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Techniques for controlled atmosphere storage of fruits and vegetables

Canada

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Techniques for controlled atmosphere storage of fruits and vegetables

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CONTENTS

SUMMARY

This report outlines the various parameters affecting the choice of a system for establishing and maintaining optimum conditions for storage of a particular horticultural crop. Two categories of gas control are reviewed: 1) oxygen control systems, and 2) carbon dioxide control systems. Ethylene removal is also described, but the existing systems permit only a limited control of this gas and are not yet economical. The most promising systems for gas control are those that can control the levels of more than one gas such as the pressure swing absorption and hollow fiber membrane separator systems.

INTRODUCTION

Controlled atmosphere (CA) storage is, by definition, the addition or removal of gases resulting in an atmospheric composition around the commodity that is different from ambient air (78.08% N_2, 20.95% O_2, 0.03% CO_2) (Kader 1992). In most CA storages there is a reduction of O_2 and/or increase in CO_2 concentrations.The CA technique has been successful in extending the storage life of apples, pears, cabbages, kiwi fruits, berry crops, stone fruits, bananas, nuts, and dried fruits and holds promise for extended storage of other commodities. Application of CA technology in some cases can extend the storage life to cover a harvest-to-harvest cycle of 9–12 months.

Respiration of plant material is slowed by reducing the O_2 and increasing the CO_2 in the storage atmosphere, thereby slowing internal consumption and transformation of organic compounds within the commodity. In addition, CA storage can control the evolution of ethylene, an initiator of ripening. Some advantages of refrigerated CA storage and high relative humidity, are 1) reduction of respiration and transpiration rates, 2) prevention of chlorophyll degradation, 3) retardation of softening and firmness retention, 4) reduction of bacterial and fungal infections (Bohling et al. 1977, Smock 1979), and 5) lower refrigeration costs because of reduced respiration and heat evolution.

Controlled atmosphere storage systems, with low levels of oxygen, can be dangerous if not well understood and carefully managed. Low oxygen levels in the atmosphere are hazardous to human and animal life.

This report describes current controlled atmosphere technology, system design factors and methods for providing the proper atmosphere.

CA STORAGE DESIGN FACTORS

When designing a new CA storage room and selecting appropriate control systems, several factors should be considered: 1) structural design of the storage room, 2) standard free volume, 3) infiltration rate, and 4) desired CA composition and the period allowed to establish CA (Bartsch and Blanpied 1990, Bishop 1990).

Structural design of the storage room

A CA room is essentially an airtight conventional cold-storage room. Construction and insulation materials are subject to construction costs, stability under windy conditions, ease in maintaining airtightness as well as building and fire safety regulations (ASHRAE 1986). Concrete blocks with sealed metal sheathing on inside walls for airtightness, tilt-up concrete walls, metal-faced insulated panels that are locked together and taped, and wood frame or metal quonset with at least two layers of foamed-in-place polyurethane insulation providing an air and vapour barrier can provide effective CA storages (Bishop 1990). Concrete or metal quonset structures are the most stable under windy conditions and the least susceptible to air infiltration. Construction with concrete blocks is generally the most expensive whereas wood frame is the least expensive. Minimum insulation requirements are 4.6 m^2 °C W^{-1} in the ceiling, 4.2 m^2 °C W^{-1} in the walls, and 2.3 m^2 °C W^{-1} in the floors (ASHRAE 1986).

The door is an important part of the room construction since it can be a major source of air leakage and heat penetration. The door can be a sliding type with a high insulation factor and an airtight gasket system or a lightweight panel held over the door opening with tension-adjustable hooks. Ideally, there should be only one door into the room, to prevent air infiltration and to avoid the risk of accidental suffocation of employees. A double- or triple-glazed removeable viewing window at ground level or at ceiling height may be necessary for viewing or reach-in access to the product. Ceiling windows are advantageous as more product is visible and expansion coils and the refrigeration fans can be visually monitored. A fixed acrylic dome window will enhance the field of view. Various gaskets and sealing compounds are available for sealing the perimeters of the door and window. Petroleum jelly is economical, odorless, and effective for sealing doors as well as plugging small air leaks.

A safe and effective product sampling system can be constructed using a sloped PVC sewer pipe running along an inner wall, exiting through a sealed opening to the outside, and sealed with a threaded cap on the end. The pipe is loaded with sufficient product before the room is sealed and sampling is done simply by removing the external threaded cap and allowing a sample of the product to roll out. This system can be modified to suit individual differences in fruit size and sampling requirements. Product samples placed in mesh bags before room sealing can also be sampled through a resealable opening in the door or ceiling using a long-handled gaffe.

CA room size is an important consideration and should be determined by 1) the anticipated volume of produce requiring CA storage, 2) the marketing period for the product once the room is opened, 3) the ability of the operator to fill the room rapidly at harvest (two days or less), 4) the temperature and humidity compatibility of all the cultivars and products being stored, and 5) the potential economic return. Experience has shown that total storage capacity should be divided into as many rooms as can be justified economically. Smaller rooms allow for the greatest flexibility in filling at harvest, opening of rooms, and flexibility in storage conditions.

Since CA can substantially extend storage time, product weight loss caused by excessive moisture loss can be a problem. Moisture loss is accelerated by improper air circulation, which creates a temperature differential between the air and room surface. Condensation on cold ceilings, walls, and cooling unit, or infiltration of low-humidity air decreases humidity and increases moisture loss. Product moisture retention can be achieved by consideration of the following points:

1) The product should be held at the lowest acceptable temperature. Low temperature reduces the product's potential for moisture loss but does not freeze it.

2) The temperature differential between the warmest surface (product surface) and the coolest surface (cooling unit) should be as small as possible. Small temperature differential can be achieved by a) ensuring that the cooling units have the maximum surface area possible. Large surfaces reduce both the condensation of moisture and the need for cooling unit defrosting; b) the use of plastic sheets on top of the bins in front of the discharge to direct cold air from the coils to the back of the room; and c) properly align bins so that return air flows uniformly through the product while returning to the cooling unit.

3) The frequency of refrigeration and fan operation should be reduced as much as possible after the room temperature has been stabilized, since the cooling unit removes moisture and associated fans add heat to the room. Fans can be set to run periodically, even when the refrigeration system is turned off, thereby maintaining a uniform room temperature and atmosphere and also assisting in coil defrosting.

4) The moisture drained off the cooling unit, should not be drained from the room but allowed to run onto the floor where it can remoisturize the air.

