Design and implementation of an automated controlled atmosphere storage facility for research

B. Goyette[1], C. Vigneault[1], N.R. Markarian[1] and J.R. DeEll[2]

[1]Horticultural Research and Development Center, 430 Boul. Gouin, Saint-Jean-sur-Richelieu, Québec, Canada J3B 3E6; and [2]Ontario Ministry of Agriculture, Food and Rural Affairs, 4890 Victoria Ave N., Box 8000, Vineland Station, Ontario, Canada L0R 2E0.

Goyette, B., Vigneault, C., Markarian, N.R. and DeEll, J.R. **Design and implementation of an automated controlled atmosphere storage facility for research**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **44**: 3.35-3.40. An advanced automated control system for controlled atmosphere (CA) storage research was developed. The new system was used to control CO_2 and O_2 levels in 42 independent chambers. In addition to the standard rigid containers that are used in most research stations, unique variable volume mini-chambers (VVMC) that remain airtight by means of a water channel were developed. The VVMC were used to store apples and squash in the 2000-2001 storage season with gas concentrations ranging from 1.0 to 4.5% O_2 and 2.5 to 8.5% CO_2. The new control system provided accurate control of these gas concentrations in the chambers. The system offers the versatility to investigate the application and consequences of CA storage for different fruits and vegetables. In contrast to the commercial CA systems available, this custom-made system has the flexibility to be modified any time. **Keywords**: control system, variable volume chamber.

Un système avant-gardiste permettant la gestion d'un complexe d'entreposage sous atmosphère contrôlée (AC) a été développé. Grâce à ce nouveau système, les niveaux de O_2 et de CO_2 peuvent être suivis et contrôlés dans 42 mini-chambres indépendantes. En plus d'utiliser les chambres rigides couramment rencontrées en recherche, une mini-chambre à volume variable (MCVV) demeurant étanche grâce à un canal d'eau a été développée pour être utilisée en recherche sur l'entreposage des produits horticoles. Les MCVV ont été utilisées avec succès pour la conservation de courges et de pommes pendant la saison 2000-2001 avec des concentrations de 1.0 à 4.5% d'O_2 et 2.5 à 8.5% de CO_2. Le nouveau système de contrôle a permis de maintenir avec précision les concentrations des gaz dans ces deux types de chambres. Ce système versatile permet d'évaluer les effets de l'AC sur différents fruits et légumes. Contrairement aux systèmes commerciaux, ce système de fabrication domestique peut être modifié à tout moment.

INTRODUCTION

Computer based control has shown to optimize processes and equipment efficiency (Mittal 1997; Landry and Norris 1995). The major advantage of such control systems in research laboratories is the possibility of collecting real time data on stored produce under different CA storage conditions.

Laboratory-scale CA storage facilities have been used by many in research experiments (Lyndall et al. 1997; Lauro et al. 1987; Waelti 1985). Lyndall et al. (1997) developed an open system where gas composition is varied by altering the length and internal diameters of capillary bore glass tubing. The system had very good performance, but lacked the ability to collect data. In addition, open systems such as the latter require the use of large amounts of gas to control the atmosphere. As a result, the system becomes very expensive to operate on long term. Lauro et al. (1987) developed an automated CA system to control gas levels in 30 portable storage containers using a gas analyser and a set of valves controlled via a computer and data acquisition unit. The system was proved to be reliable in providing accurate results with minimum supervision. However, the storage volume was limited due to the rigid containers used in the setup. In the early 1990s, a laboratory-scale CA storage facility was developed using small volume independent rigid mini-chambers (RMC) (Vigneault et al. 1991). This preliminary system was used as a research tool by postharvest physiologists to assess CA storage characteristics of new varieties of fruits and vegetables. Although the performance of the gas control was evaluated and proved to be satisfactory (Vigneault et al. 1991), the system was limited due to non-automated gas sampling and control. An operator was required to manually inject gas samples into the gas analyzer and given the gas concentrations, the operator then had to program the programmable controller unit, which provided the control to open and close the valves. Furthermore, the volume of produce used in experiments with this preliminary system was limited due to the rigid structure of the containers. Therefore, there was a need for more flexible and variable containers with a small to large storage capacity.

