Design procedure for the silicone membrane system used for controlled atmosphere storage of leeks and celery

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[1]*Agricultural Engineering Department, Macdonald College of McGill University, 21,111 Lakeshore Sainte-Anne-de-Bellevue, Quebec, Quebec H9X 1C0;* [2]*Département de génie rural, Université Laval, Sainte-Foy, Québec G1K 7P4; and* [3]*Research Institute, Research Branch, Agriculture Canada, Building 74, Ottawa, Ontario K1A 0C6.* *Contribution no. I-862, from the Engineering and Statistical Research Centre, Research Branch, Agriculture Canada, Ottawa, Ont. K1A 0C6. Received 19 November 1986, accepted 28 April 1988.*

Gariépy, Y., G. S. V. Raghavan, R. Thériault, and J. A. Munroe. 1988. **Design procedure for the silicone membrane system used for controlled atmosphere storage of leeks and celery**. Can. Agric. Eng. 30: 231–236. The silicone membrane is used to control the atmospheric composition in fruit and vegetable storage. This is done through two simultaneous processes: selective membrane permeability and product respiration. The best controlled atmospheric compositions for long-term storage of leeks and celery grown in Canada were determined using the silicone membrane installed as a window on laboratory scale chambers. Various atmospheric compositions were obtained using different window surface areas. A new design procedure, based on parametric relationships, is suggested for selecting the silicone membrane area for long-term CA storage of leeks and celery.

INTRODUCTION

The aim of storage is to extend the period of availability of freshly harvested products by preserving them in their most usable form for consumers and processing industries. Low temperature with regular atmosphere storage (RA), low temperature with regular atmosphere and high relative humidity storage (HRA), and low temperature with high relative humidity and controlled atmosphere storage (CA) are the most common methods used to maintain the quality of fresh fruits and vegetables. In CA, the oxygen (O_2) is generally decreased and the carbon dioxide (CO_2) increased. At the present time, many types of CA systems are available for commercial storage of fresh fruits and vegetables (Raghavan and Gariépy 1985; Smock 1979). For one, the silicone membrane system (SMS) allows gases to diffuse at different rates according to their chemical and physical properties. In the SMS the CA composition is obtained through two simultaneous processes: produce respiration and membrane permeation. Results of ongoing experiments at Macdonald College demonstrated that cabbage, leeks, celery and rutabaga can benefit from CA for long-term storage (Gariépy et al. 1984, 1985, 1986; Plasse and Raghavan 1983; Raghavan et al. 1984). In these studies, CA conditions were achieved and maintained with relative humidity close to saturation using the silicone membrane installed in a window fashion on the experimental chambers. Other researchers have reported on the utilization of CA to improve the keeping quality of celery (e.g., Smith 1983) and leeks (e.g., Baugerod 1980; Isenberg 1979).

The first part of this paper reports on the various applications of the silicone membrane for modified and controlled storage. Research results on the CO_2 and O_2 relation for leeks and celery storage, as well as how they relate to the ratio of membrane surface area to product mass (A/M), are presented in the second part.

THE SILICONE MEMBRANE SYSTEMS

The silicone membrane

The silicone membrane consists of fine Tergal net (52–54 g/m^2) covered with a thin (about 90 μm) and uniform layer of silicone rubber (dimethylpolysiloxane). At one atmosphere, its permeabilities to CO_2, O_2 and C_2H_4 are respectively, 1750, 320 and 700 L/d-m^2-Atm. At a given temperature, the amount of gas diffusing through the silicone membrane will depend on the membrane surface area, its permeability and the gas partial pressure difference across the membrane.

Commercial CA storage systems that utilize the silicone membrane are: the Pallet Package, the Marcellin and the Atmolysair systems. Although commercially utilized in many European countries, the silicone membrane systems are rarely used in North America.

The pallet package system

The first commercial application of the silicone membrane for long-term storage of fresh produce, "The Pallet Package System", was developed by Marcellin (1978). This system consists of a pallet box wrapped in a heavy gauge polyethylene bag with a silicone membrane window installed to regulate gas exchange (Fig. 1). The advantages of this system are ease of manipulation and the possibility of marketing the stored produce progressively without affecting the atmosphere in the remaining pallet boxes. However, in order to work efficiently, the pallets need to be well spaced, thereby reducing the capacity of the storage room. Other disadvantages of this system are the amount of work required to wrap and unwrap each pallet and the special care required in handling the boxes. Although this application was initially developed for long-term storage of fruit, its limitations made it more suitable for short and medium term storage and for produce in transit.