5) Wooden bins should be pre-soaked in water to increase humidification of the storage room atmosphere; water can be placed on the floor before the room is sealed; or humidifier nozzles can be placed in front of the fans in the cooling unit. Humidification of the storage atmosphere must not lead to surface condensation on the produce as this will increase quality loss.

Standard free volume

The standard free volume is the volume of the storage enclosure not occupied by the commodity and containers. The free volume is usually expressed as a standard free volume (volume of air in the storage per volume of commodity) and in many warehouses varies from 1.5 to 3.0 m^3 of gases per cubic metre of commodity. Bulk as opposed to crated storage, commodity shape and density, room geometry, and commodity stacking arrangement all affect standard free volume.

Infiltration rate

The efficiency of a CA storage room is determined by its airtightness. Air infiltration into the storage room results from construction flaws, barometric pressure fluctuations, wind, and temperature gradients between the storage room and surroundings (Bartsch and Blanpied 1990). Infiltration caused by barometric fluctuations can be minimized by connecting a breather bag with a capacity of 1.5% of the total room volume to the room. When barometric pressure drops, the bag inflates with CA expelled from the room and when the pressure increases, this CA returns to the room.

The water trap provides pressure relief to barometric changes but allows external air into the room when negative room pressures develop. A pipe from the storage room is placed in 12 mm of water, thus allowing for a pressure difference of up to 250 Pa or 25 mm of water (Bishop 1990). A two-way mechanical pressure-relief valve could be substituted for the water trap.

Each room should be tested for airtightness before it is filled with product. Airtightness can be checked in the following manner. Seal all openings and attach a pressure gauge to the system, then pressurize the room up to 250 Pa (25 mm water) with an air fan or vacuum cleaner outlet. Do not exceed this pressure as it can cause structural damage. Monitor the time for the pressure to drop to half the initial value. The lower the desired oxygen level in the room, the more airtight the room should be. For 1% oxygen the time should be close to 30 minutes and for 3% oxygen 20 minutes is acceptable (Bartsch and Blanpied 1990).

If the room is not airtight enough, leaks can be detected by placing a smoke machine inside the room and repeating the pressurization step. Smoke will exit with the air leaks, which can then be sealed with any acceptable sealant. If the room requires extensive sealing it might be better to coat the entire interior surface with an elastomeric coating or 2-m wide nylon-reinforced Hypalon sheets (Waelti and Bartsch 1990).

Optimum CA composition and the period to establish CA conditions

Respiration involves the oxidative breakdown of organic compounds such as sugars. The main products are CO_2, H_2O, and energy. The respiration rate of a commodity is influenced by physiological age, presence or absence of injury or disease, and temperature and atmospheric composition.

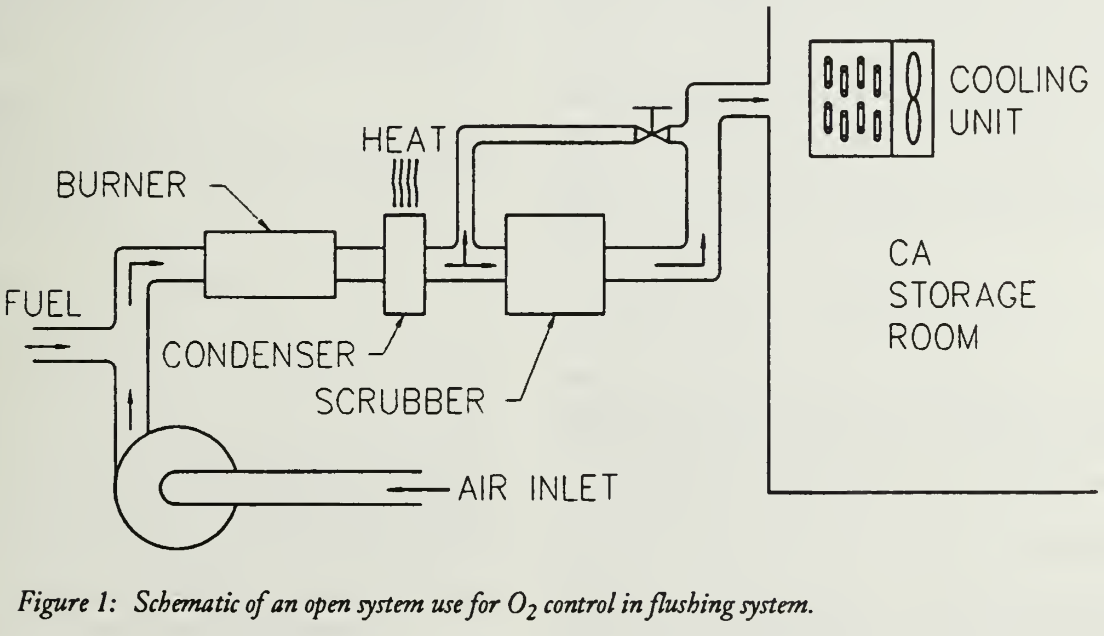

Figure 1: Schematic of an open system use for O_2 control in flushing system.

The choice of a CA control system and its management depends on the atmospheres required and rate of atmosphere establishment. Postharvest technologies that extend storage life are successful because they reduce product respiration, primarily by lower temperatures. Additional benefits of CA result primarily from oxygen reduction. CA can be improved by using a rapid oxygen pull-down on apples. Sharples and Munoz (1974) found that a pull-down exceeding 7 days resulted in significantly poorer results for Cox's Orange Pippin apples. Lau (1983) obtained better quality of Golden Delicious and McIntosh apples stored in rapid CA (2.5% O_2 within 2 or 3 days after sealing the room) compared to a slow pull-down of 20 days. Additional benefits may also be obtained for other CA-stored products. If the desired level of oxygen is to be as low as 1–2%, then the most efficient CA system possible should be considered. Higher oxygen levels and less-critical pull-down times could be served by less-efficient CA systems.

For large storage rooms, the desired low oxygen level is not achieved solely with external oxygen removal systems. Product respiration should be used for the final stages of oxygen pull-down and for elevating the carbon dioxide content.

The choice of a CA control system must also take into consideration carbon dioxide scrubbing requirements. High carbon dioxide levels can cause injury in many varieties of fruits (Lidster et al. 1990) and the CA storage system should, therefore, be able to remove carbon dioxide. Low oxygen levels can cause injury in many stored products (Lidster et al. 1990) but oxygen depletion is overcome by opening small vents into the room.

OXYGEN CONTROL SYSTEMS

If product respiration does not reduce the oxygen level fast enough then one of the following methods should be considered: 1) external burners, 2) liquid or gaseous nitrogen, and 3) gas separator systems.