The objectives of this part of the study were to: a) design variable volume mini-chambers (VVMC), as an alternative to the common rigid plastic containers; b) design and implement a CA storage research facility with an advanced automated control system; and c) to present an example of the results obtained by this new system using the VVMC.

MATERIALS and METHODS

Research facility

Figure 1 shows a schematic diagram of the research facility, which consists of three refrigerated rooms (20 m^3 each) and a separate room that contains the control unit. The three refrigerated rooms can be maintained at different temperatures. A total of 42 chambers were equally distributed in the three refrigerated rooms to maximize their utilization.

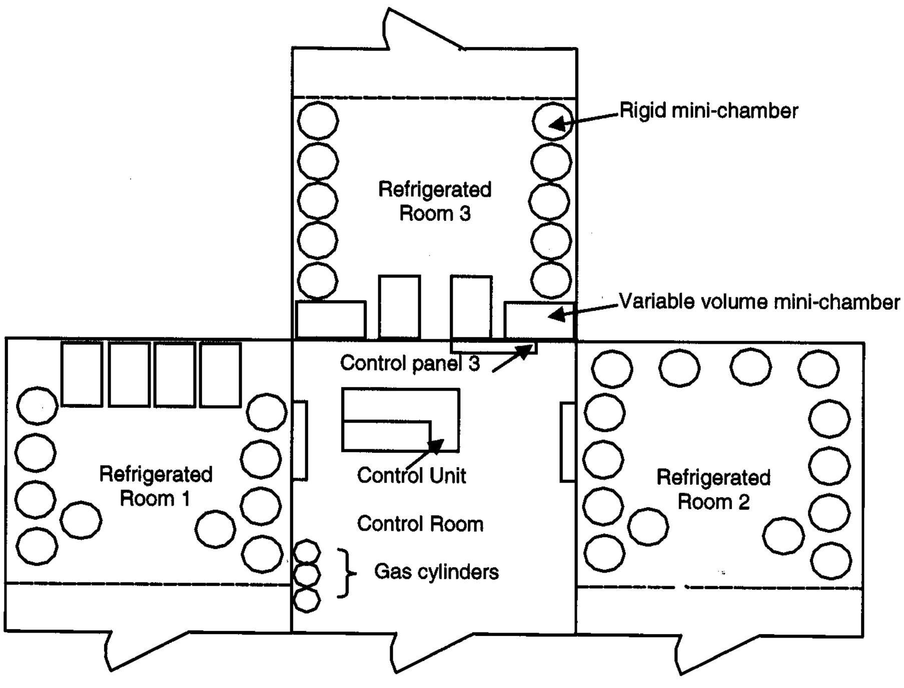

Fig. 1. **Experimental research facility for CA storage at the Horticultural Research and Development Centre of Agriculture and Agri-Food Canada.**