The Marcellin system

The Marcellin system (Fig. 2) regulates the CA condition in a storage room with a series of rectangular bags of silicone rubber connected in parallel (Marcellin and Leteinturier 1966, 1967). The number of bags on the unit depends on the size of the cold

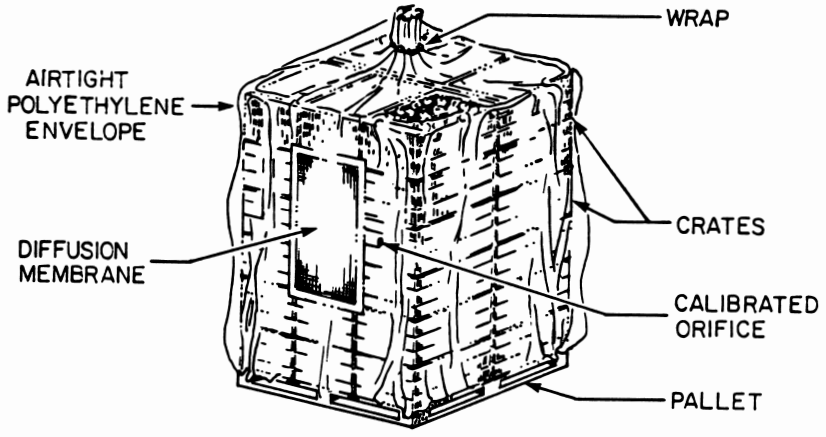

Figure 1. Diagram of the Pallet Package System for CA storage.

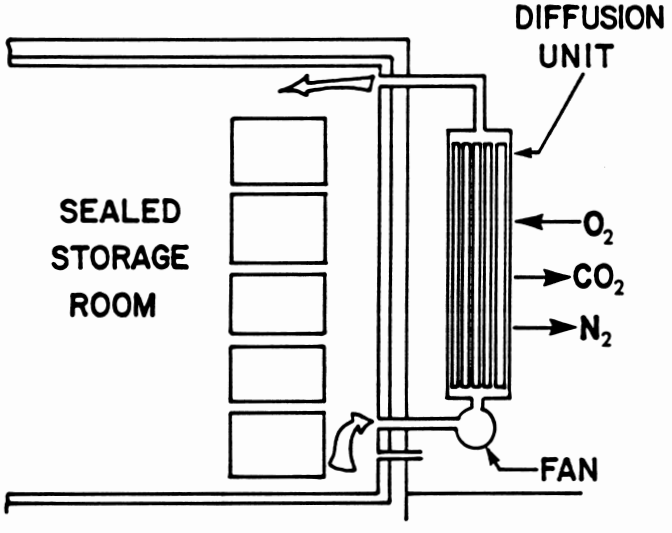

Figure 2. Diagram of the Marcellin System for CA storage.

room, the storage temperature, and the type of produce stored. Analysis of the CA composition will indicate whether or not more bags should be used. To maintain an atmosphere of 3% CO_2 and 3% O_2, 50 m^2 of silicone membrane is required per 100 t of fruit at a bulk density of 200 to 250 kg/m^3. These units can be installed inside or outside the cold room (Guertin 1979).

The Atmolysair system

A modified version of the Marcellin system has been developed in Canada by Atmolysair Ltd. (Fig. 3). The unit consists of gas diffusion panels enclosed in an airtight metallic container with two separate air flow paths and a control board (Raghavan et al. 1984). The gas diffusion panels are made of square frames in which the silicone membrane is fixed. They are banked side by side in an airtight arrangement so that the outside air and the CA flow on opposite sides of the membrane without direct mixing. The air circulation is maintained by centrifugal blowers operated by a timer. The main advantages of this system over the Marcellin system are its ease of management and its potential for complete automation.