External burners

External burners have been used for many years for oxygen pull-down. They remove the oxygen through combustion of propane or natural gas to produce a mixture of carbon dioxide and water vapor, which is fed to the storage room. There are two types of burners:

1) The open flame burner uses outside air as the air supply and releases the low oxygen exhaust into the CA room. The air could be recirculated but low oxygen air does not easily maintain a flame. In Figure 1, air is mixed with a hydrocarbon fuel and burned by an open flame. The exhaust gas is cooled by a water spray and blown into the storage room.

2) The catalytic burner is usually preferred because it allows for continuous complete combustion with a catalyst, bringing the O_2 level as low as 3%.

External burners are inexpensive but pose an explosion hazard from the combustion process. Disadvantages are production of large quantities of carbon dioxide and ethylene and an effluent gas that is hot requiring scrubbing and cooling.

Liquid or gaseous nitrogen

Liquid or gaseous nitrogen are also effective means for establishing rapid CA conditions. The quantity of N_2 required to bring the O_2 level down is a function of the desired O_2 concentration and the standard free volume of the storage room (Figure 2). Liquid nitrogen is

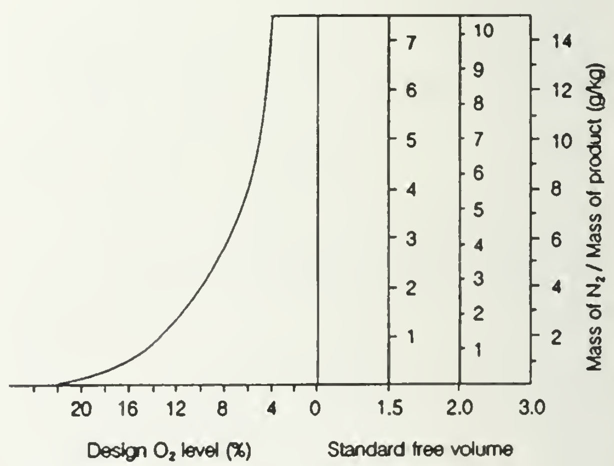

Figure 2: Quantity of N_2 required for O_2 flushing as a function of the desired final O_2 concentration and the standard free volume.

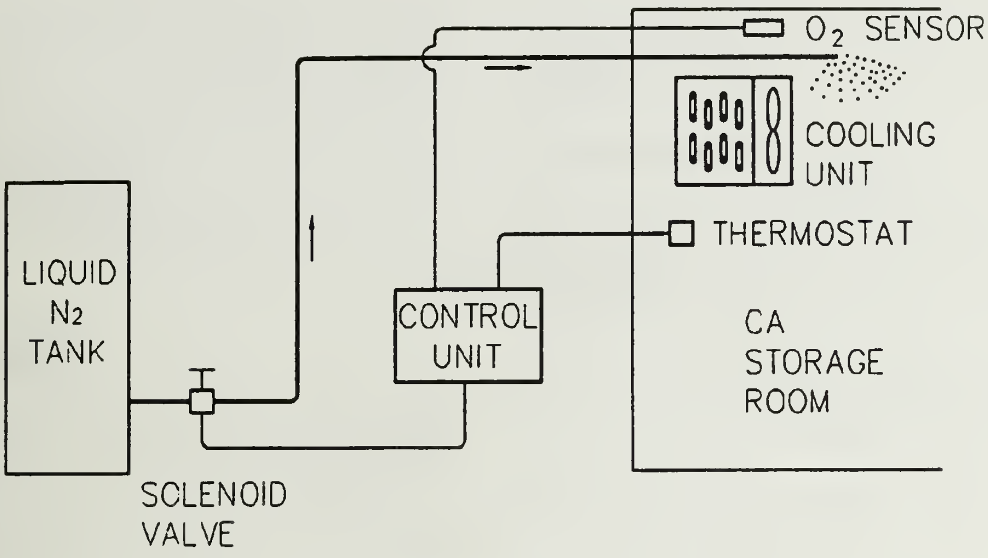

Figure 3: Schematic of a liquid nitrogen atmospheric generator suitable for CA application.

sprayed into the storage room via spray headers placed in front of the cooling unit fans (Bartsch 1986), thus atomizing the N_2 (Figure 3). The injection of liquid nitrogen in the storage room provides some refrigeration, but the extra cost for insulating the supply lines to the room and the potential freezing burns to the fruit may offset refrigeration savings (Waelti and Cavalieri 1990). Alternatively gaseous nitrogen is usually introduced in the storage room until the O_2 level has reached 5% or less within 48 hours. Fruit respiration is used to adjust O_2 concentration to the desired level and allow accumulation of CO_2.

This method of oxygen pull-down is nonexplosive and does not introduce ethylene or other gases but is comparatively expensive unless on-site nitrogen is available.

Gas separator systems

Three types of gas separators are available on the market. These are i) the pressure swing absorption (PSA) system, ii) the hollow fiber membrane separator (HFMS) system, and iii) ammonia cracking at high temperature. They can also be used to control the CO_2 level, but other CO_2 scrubbing systems are usually preferred (Bartsch and Blanpied 1988).

Pressure swing absorption system

Most PSA systems work on a common principle (Anon. 1987). A stream of air (Figure 4) is compressed, purified by filters, and pushed through a molecular sieve, which selectively absorbs O_2. The gas stream that leaves the gas separator contains high levels of N_2. The O_2 retained in the gas separator is released to the ambient atmosphere by ventilation of the separator. Two sorption vessels mounted in parallel permit the absorption/desorption cycle to take place without affecting the flow of N_2 rich stream. The purity of the N_2 gas output can vary between 90 and 99.9%, depending on pressure, air flow circulating through the PSA, and gas temperature. PSAs have proved successful in apple CA storage (Bartsch and Blanpied 1988). They require air free of oil and water, and the system requires periodic mechanical checks. Initial cost is fairly high.

