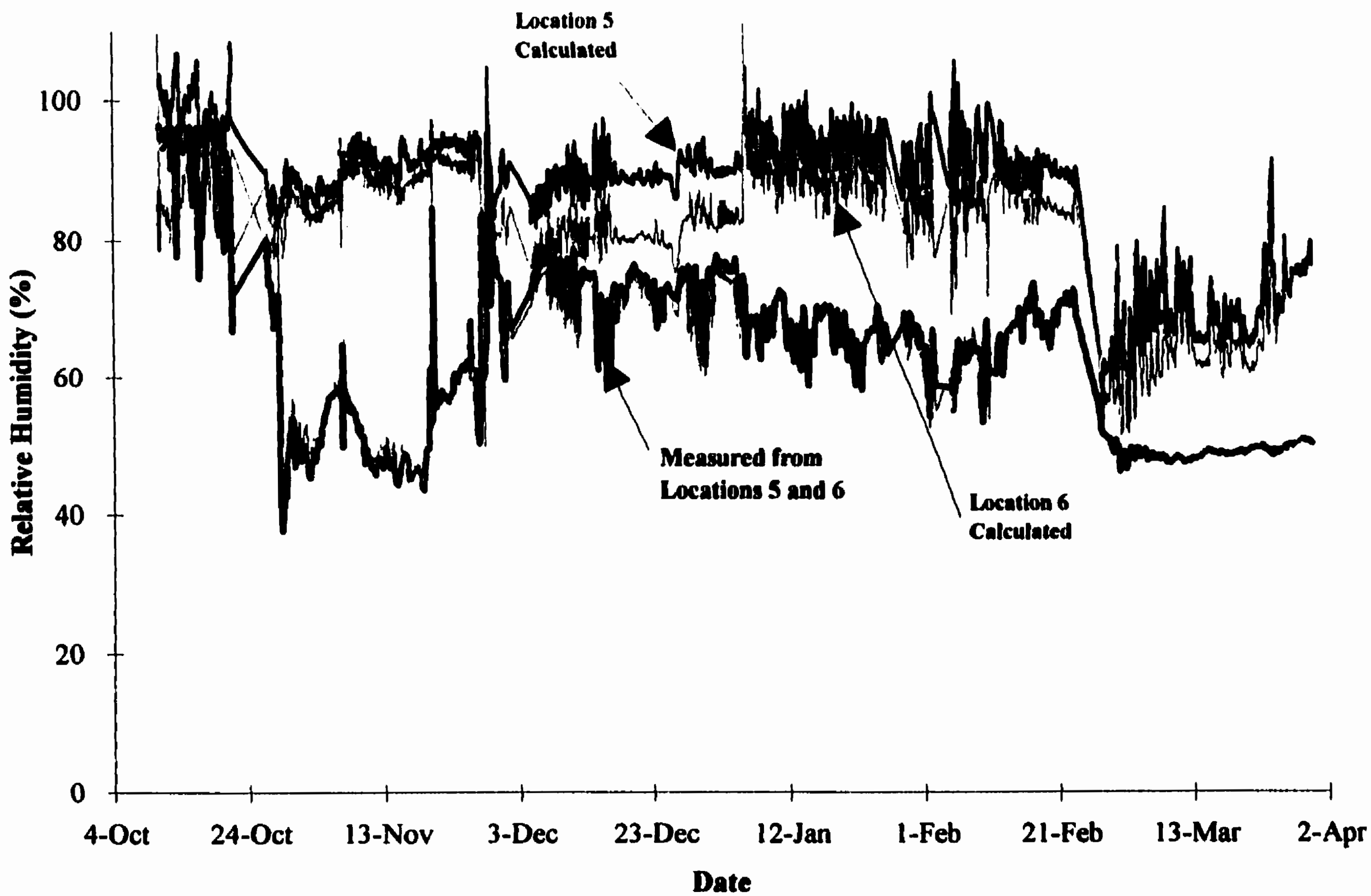

Figure 13. Bin 13 relative humidity at locations 5 and 6 (1992/93), calculated assuming sensible heating of the sample before measurement.

was not exceeding 0.4% concentration. Again, this was due to the effect of other fans operating in the storage complex. On Dec. 9 the fan was manually activated since temperatures at the top of the pile had increased beyond desired levels. Once fan operation resumed it took only a day for temperatures between the top and bottom to be within 0.5 °C of each other, again indicating that the accumulation of heat was not substantial.

During the period of non ventilation prior to Dec. 9 the plenum had become quite cold, the temperature at the bottom of the pile had decreased and the top had increased (Fig. 12). The temperature differences between upper and lower measurement locations were about 1.6 °C when the fan was turned back on in bin 12. As occurred in November, it appears that the air movement through the pile was vertical which may also explain the higher CO_2 levels in upper elevations of the bin.