The procedure to calculate the membrane surface area required to maintain the desired CA composition is described in Raghavan et al. (1982) and can be summarized by the following equation:

$$\text{AREA} = \frac{RR \times M}{P_{CO2} \times CO_2} \quad (1)$$

where:

Area = silicone membrane surface area (m^2);
P_{CO2} = permeability of the silicone membrane to CO_2 (1750 L/d-m^2-Atm.);
RR = respiration rate of the product stored under CA (L of CO_2/kg-d);
CO_2 = desired CO_2 partial pressure difference across the membrane (Atm); and
M = mass of stored produce (kg).

When the RR of the produce stored under the desired CA is not known, it is estimated as 60–70% of its value under normal air composition, at the same temperature. Although it seems relatively simple to determine the required membrane area, this equation has two limitations. Firstly, the *RR* and respiratory quotient (*RQ*, volumetric ratio of the CO_2 produced to the O_2 consumed of the stored produce) of many commodities stored under CA are rarely available; and secondly, the equation does not consider the amount of O_2 consumed by the stored produce nor the level of O_2 to be maintained. For these reasons, new design procedures were derived from the data gathered from CA storage experiment on leeks and celery.

MATERIALS AND METHODS

Two sets of experiments were performed to assess the suitability of the silicone membrane system for long-term CA storage of locally grown leeks (*Allium porrum* L. cv. Alaska) and celery (*Apium graveolens* cv. Clean Cut). In this paper, they will be respectively referred as Alaska leeks and Clean Cut celery.

The chambers used in these experiments were made of sections of PVC pipe, 500 mm long and 250 mm in diameter (Fig. 4). The ends of each unit were closed with a square lid of clear acrylic, 6 mm thick, and held in place with six threaded rods. Neoprene gaskets were used on both ends to ensure near perfect airtightness. The silicone membrane was installed on the lid in a window-like fashion. The advantages of this design were: (i) Durability; (ii) Ease of construction; (iii) Near perfect airtightness; (iv) Quick and simple opening and closing procedures; (v) Possibility for visual assessment of the product during storage; (vi) Low maintenance requirement; and (vii) Ease of stacking.

The Alaska leeks were stored under four different CA compositions for 133 d and the Clean Cut celery under three dif-

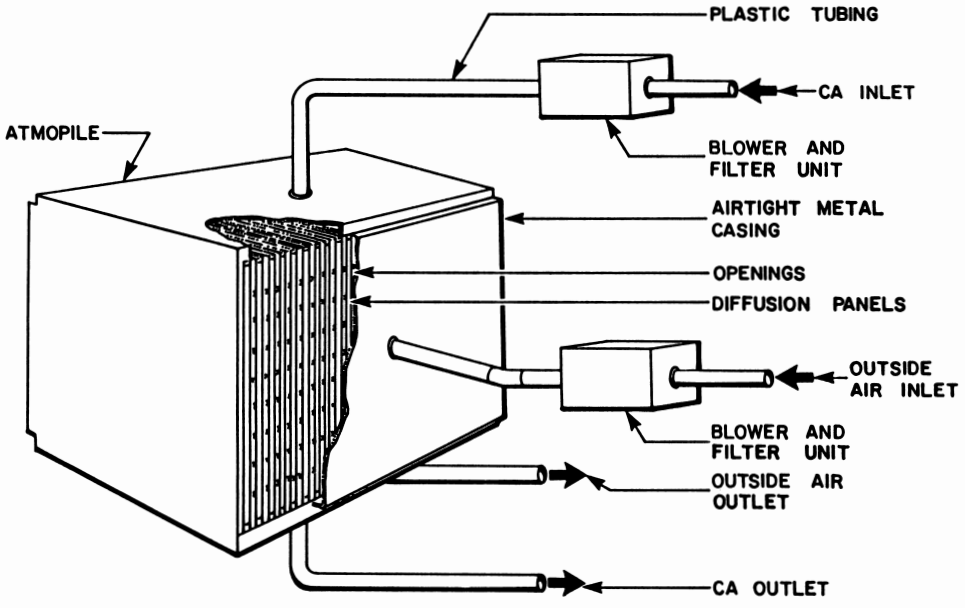

Figure 3. Diagram of the Atmolysair System for CA storage.