Hollow fiber membrane separator system

This system is based on different permeation rates for the gases passing through a membrane. As can be seen from Figure 5, compressed heated air is filtered and forced into a hollow fiber membrane chamber where O_2 and CO_2 gases are separated from the N_2 by their higher differential permeabilities. The stream rich in O_2 and CO_2 is vented to the ambient atmosphere

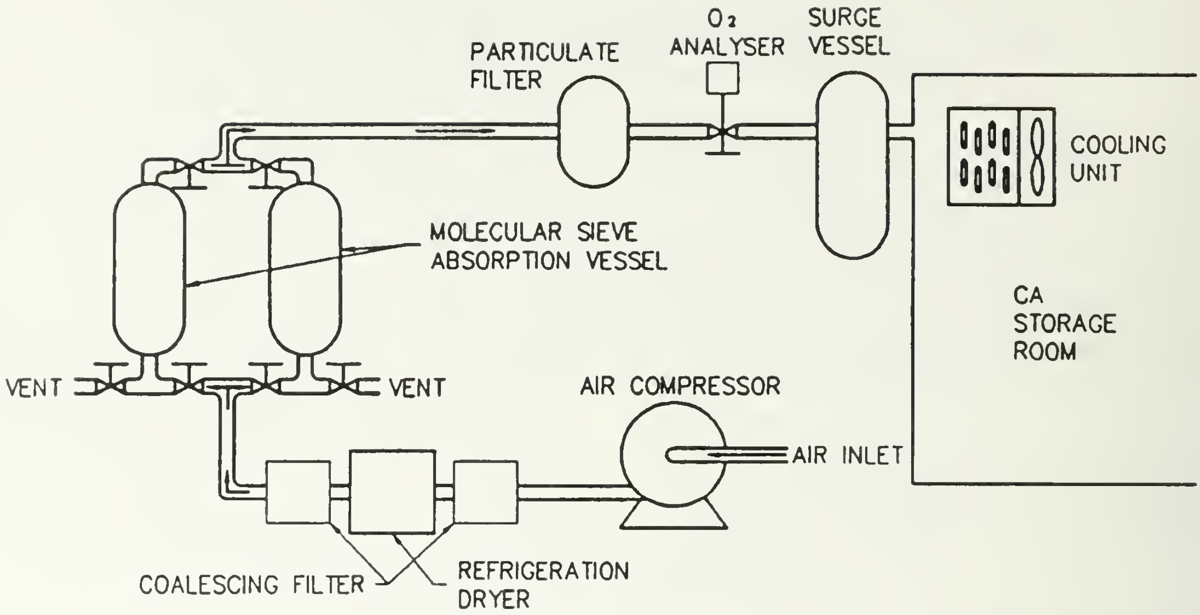

Figure 4: Schematic of a pressure swing absorption system.

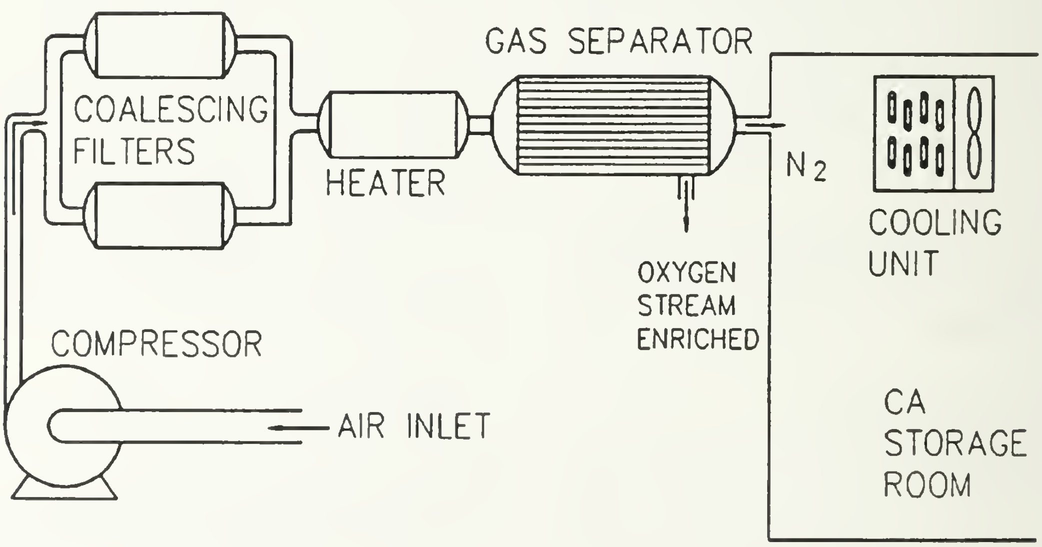

Figure 5: Schematic of a hollow fiber membrane separator system.

while the nearly pure N_2 gas is fed to the storage room to purge the O_2 and establish the desired gas concentration. HFMS has been used successfully in apple CA storage (Bartsch and Blanpied 1988). An HFMS system has a high initial and replacement cost. Like the PSA system, air must be free of both water and oil. There is less maintenance than with a PSA system.

Ammonia cracking

Ammonia cracking is a process in which anhydrous ammonia is split at high temperature into nitrogen and hydrogen gas. Storeroom air is circulated through this system and oxygen reacts with the hydrogen to form water. The return air consists of nitrogen and water vapor free of carbon dioxide and hydrocarbons. The system requires ammonia gas, which can be dangerous; operating cost is high and the nitrogen air stream requires cooling before entry into the room (Bishop 1990).

CARBON DIOXIDE CONTROL SYSTEMS

Five systems are commercially available for removal of excess CO_2 from the CA storage room. They are 1) caustic soda, 2) hydrated lime, 3) water, 4) activated charcoal and molecular sieves, and 5) membranes. The operation of these scrubbing systems requires routine measurement of the room atmosphere for CO_2. CO_2 scrubbing is regulated by the flow through the scrubber.

Caustic soda CO_2 scrubber

Caustic soda (NaOH) dissolved in water is one of the oldest CO_2 scrubbing procedures in CA storage (Pflug 1960). CO_2 level is controlled by adjusting the time of exposure of caustic soda solution to the chamber atmosphere. Caustic soda has been largely discontinued because of the corrosiveness of the soda–water mixture. However, systems using dry caustic soda have been introduced and may be a viable alternative to water solutions (Bartsch and Blanpied 1990).