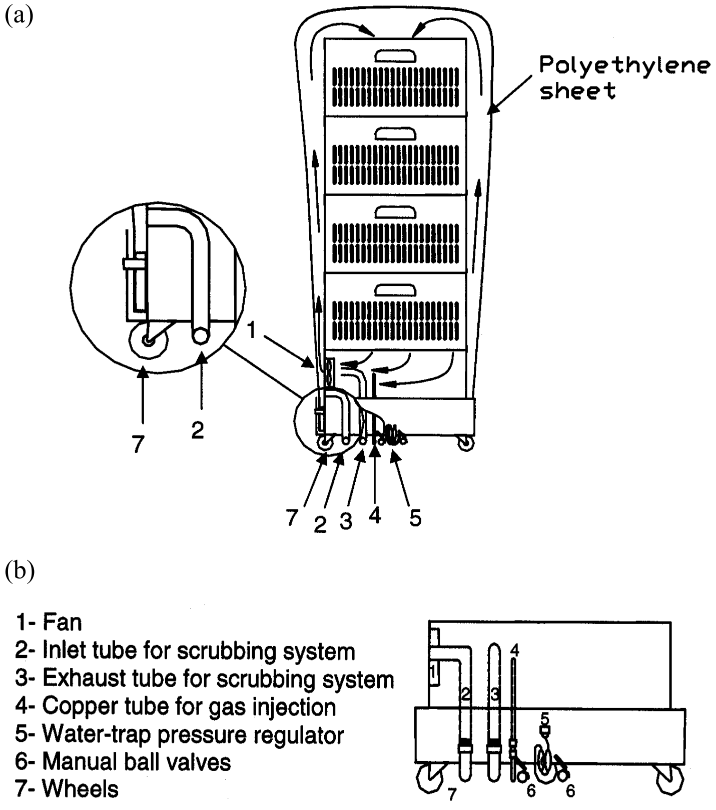

Fig. 2. **VVMC: (a) air circulation pathway with enlargement of the water channel; (b) acrylic base.**

Variable volume mini-chambers (VVMC)

VVMC were designed using the same criteria as the rigid circular plastic containers described by Vigneault et al. (1991). An acrylic base supporting standard stackable plastic containers patented by Vigneault and Émond (1997, 1998) was the starting block for the design of the VVMC. The air circulation pathway and the acrylic base of the VVMC with an enlargement of the water channel are shown in Fig. 2. The number of stacked containers is determined by the desired volume of stored produce and is limited by the refrigerated room height. The stackable containers of produce are covered with a 0.020 mm thick polyethylene sheet (Fig. 2a), with O_2 and CO_2 permeability of 450 and 2355 $\text{mL m}^{-2}\ \text{d}^{-1}\ \text{atm}^{-1}$, respectively, at 10°C (MOCON, Minneapolis, MN). The acrylic base (Fig. 2b), 485 mm in width by 685 mm in length, is composed of 9.5 mm thick acrylic joined with water resistant silicone. The base is divided in two compartments: an inner compartment located at the centre of the base that holds the plumbing and tubing for all connections, and an outer compartment that makes up the water channel (Fig. 2a). Adding water in the channel ensures airtightness of the VVMC. The polyethylene sheet and the acrylic base are held together with a rectangular acrylic strip placed in the water channel. The following components are mounted on the inner compartment of the acrylic base (numbers in parenthesis correspond to those in Fig. 2):

- A 3.11 m^3/min fan (110 VAC) (1), which is placed in proximity of the gas injection (4) and CO_2 scrubbing tubes (2 and 3). The fan moves air downward through the produce mass. The vertical walls of the containers are covered with cellophane, forcing the air to circulate along the sides, towards the top.
- Two tubes, 12.7 mm inside diameter, are connected to a CO_2 scrubber (2 and 3), which enables the absorption of excess CO_2 from the chamber. A solenoid valve activates the scrubbing process. The scrubbers and their performance are described in Vigneault et al. (1991).
- A gas injection copper tube (4), 3.2 mm inside diameter, is used to inject air, N_2, or CO_2 into the chamber. This tube also serves as a gas-sampling inlet. Solenoid valves activate the injection or the sampling process.
- A water-trap pressure-regulator (5) is used to protect the chamber from pressure exceeding 25 mm of water as recommended by Bishop (1990).
- Two drainage ball valves (6), one connected to each compartment of the acrylic base, are used to manually drain water from the base.