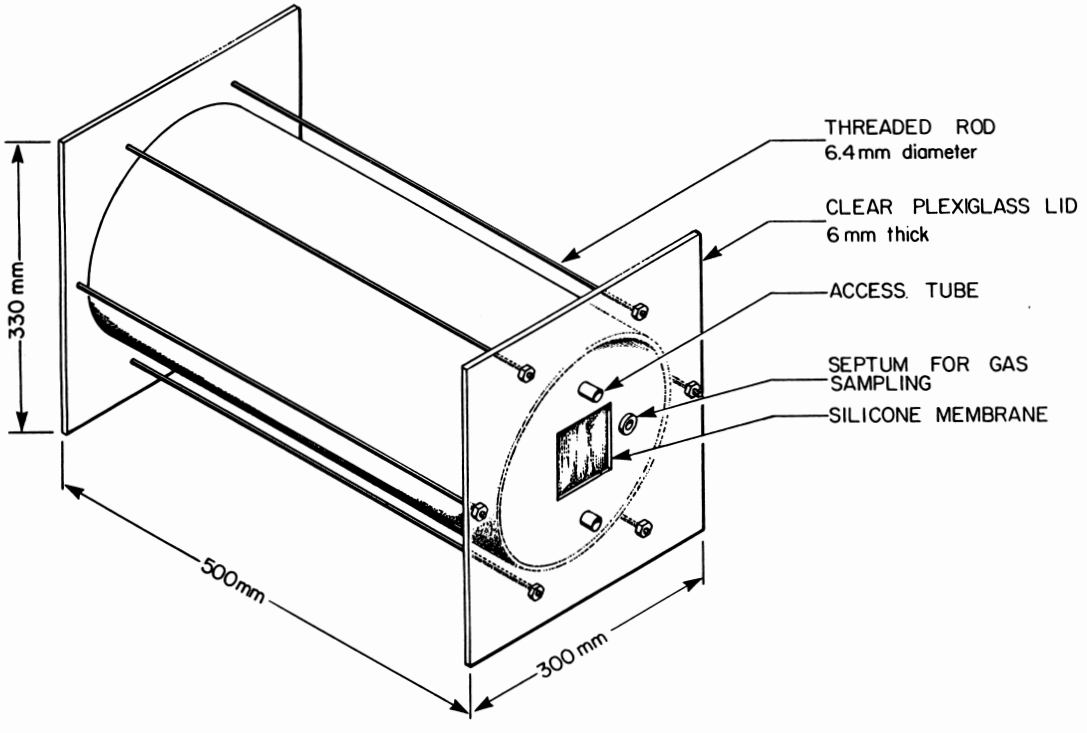

Figure 4. Diagram of the experimental chamber used to study the storability of locally grown leeks and celery under different CA conditions.

ferent CA compositions for 71 d (Table I). The membrane surface area required to maintain the design level of CO_2 was calculated using Eq. 1. The experiments were laid out according to a completely randomized statistical design in which each CO_2 level was replicated four times. For the complete duration of the experiments, the CA compositions were analyzed by gas chromatography.

RESULTS AND DISCUSSIONS

For both products studied, the progression of the CO_2 and O_2 concentrations followed a trend characteristic of the SMS and the levels maintained in the CA chambers depended on the membrane surface area. Figure 5 shows the progression of the CO_2 and O_2 concentrations in a chamber equipped with the silicone membrane. Additional information on the quality and physiological aspects are available in Gariépy and Raghavan (1983, 1985, 1986), and Gariépy et al. (1984, 1985, 1986).

For each product studied, a plot of the mean CO_2 and O_2 concentrations maintained in each CA chamber was obtained by integrating the gas concentration curve over the complete

Table I. Design parameters for the CA storage experiments on Alaska leeks and Clean Cut celery with the silicone membrane system

Vegetable, cultivar	Initial mass (kg)	Treatment	Designed CO_2 level (%)	Membrane area (cm^2)	Storage length (d)
Leeks, Alaska	3.5	A	3.0	130	133
		B	4.5	91	133
		C	6.0	70	133
		D	9.0	36	145
Celery, Clean Cut	6.0	A	1.5	182	71
		B	3.5	75	71
		C	5.5	49	71

storage period (Figs. 6 and 7). These values were then plotted against their respective A/M ratio (Figs. 8 to 11). For the range studied, the relationship between A/M and CO_2 was found to be similar to that of O_2 and CO_2, while A/M appeared to be linearly related to O_2. The best fit curve equations were obtained from the regression analyses performed on the data using the following statistical models:

For the O_2:CO_2 and A/M:CO_2 relationships:

$$Y = a + b \times X^{-1} + c \times X^{-2} + d \times X^{-3} + e \times \ln(x) \quad (2)$$

For the A/M:O_2 relationship:

$$Y = a + b \times X \quad (3)$$

In these models, Y is the dependent variable (O_2 or A/M), X is the independent variable (CO_2 or O_2) and a,b,c,d, and e are the regression parameters. Results of the analyses are summarized in Tables II and III.