Accumulation of CO_2 was more rapid during this period than previously in early November. One explanation may be that the potatoes were stressed from the CIPC application. Mazza and Siemens (1990) and Shamaila (1985) reported consistently higher levels of CO_2 in commercial storage bins following the application of CIPC for prolonged periods of time. However, Boe et al. (1974) concluded that the application of CIPC reduced respiration of potatoes. Temperatures between Dec. 4 and Dec. 9 were similar to those between Nov. 6 and Nov. 14, which rules out temperature difference as a potential source of increased respiration. In this particular case, a more likely explanation for the higher concentrations and more rapid accumulations of CO_2 is the fan activity in other bins. In early November, other fans were operated almost continuously, while between Dec. 4 and Dec. 10, fans were being turned off during the day when grading was ongoing to conserve power and minimise the demand for energy in the month of December.

Control was once again resumed with both CO_2 and temperature set points on Dec. 10. Temperature set points were prevalent initially once the lower set point was reached and the fan turned off, it remained off until the upper 0.4% CO_2 set point was reached on Dec. 15 causing some fan cycling. On Dec. 16 the fan was manually turned on until Dec. 24.

During the continuous ventilation period, the temperature controller kept the plenum and bin temperatures very uniform (Fig. 12). This may have been possible because accumulated heat within the potato mass from the previous periods of non-ventilation slowly released and maintained the temperature during continuous ventilation. In bin 13, the temperatures decreased substantially during the same period (Fig. 14) with almost the same amount of continuous fan operation. This is a good example of an automatic temperature controller's ability to maintain temperatures in the plenum, while a manual intake door such as in bin 13, set in one position cannot do the same.

On Dec. 24 computer control was resumed but since settings had not been changed, the computer held the fan off once again for an extended period of time. The bin 12 plenum temperature dropped to a cold enough level to trigger the cold temperature shut-down built into the H970R control panel, set for approximately 4.4 °C. On numerous occasions between