Hydrated lime CO_2 scrubber

One of the simplest and most efficient methods of regulating CO_2 levels in a CA room is the hydrated lime [$Ca(OH)_2$] scrubber. The scrubber consists of an insulated and airtight plywood box (or other material) externally connected to the CA room (Figure 6). The box contains enough lime for the entire storage period, however the lime should be replaced if its CO_2 absorption drops. Airflow to the scrubber may be by natural convection or regulated by blowers and dampers. The CO_2 and hydrated lime react in a 1:1 ratio to form $CaCO_3$ (limestone) and H_2O. Dolomitic lime, which has a high Mg content, is not as efficient as calcitic lime. Since the efficiency of

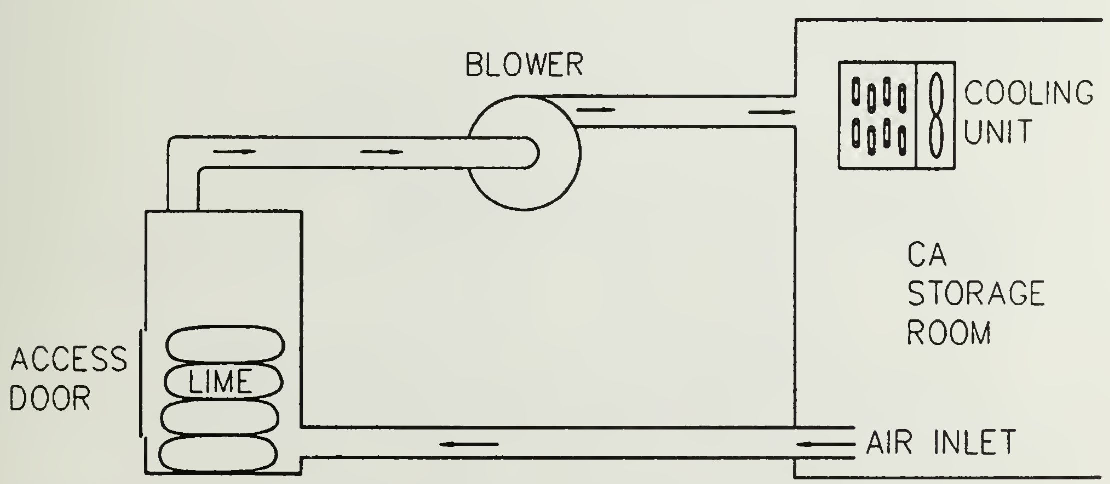

Figure 6: Schematic of a lime scrubber for CA storage.

the CO_2 scrubbing by the lime is determined by the surface area of the exposed lime, lime with a smaller particle size (fine mesh) is more efficient than lime with a larger particle size (coarse mesh). Lime should be packaged in 25-kg bags that have no polyethylene liner; lime bags should be stacked on a pallet with a 10-cm space between layers to maximize air circulation. Improved efficiency may be obtained if each bag is only partially filled, e.g. 50%, because less than 20% of the lime in a 25-kg bag is consumed due to outer layer hardening. To keep CO_2 below 2%, about 12 kg of lime per tonne of apples is recommended for each 3 – 4 months of storage.

Fifty percent of the recommended lime for the anticipated storage period may be placed on pallets on the floor or in single layers on pallets placed on the uppermost bins. This lime will consume the CO_2 produced by some oxygen scrubbers and the initial CO_2 production of the fruit.

Water CO_2 scrubbers

There are two types of water scrubbers, the brine CO_2 scrubber (Figure 7, Palmer 1959), and the modified system (Figure 8) of Smock et al. (1960). In the brine scrubber, brine is pumped over the cooling unit, where it absorbs the CO_2,

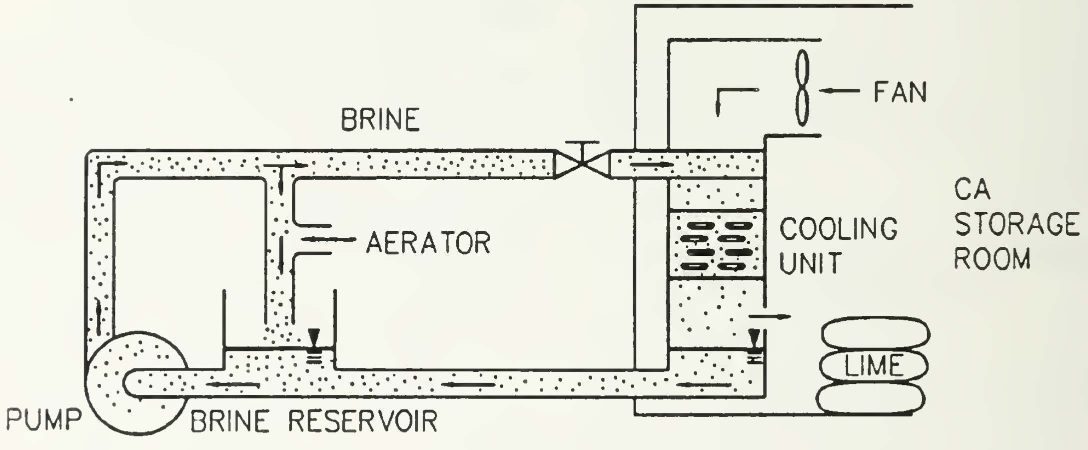

Figure 7: Schematic of a brine CO_2 scrubber for CA storage.

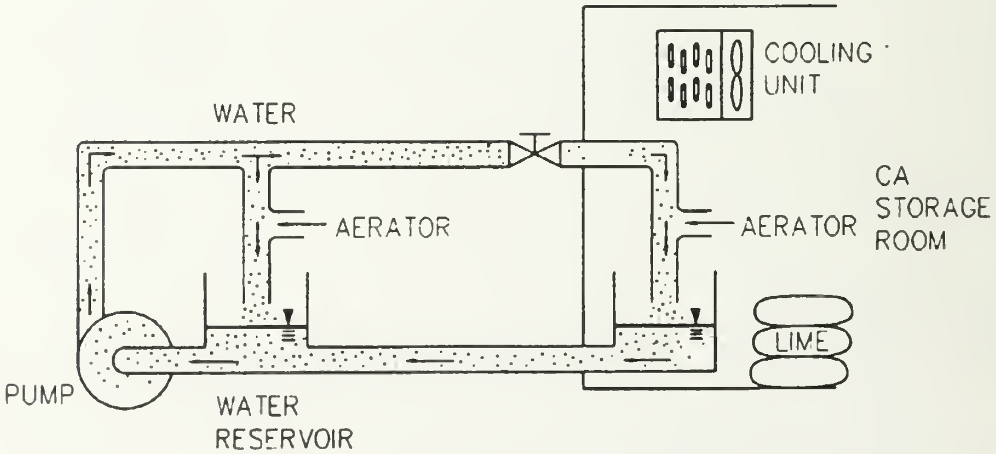

Figure 8: Schematic of a modified water CO_2 scrubber for CA storage.

gravity-fed to a water reservoir located outside the CA room, and then pumped from the reservoir to an aerator where the CO_2 is released to the outside air. The corrosion problem resulting from the use of brine can be avoided when a dry cooling unit is used. The modified system of Figure 8 uses two aerators: one located outside and one inside the storage room.