These graphs and equations can be used: (i) To estimate the required silicone membrane surface area to maintain a desired level of CO_2; and (ii) To obtain an estimate of the matching O_2 concentrations. For example, CA storage of Alaska leeks at 5% CO_2, in a storage facility equipped with the silicone membrane system, will require 1.15 m^2 of membrane per tonne of product and the O_2 concentrations maintained in the storage should be approximately 2.5%. These procedures also allow the user to obtain the required silicone membrane area from the desired O_2 concentrations. This was not possible with Eq. 1. One of the most promising applications of the CO_2:O_2 regression model is as a part of a computer program designed for the automatic control of silicone membrane systems such as the Atmolysair unit. The model could be used to predict gas concentrations and to determine the magnitude of the change in time of operation of the unit.

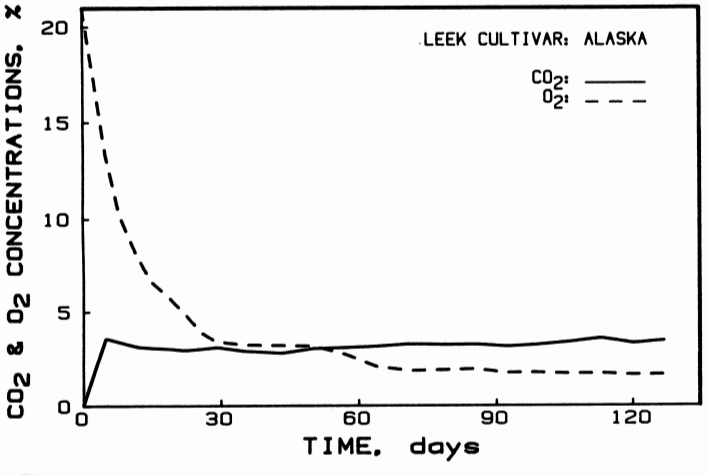

Figure 5. Progression of the CO_2 and O_2 concentrations in a chamber containing Alaska leeks. This chamber was designed to maintain 4.5% CO_2.

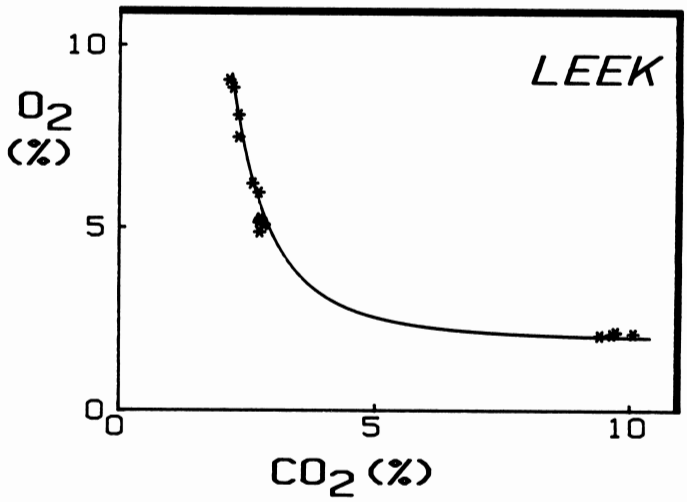

Figure 6. Mean CO_2 and O_2 concentrations maintained in each of the 16 CA chambers during the CA storage experiment with Alaska leeks. The best fit curve equation is:
$\%O_2 = 1.92 + 77.7 \times (\%CO_2)^{-3}$.

Disadvantages of the new procedure are: (i) It has to be obtained through experimentation; and (ii) Its utilization is limited to the range for which it has been established.

It was also observed that factors such as: cultivar, level of prestorage preparation, growing location and prestorage chemical treatments did affect the gas concentrations maintained in the chambers. However, the CO_2:O_2 combinations observed remained very close to the regression model. More research is required to better understand these phenomena and to broaden the range over which the models can be applied.