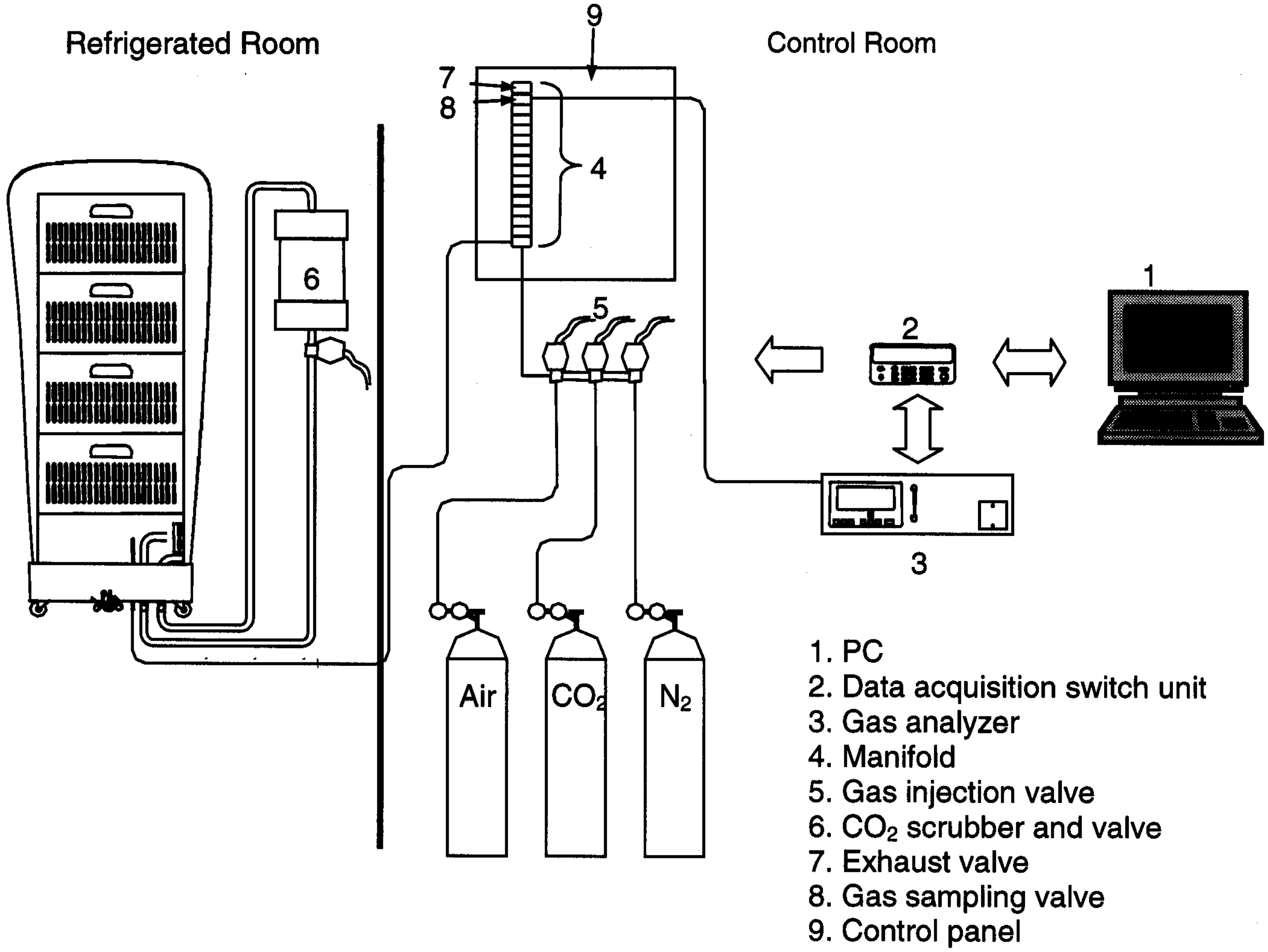

Fig. 3. Control system for a single refrigeration room.

- Wheels (7) are mounted under the base, to provide chamber mobility.
- A thermocouple is placed in each VVMC, to monitor temperature.

Rigid containers require an expansion bag to compensate for atmospheric pressure and temperature variations (Vigneault et al. 1992). As opposed to this, the polyethylene covering the VVMC can expand or deflate to regulate the volume, which prevents air exchange with the exterior.

Control system component description

The control system consists of three main components: Personal computers (PC), data acquisition/switch units (DAQ), and instrumentation to monitor and control the environmental conditions. Figure 3 shows a schematic diagram of the control system for one refrigerated room.

The control of the chambers in each refrigerated room was designed to be independent, with a separate PC, DAQ, and control panel. Therefore, the corresponding system can be shut down in the occurrence of a problem in one room, without disturbing the control of the chambers in the other refrigerated rooms. Two gas analyzers are shared within the three systems. In the detailed descriptions of the control system components that follow, numbers in parenthesis correspond to those in Fig. 3.

PC The PC enables the process control to operate (1). All PCs are Pentium II, running Windows 95^{TM}, interfaced with an HP34970A (Hewlett Packard®, Loveland, CO) DAQ unit using the RS-232 port.