Water systems can efficiently control CO_2 levels and increase the relative humidity levels inside the storage room. The CO_2 level is maintained by adjusting the water flow rate through the aerators and by the operating time. Since the respiration rate may be higher at the beginning of storage, Bartsch and Blanpied (1984) recommend that some hydrated lime be placed inside the CA room, to assist control of CO_2 levels. The combination of hydrated lime and water scrubber is a less-expensive alternative than building a water scrubber having the capacity to meet the higher respiration rates encountered early in the season.

The CO_2 absorption system for the CA storage room should be designed on the basis of quantity of commodity in the CA room, the CO_2 production rate of the commodity and the CO_2 target level required. Pflug (1960) recommended 100 litres of water per hour per tonne of apples, for 5% CO_2 plus 3% O_2 at a storage temperature of 1°C. This gives a scrubbing capacity of 0.02 m^3 of CO_2 per cubic metre of water circulated through the scrubber.

Water scrubbers should be used in rooms that are held above 0°C to avoid freezing. A drawback to water scrubbers occurs when water is aerated outside the room to release CO_2; it absorbs O_2, which is then introduced into the room. Water scrubbers are declining in popularity.

Activated charcoal and molecular sieve CO_2 scrubbers

Activated charcoal and molecular sieve units (Figure 9) consist of a container filled with activated charcoal or molecular sieve, two blowers and four timer-controlled valves. The operation requires two consecutive steps; 1) air from the CA room passes through the scrubber where CO_2 is absorbed, and 2) CO_2-saturated absorbent is reactivated by circulating outside air through the scrubber. When a molecular sieve is used, a heater is required to increase the temperature of the absorbent during the reactivation process. Both systems have low operating costs requiring the absorbents to be replaced every 5 years.

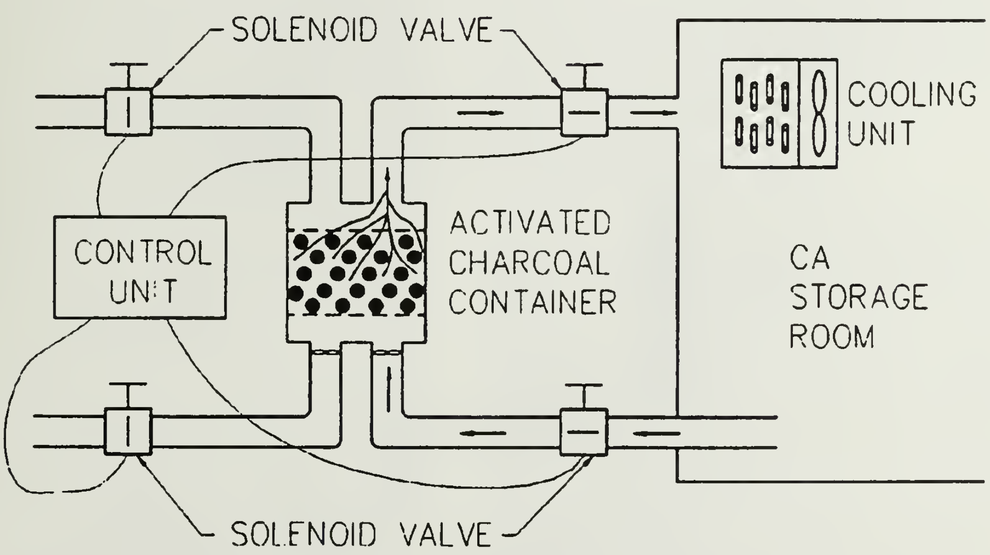

Figure 9: Schematic of an active charcoal CO_2 scrubber for CA storage.

This system, like the water scrubber, can return some O_2 to the room because fresh outside air is allowed into the scrubber during the reactivation process. This problem is eliminated by using N_2 gas during the reactivation process.

Semipermeable membrane system

When fruits and vegetables are packaged in polymeric films, the atmospheric composition of the headspace is affected by product respiration and by the gas permeation through the membrane. More than 40% of the produce in some markets is now marketed in such packages (Desrosiers and Desrosiers 1977). Composition, thickness, and surface area of the package, as well as temperature and partial pressure difference between the outside and the inside of the package, are the main parameters contributing to the gas exchange through the package semipermeable membrane. Each gas has a characteristic permeation rate that is a function of its ability to dissolve and diffuse through a membrane, which, in part, determines its internal concentration.

Marcellin and Leteinturier (1967) have extended the use of the semipermeable membranes to large pallet loads and storage rooms. The system creates a CA condition by means of a series of rectangular bags of silicone rubber connected in parallel (Figure 10). Exchanger size depends on the size of the cold room and on the respiration behavior of the stored commodity. These units can be installed inside or outside the cold room. When the unit is located outside the cold room (exposed to ambient air), the CA circulates inside the silicone rubber bags. Analysis of the CA composition indicates whether enough bags are in use. To maintain a CA of 5% CO_2 and 3% O_2, 50 m^2 of silicone membrane are required per 100 tonnes of fruit when the standard free volume is about 2.9 – 3.6 (Raghavan and Gariépy 1984). Although this system was initially designed for apples and pears, it has potential for storage of vegetables such as cabbage, leeks, celery and rutabaga (Gariépy et al. 1984).

A modified version of the Marcellin system (Figure 11) consists of gas diffusion panels enclosed in an airtight metallic container with two separate air flow paths and a control unit (Raghavan et al. 1984). The gas diffusion panels are made of square frames on which silicone membranes are fixed in an airtight arrangement such that they permit the outside air and the cold room air to flow on opposite sides without any mixing. Circulation of both room and outside air in the diffuser is maintained by centrifugal blowers controlled by a timer on a percentage basis of a complete cycle. Although this system is relatively

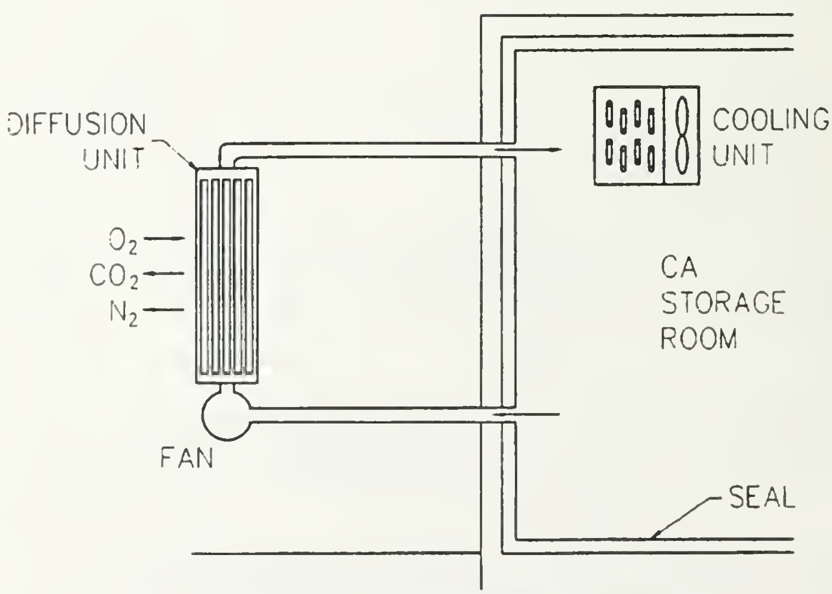

Figure 10: Schematic of a semipermeable membrane system for CA storage.