CONCLUSIONS

The silicone membrane system was found suitable for long-

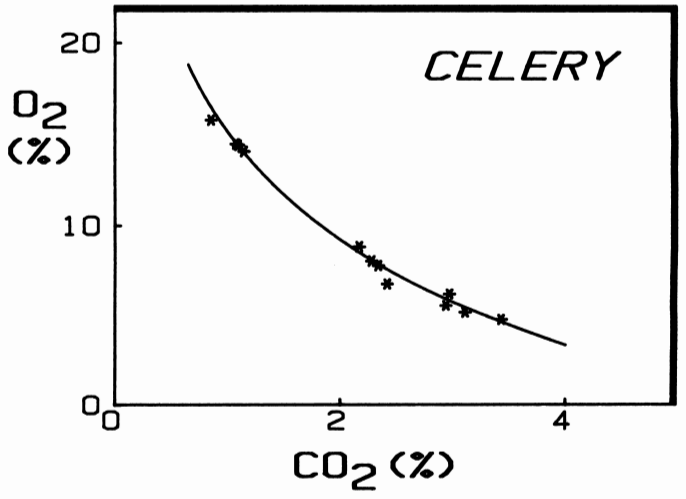

Figure 7. Mean CO_2 and O_2 concentrations maintained in each of the 12 CA chambers during the CA storage experiment with Clean Cut celery. The best fit curve equation is:
$\%O_2 = 15.1 - 8.53 \times \ln(\%CO_2)$.

Table II. Results from the regression analyses performed on the O_2:CO_2 and A/M:CO_2 data from the experiments on CA storage of leeks and celery with the silicone membrane system. The statistical model used for the analyses was:
$Y = a + b \times X^{-1} + c \times X^{-2} + d \times X^{-3} + e \times \ln(X)$

Vegetable, cultivar	Variables		Regression parameters						
	Y	*X*	*a*	*b*	*c*	*d*	*e*	R^2	*Pr>F*
Leeks,	O_2	CO_2	1.92	0	0	77.7	0	0.9852	0.0001
Alaska	A/M	CO_2	9.11	0	0	325.0	0	0.9295	0.0001
Celery,	O_2	CO_2	15.1	0	0	0	− 8.53	0.9926	0.0001
Clean Cut	A/M	CO_2	31.8	0	0	0	−21.2	0.9749	0.0001

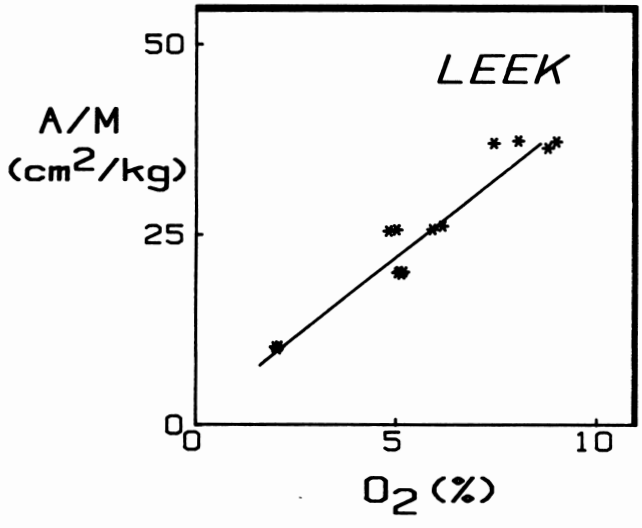

Figure 8. Membrane requirement per unit mass of leeks as a function of the mean O_2 concentration. The best fit curve equation is: A/M = 1.1 + 0.42 × %O_2.