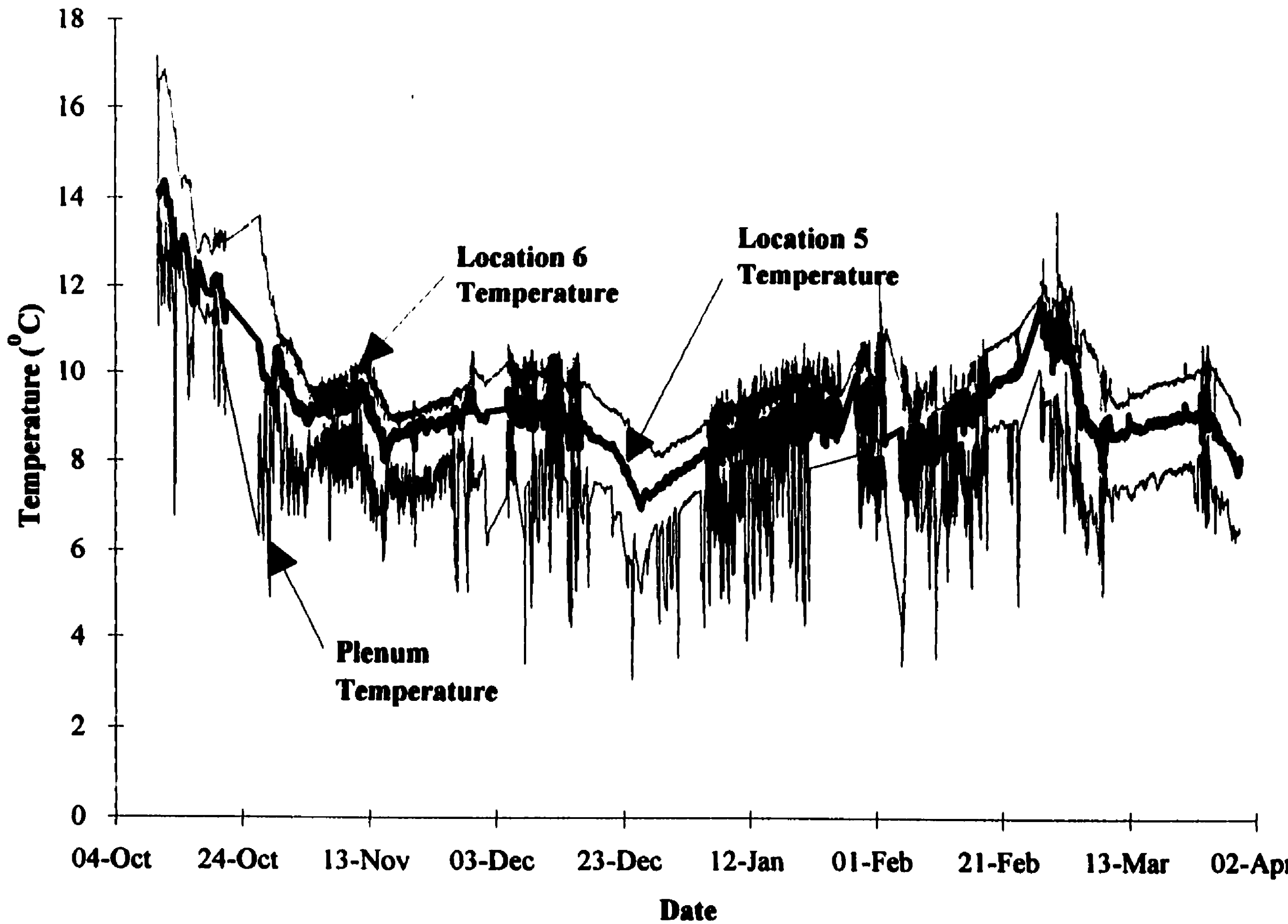

Figure 14. Bin 13 temperatures in the plenum and locations 5 and 6, 1992/93 .

Dec. 28 and Jan. 5 the computer attempted without success to turn on the fan in bin 12 due to exceeded CO_2 set points while bin 13 and other fans had been off during daytime grading. This is another good example of a time when the fan in bin 12 was definitely not cycling on and off and as a result, the CO_2 accumulated to set point levels. Figure 8 shows that between these dates, there were several different occasions when the fan came on briefly and quickly shutdown. The fan had come on because the storage operator had turned it on manually. The fan shut down shortly afterward due to the cold temperature shut-down feature. Only manual reset could then be used to turn the fan on again.

Except for a couple of days of daytime grading, during the Dec. 28 to Jan. 5 period, the fan in bin 13 was continuously operated and possibly helped remove heat from bin 12 as well as CO_2. The temperatures at the bottom of bin 12 reduced when the fan was off while the top temperatures increased very little.

On Jan. 5 the fan in bin 12 was turned on for a day to bring the plenum temperature back up and reduce temperature variation within the bin. Temperatures quickly became uniform and intermittent operation was resumed. From this point forward until Feb. 8, intermittent ventilation was allowed to continue. During this time, the temperature set point was exceeded occasionally while bin 13 and other fans were running but when they were turned off, CO_2 in bin 12 (Fig. 10) and bin 13 (Fig. 11) increased to exceed the 0.4% set point. As a result of the upper and lower CO_2 setpoint being intermittently reached, the CO_2 in bins 12 and 13 were maintained closely to 0.4% while the other fans were off. The fans in all bins except bin 12 were manually turned off for approximately 8 h almost daily during this time to reduce demand energy consumption. Even while other fans were on during this period, CO_2 maintained a consistently higher level than seen previously under such circumstance. Some storage facilities with more airtight bins and timed ventilation strategies during the holding period would surely have an even higher base level of CO_2.

5.0 CONCLUSIONS

Based on the results of this study, the following conclusions were made:

1. The 'non-dispersive infra-red type' monitors used in this study for continuous measurement of CO_2 concentration and for air sample retrieval were adequate for this purpose in commercial potato storage bins.
2. CO_2 concentration alone is not an adequate criterion for ventilation to start in a bin when an adjacent bin has a ventilation fan on. Ventilation in a bin lowers the CO_2 concentration within itself and within adjacent bins that have ventilation turned off.
3. When all fans are off in a potato storage, CO_2 concentration could be used as one of the criterion for ventilation.
4. When CO_2 concentration is used as a criterion to ventilate, some other form of fan shut-off criterion should be used to avoid excessive switching on and off of the fan.
5. Concentrations of CO_2 are frequently higher in the upper levels of the potato bulk than in the lower levels.
6. Assurance of sensible heating in sample tubes from potato bulks to a connected relative humidity sensor outside of the storage, throughout the storage season, proved impossible.
7. Relative humidity sensor/transmitter units were adequate for measuring relative humidity of sample streams to the carbon dioxide monitors from the potato bulk.

8. Operating the fans of adjoining bins intermittently and at different times throughout a storage season in a multi-bin facility should not be done without monitoring differential temperatures between the upper level and lower level of the bin and incorporating these temperatures into the control criterion.

9. Storage operator/owners could take advantage of substantial savings in electric costs by turning ventilation fans off while using large amounts of energy for other electrically driven operations such as water pumping and grading during winter months. While fans are off, measured CO_2 concentrations in the upper bin level could be used as a criterion to ventilate. Since the CO_2 concentration is reduced in bins adjacent to a ventilated bin, in a facility such as the one in this study, an energy demand control procedure could be used to limit the number of bins ventilated simultaneously. Differential temperature measurements in the bulk potato storage bins could be used to turn fans off when a predetermined differential is achieved and measurements could be used to turn fans on when a differential temperature becomes excessive. This type of CO_2 and temperature control could be performed on a priority basis in cooperation with energy demand control if a microcomputer based system is used to continuously adapt to changing priority criterion.

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