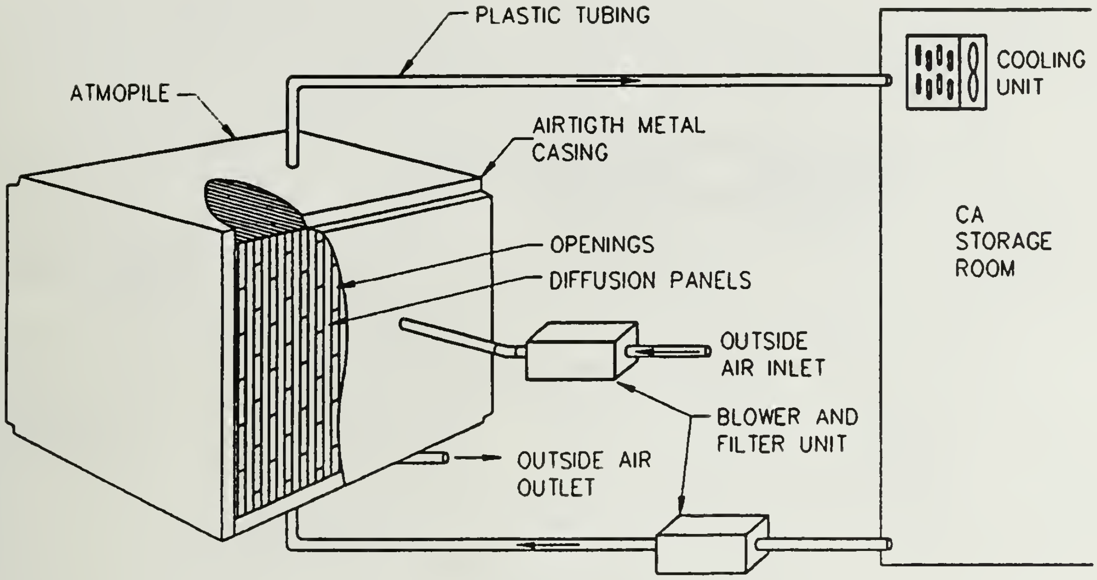

Figure 11: Schematic of the modified Marcellin system for CA storage.

new in Canada, it has been used successfully with a commercial cabbage facility since 1982.

ETHYLENE CONTROL SYSTEM

Ethylene (C_2H_4) often needs to be removed from storage rooms because it induces ripening of many fruits and causes physiological disorders in vegetables (Phan 1971). Concentrations as low as 0.1 ppm inside the fruit induce ripening of apples (Blanpied 1985) and kiwi fruits (Bishop 1990). Although low O_2 and high CO_2 concentrations reduce ethylene production and ethylene sensitivity (Phan 1971) the ethylene produced by apples and other sources like fungi, must be removed. There are several types of ethylene scrubbers which have been promoted (Blanpied 1989), but all of them have limitations that restrict their acceptance. Two of them are commercially available: i) heated catalyst and ii) ethylene-absorbing beads. It has also been demonstrated that ultraviolet radiation of certain wavelengths and ozone gas can be used to oxidize ethylene. However, more research and development is needed to produce a commercially acceptable system.

The type of CO_2 scrubbing system also influences the ethylene levels. If atmospheric flushing is used, e.g., nitrogen generators or gas, it removes most but not all the ethylene being generated by apples. For products that generate less ethylene than apples, this method may be sufficient for ethylene control. If activated carbon is used to scrub the CO_2, it will also absorb ethylene. This ethylene can be released to the atmosphere during the CO_2 desorption cycle. Ethylene removal using activated carbon has not been efficient enough for apple storages but may be successful for products that produce less ethylene.

Heated catalyst

A heated catalyst is capable of maintaining 1 – 2 ppm ethylene for bulk-filled McIntosh apples in a 360-m^3 storage room (Blanpied 1985). This system has a fan that blows storage room atmosphere through two ceramic packings used as heat exchangers where it contacts with an electrically heated catalyst (Figure 12). A damper motor permits air flow reversal through the packings at timed intervals. The ceramic heat exchanger works very efficiently, but permeable ceramic packing would reduce the energy

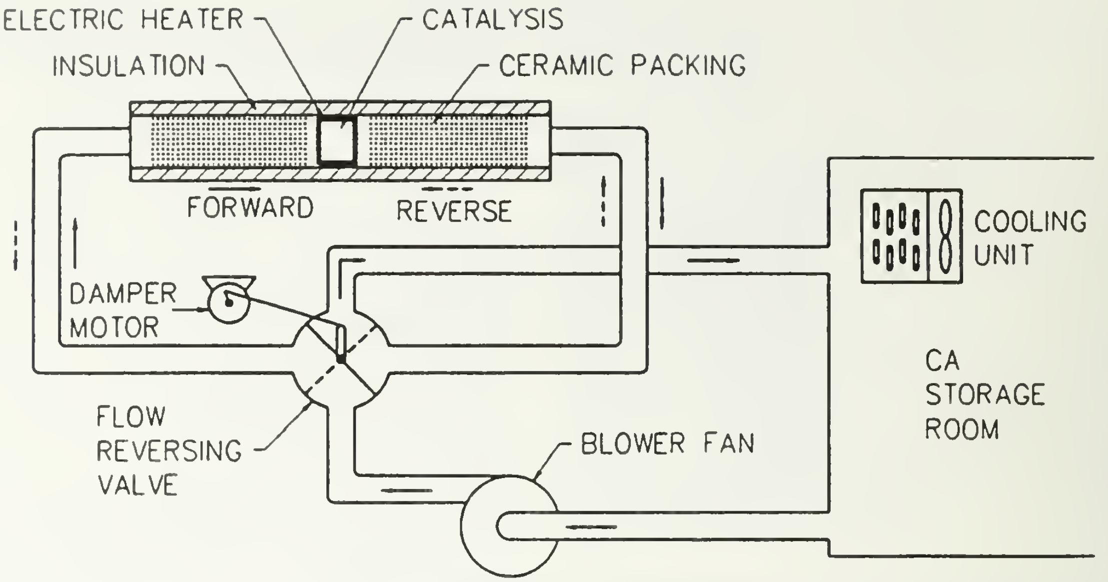

Figure 12: Schematic of the catalyst ethylene scrubber system for CA storage presented by Blanpied (1985).