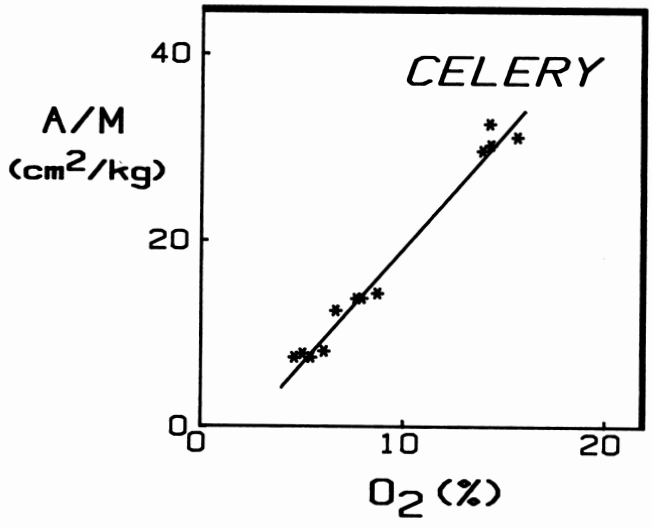

Figure 10. Membrane requirement per unit mass of celery as a function of the mean O_2 concentration. The best fit curve equation is: A/M = −5.8 + 2.5 × %O_2.

term CA storage of many vegetables grown in Canada. It was demonstrated that only limited combinations of CO_2 and O_2 concentrations can be achieved with the studied system. Nevertheless these combinations were found suitable for long-term storage of domestically produced leeks and celery. As a result, new procedures have been derived for the design of the silicone membrane system for long-term storage of leeks and celery. With the new parametric relations, the design of the silicone membrane system can be based on either the desired O_2 or CO_2 concentrations.

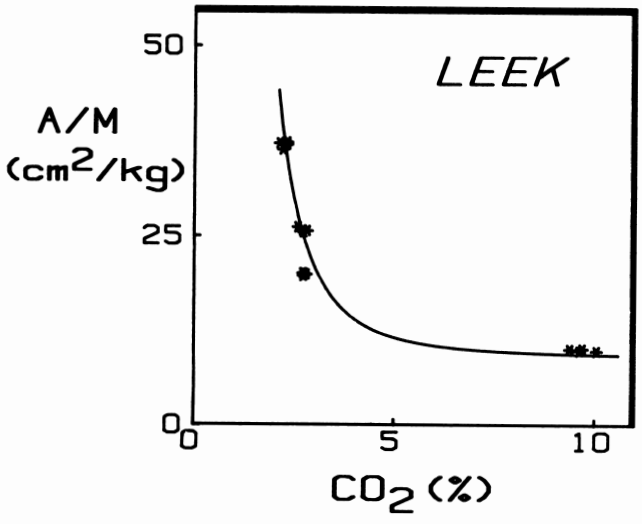

Figure 9. Membrane requirement per unit mass of leeks as a function of the mean CO_2 concentration. The best fit curve equation is: A/M = 9.11 + 325 × (%CO_2)$^{-3}$.

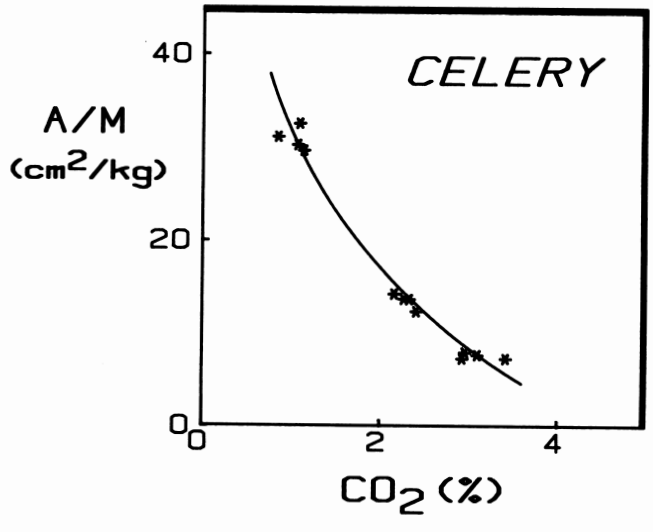

Figure 11. Membrane requirement per unit mass of celery as a function of the mean CO_2 concentration. The best fit curve equation is: A/M = 31.8 − 21.2 × ln (%CO_2).

Table III. Results from the regression analyses performed on the A/M:O_2 data from the experiments on CA storage of leeks and celery with the silicone membrane system. The statistical model used for the analyses was: $Y = a + b \times X$

Vegetable, cultivar	Variables		Regression parameters			
	Y	X	a	b	R^2	$Pr>F$
Leeks, Alaska	A/M	O_2	1.1	4.2	0.9619	0.0001
Celery, Clean Cut	A/M	O_2	−5.8	2.5	0.9802	0.0001

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