Data acquisition unit The HP34970A DAQ unit (2) features 6.5 digits (22 bits) of resolution, 0.004% basic DCV accuracy, and ultra-low reading noise with a scan rate of up to 250 channels/s. The switch unit allows manual control of the instrumentation, while the HP34970A enables the acquisition of gas and temperature measurements and the control of the instrumentation. Three plug-in modules were used for each HP34970A unit: one 20 channel multiplexer (HP34901A) and two 20 channel actuators (HP34903A) providing a total of 20 channels for thermocouple readings, two channels for analog input, and 40 channels for digital output/input for each refrigerated room. Additional channels were considered for further expansion of the system.

The HP34901A module (Hewlett Packard®, Loveland, CO) is comprised of 20 channels of 300 V switching and two channels for DC or AC current measurements (100 mA to 1 A). It has built-in thermocouple reference junctions enabling direct

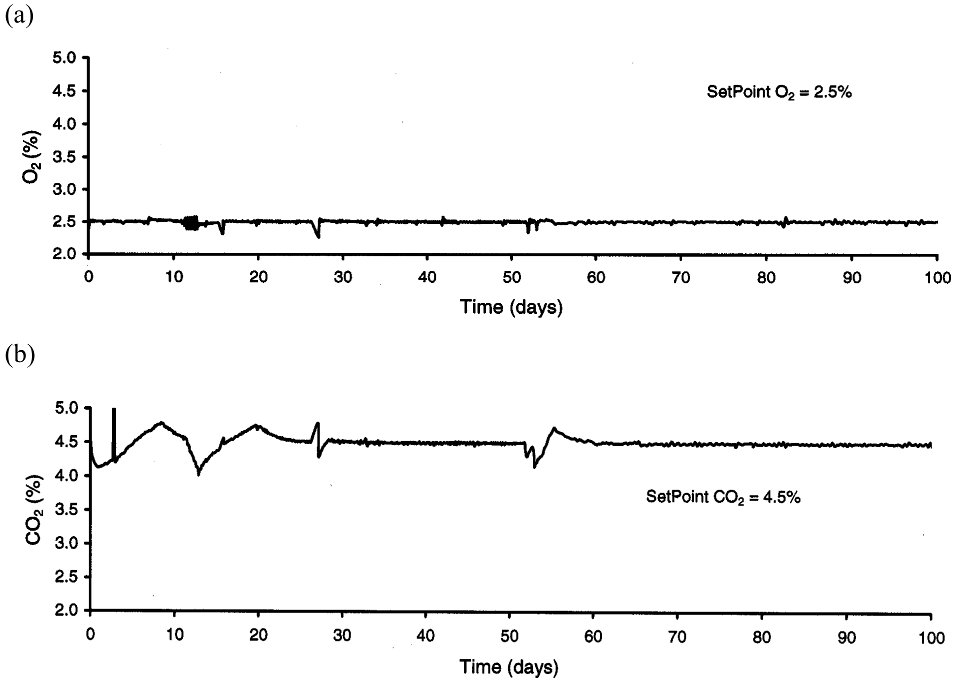

Fig. 4. Gas concentration of O_2 (a) and CO_2 (b) over time for a 285-L VVMC containing apples.

type T thermocouple connections for the 14 chambers within one refrigerated room. Analog outputs for both O_2 and CO_2 concentrations from the gas analyzer (3) are also connected to this module.

The two HP34903A modules (Hewlett Packard®, Loveland, CO) include a 20-channel actuator (300 V, 1 A contacts), which can handle up to 50 W. These cards activate the various solenoid valves used throughout the system: 16 manifold solenoid valves (4), three valves for air, N_2, and CO_2 injection (5), and 14 valves for the CO_2 scrubbing process (6).

Gas analyzer The Siemens Ultramat 23™ (Willer Engineering, Montréal, QC), (120 VAC, 60 Hz) gas analyzer is used to measure the O_2 and CO_2 concentrations in each mini-chamber (3). The range of measurement is 0 to 25% for both gases. Measured readings are sent to the DAQ using a linearized 0 to 20 mA output signal. The gas analyzer and tubing length requires a gas volume of approximately 1.1 L for each analysis.

Valves Two types of ASCO (Emerson, St. Louis, MO) valves are used in the control system: two-way, direct action solenoid valves (model #8262G2 and #8210G94) (120 VAC, 60 Hz, 2.5 W) and three-way, two position (NC) valves with manifold sub-base (4) (model #18900001) (120 VAC, 60 Hz, 2.5 W).

General control process Rapid O_2 pull-down is achieved by manually purging the chamber with pure N_2 gas. Once gas composition is near the desired concentrations, the control software is started to provide automatic control of the system. For each operational chamber, the software communicates with the DAQ to perform gas analysis at preset time intervals. The necessary actions to maintain or control the gas concentrations in each chamber are based on the gas analysis and setpoints. The software sends this control strategy to the DAQ, which executes the control process. Data are collected into files, which are automatically backed up on a daily basis through a network system. Although the whole system is connected to a generator for extra security, the PCs, analyzers, and DAQs are connected to two UPS battery packs (APC, UPC 300, West Kinston, RI). Remote monitoring and control is achieved with PcAnywhere™ (Symantec Inc., Cupertino, CA).

Prior to each gas injection, the exhaust valve (7) is activated to flush the manifold with N_2 gas to prevent residual gas in the line from entering a mini-chamber. Detailed information on the software and controller logic is presented in Markarian et al. (2002).

Performance evaluation

Airtightness A pressure test was used to evaluate the airtightness of each VVMC. The pressure test consisted of setting up an empty VVMC, closing all valves, and subjecting it to a 25 mm of water pressure or vacuum while monitoring the pressure within the chamber for 60 min (Vigneault et al. 1992). This test essentially determines the time required for the pressure to drop to half that of the initial value, $t_{1/2}$. The air temperature was monitored and controlled to within 0.1°C of the initial value to avoid pressure variations due to air temperature fluctuations. An acceptable airtightness of a commercial low O_2 storage room is $t_{1/2} > 30$ min (Bartsch and Blanpied 1984).

Control system The current control system was used for two consecutive storage seasons (1999-2000 and 2000-2001) using different types of fresh produce: apples (DeEll et al. 2000), broccoli (DeEll et al. 2001), winter squash (Bissonnette et al. 2001), and cauliflower (Demian et al. 2000). The first tests (1999-2000) involved only the older RMC, whereas the VVMC were also used to store apples and squash in the second (2000-2001) season, with gas concentrations ranging from 1.0 to 4.5% O_2 and from 2.5 to 8.5% CO_2. The conditions in the chambers, such as the quantity of stored produce per unit volume, time for O_2 pull-down, air circulation, and gas control, were representative of commercial storage rooms.

RESULTS and DISCUSSION

Airtightness

The pressure test demonstrated that the airtightness of the VVMC was sufficient for maintaining constant pressure for >30 min. This airtightness is better than that recommended for ultra-low O_2 storage (Vigneault et al. 1992).

Control system

Although the performance of the control system is analysed in another manuscript (Markarian et al. 2002), an example of control using the VVMC is provided. Figures 4 and 5 show the concentrations of CO_2 and O_2 over time in two typical VVMC: a 285-L holding ‘McIntosh’ apples, and a 500-L holding

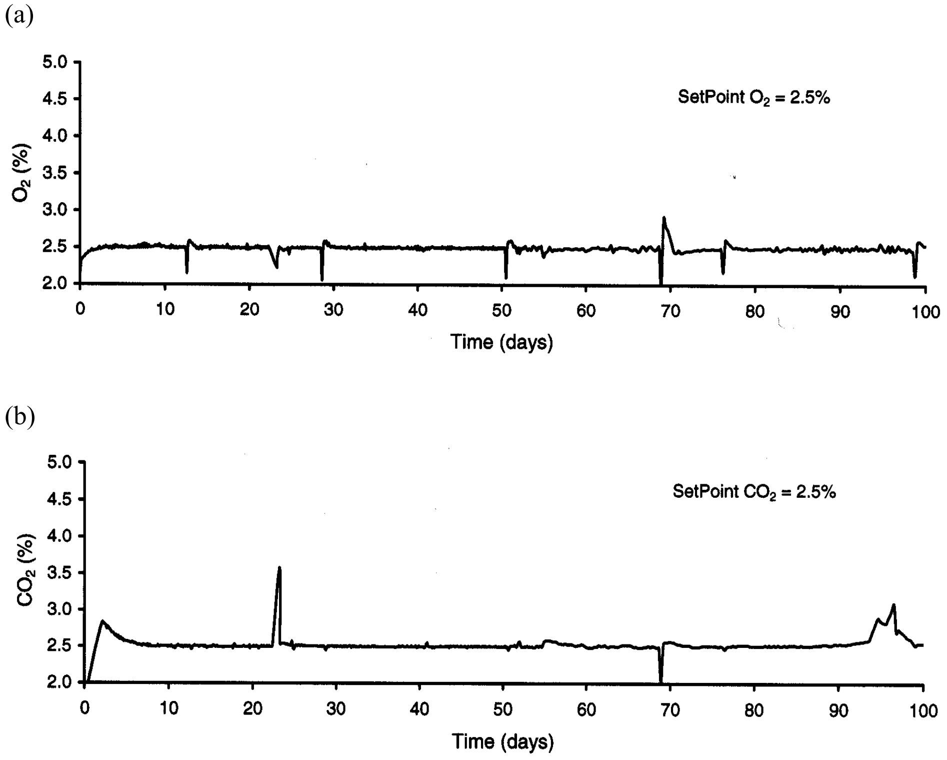

Fig. 5. Gas concentration of O_2 (a) and CO_2 (b) over time for a 500-L VVMC containing apples.

'Spartan' apples. The controller maintained both CO_2 and O_2 gas concentrations very close to the desired setpoints at all times; 4.5% CO_2 and 2.5% O_2 for the 285-L chamber (Fig. 4) and 2.5% CO_2 and 2.5% O_2 for the 500-L chamber (Fig. 5).

Table 1 shows the results from statistical analysis of the variation of CO_2 and O_2 from the setpoint values for the control of these two VVMC. The standard deviations obtained show precise control of the CO_2 and O_2 levels throughout the storage period. The maximal fall and rise of values from the setpoints indicate that acceptable variations of gas concentrations were encountered during the storage period. The small variations encountered were likely due to the electrical calibration of the inputs and reduced scrubber efficiencies over time. The large variations encountered were due to software failures. Due to unknown reasons, occasional software failures were encountered during the storage period, stopping the control process. This resulted in a decrease in O_2 and increase in CO_2 due to produce respiration (Figs. 4 and 5). In each of these cases, the software was restarted to resume the control process. Additional problems that arose were air leaks that resulted in an increase in O_2 and decrease in CO_2. These resulted mainly from tubing connections and improper cover sealing in the case of the RMC. The leaks were investigated and resolved. The control was stabilized subsequently.

Table 1. Results from statistical analysis of CO_2 and O_2 concentration variations from setpoint values in two typical VVMC holding different volumes of apples.

	285-L VVMC		500-L VVMC	
	CO_2 (%)	O_2 (%)	CO_2 (%)	O_2 (%)
Setpoint	4.50	2.50	2.50	2.50
Average[N]	4.50	2.50	2.53	2.50
Standard deviation[N]	0.06	0.02	0.09	0.07
Maximum fall from setpoint	0.49	0.24	0.47	0.53
Maximum rise from setpoint	0.81	0.08	1.08	0.42

[N] Number of samples = 700

CONCLUSION

An advanced, automated CA research facility was designed and implemented. Furthermore, unique VVMC were designed and proven to be adequate for storing fresh produce at different gas concentrations and volumes. Airtightness of these VVMC was better than that recommended for ultra-low O_2 storage. Overall, the control system maintained the gas concentrations in the chambers with a high degree of accuracy during the storage period. Small variations were due to electrical calibration of instruments as well as reduced scrubber efficiencies over time. A few incidences where overnight software failures were encountered resulted in large variations due to system halt. The new control system provided accurate control of these gas concentrations in the chambers. The system offers the versatility required to test the application and consequences of CA storage on different fruits and vegetables. As opposed to commercially available systems for CA storage, this custom-made system has the flexibility to be modified any time.

ACKNOWLEDGMENTS

We thank Sherif Demian, Claudia Beaudry, Yvan Gariépy, and Valérie Bélanger for their assistance during design and construction of the VVMC.

REFERENCES

Bartsch, J.A. and G.D. Blanpied. 1984. Refrigerated and controlled atmosphere storage for horticultural crops. Paper No. NRAES-22. The Northeast Regional Agricultural Engineering Services, Cornell University, Ithaca, NY.

Bishop, D. 1990. Controlled atmosphere storage. In *Cold and Chilled Storage Technology*, ed. C.V.J. Dellino, 66-98. New York, NY: Van Nostrand Reinhold Publisher.

Bissonnette, S., J.R. DeEll, B. Goyette, I. Lemay, D. Roussel, C. Roger and C. Vigneault. 2001. Potentiel de l'entreposage en atmosphère contrôlée pour différentes courges d'hiver. Confidential report presented to Le *potager Mont-Rouge*. Horticultural Research and Development Centre, Agriculture and Agri-Food Canada, St-Jean-sur-Richelieu, QC.

DeEll, J.R., S. Khanizadeh, S. Bissonnette, I. Lemay, D. Roussel and C. Vigneault. 2000. L'amélioration de la fermeté des pommes (McIntosh) du Québec. Confidential report presented to La Fédération des producteurs de Pommes du Québec. Horticultural Research and Development Centre, Agriculture and Agri-Food Canada, St-Jean-sur-Richelieu, QC.

DeEll, J.R., P.M.A Toivenen and C. Vigneault. 2001. Postharvest dips to control black speck and scar discoloration in stored broccoli. *Journal of Food Quality* 24(6):575-584.

Demian, S., J.R. DeEll, D. Roussel, M. Barrette, B. Goyette, S. Bissonnette, C. Beaudry, Y. Gariépy and C. Vigneault. 2000. Controlled atmosphere storage of cauliflower. Confidential report presented to Les Jardins Cousineau et Fils Inc. Horticultural Research and Development Centre Agriculture and Agri-Food Canada, St-Jean-sur-Richelieu, QC.

Landry, J.A. and E. Norris. 1995. Software for the control of vegetable storage environment. *Applied Engineering in Agriculture* 11(3): 453-458.

Lauro, E.M., C.L. Chu and J.D. Wismer. 1987. An integrated gas control and temperature monitoring system for controlled atmosphere storage. CSAE Paper No. 87-406. Mansonville, QC: CSAE/SCGR.

Lyndall, G.S., P.J. Hofman, R.A. Jordan and C. Lee. 1997. An inexpensive, low maintenance, multiple controlled atmosphere system for research on perishable products. *Postharvest Biology and Technology* 11:123-130.

Markarian, N.R., Y. Gariépy and C. Vigneault. 2002. Design of an advanced control system for a CA research storage facility. *Computers and Electronics in Agriculture*. (Submitted)

Mittal, G.S. 1997. Process controls in the food industry: Problems and solutions. In *Computerized Control Systems in the Food Industry*, 1-11. New York, NY: Dekker Marcel Inc.

Vigneault, C. and J.P. Émond. 1997. Contenant réutilisable pour la manutention des fruits et légumes frais. Bureau des brevets Canadians, Ottawa, ON. Brevet no: 1,487,522.

Vigneault, C. and J.P. Émond, 1998. Reusable container for the preservation of fresh fruits and vegetables. United States Patent Application Office, Washington DC. Patent Number: 5,727,711.

Vigneault, C., R.L. Granger and G.S.V. Raghavan. 1991. Mini-chambers for lab-scale research on controlled atmosphere storage. *Applied Engineering in Agriculture* 7(5): 617-621.

Vigneault, C., V. Orsat, B. Panneton and G.S.V. Raghavan. 1992. Oxygen permeability and airtightness measuring method for breathing bags. *Canadian Agricultural Engineering* 34 (2): 183-187.

Waelti, H. 1985. Microprocessor monitoring and controlled atmosphere treefruit storages. *Acta Horticulturae (ISHC)* 157:45-50.