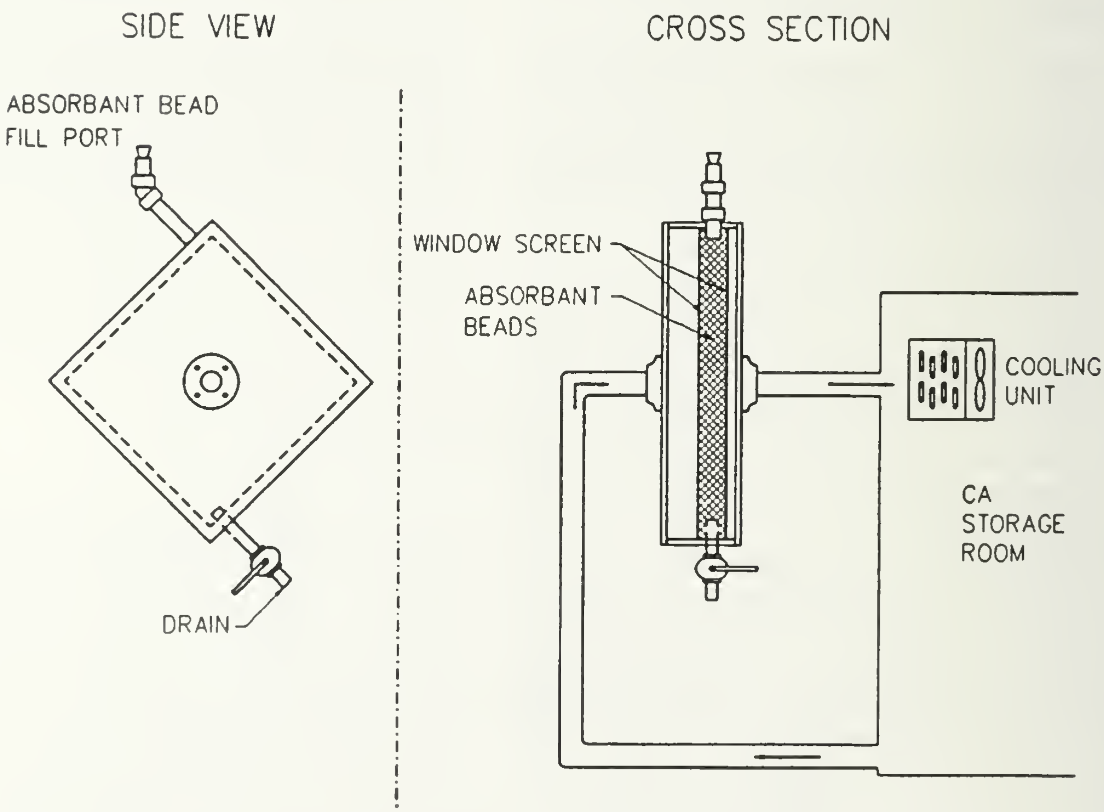

Figure 13: Schematic of the ethylene-absorbing beads system for CA storage presented by Blanpied (1985).

required to run the fan. This scrubber successfully removes up to 87% of the ethylene from the atmosphere on each pass through the unit. The main disadvantage of a catalytic system is the large amount of heat required to remove the ethylene and the subsequent heat removal prior to storage room return.

Ethylene-absorbing beads

The ethylene-absorbing beads scrubber consists of small spherical particles of aluminum silicate impregnated with potassium permanganate ($KMnO_4$). The beads are usually loaded into a sealed cartridge (Figure 13) through which air from the CA room is circulated. The reaction of ethylene with the potassium permanganate turns the color of the beads from purple to brown as the saturation point is reached.

Blanpied (1985) has recommended a removal capacity of 1.4 mL of ethylene per cubic metre of McIntosh apples per hour, and 0.28 mL m^{-3} h^{-1} for Empire apples. He also recommended two vertical beds $1.2 \times 1.2 \times 0.1$ m containing 140 kg of beads with a 280 L s^{-1} fan for a 360 m^3 McIntosh storage room. Bead performance depends on the manufacturer (Blanpied 1985). The scrubber must be checked frequently to replace used beads.

AUTOMATION

For successful application of a CA storage it is important to have adequate instrumentation to measure the conditions in the storage room. Some equipment is required to measure temperatures and gas concentrations. Measurement and control can be done with simple equipment or with complete computer-automated systems.

Oxygen measurement

Oxygen measurement and control is critical for successful operation of a modern low-oxygen CA store. Paramagnetic and polarographic oxygen analyzers are most recommended for low-oxygen applications. The chemical ORSAT analyzer is still commonly used for oxygen determination. The ORSAT capital cost is low and the accuracy is acceptable for higher-oxygen regimes, however this equipment requires a skilled operator and is not adequate for automation (Bishop 1990).

Carbon dioxide measurement

Infrared analyzers provide accurate carbon dioxide measurements. The ORSAT chemical analyzer can also be used for measuring CO_2 but has the same deficiencies noted above for oxygen analysis.

Ethylene measurement

Ethylene is difficult to measure, especially in the low concentrations required for fruit storage. The only practical method for measuring ethylene is with a gas chromatograph, which is an expensive machine requiring trained operators. A gas chromatograph could be used for simultaneous analysis of O_2 and CO_2 in addition to ethylene.

Gas sampling

Gas samples required for analysis should be taken at locations well away from any entries or exits of the CA equipment. Air leaking into samples is a common cause of improper O_2 and CO_2 levels in CA storage. Problems can be prevented through good management of installations and care in handling.

Oxygen control

To control the amount of oxygen in the store room, air is allowed to enter the chamber in a controlled manner. The amount of air required depends on the storage facility airtightness and on the product respiration. Automatic control of oxygen is desirable in low-oxygen conditions for better and easier stabilization of the oxygen levels. CA stores can easily be automated by adding a simple solenoid valve to the air inlet. The air valve is automatically opened for a given period of time whenever the gas analysis prescribes it (Bishop 1990).

Carbon dioxide control

The control of carbon dioxide depends on the method of removal. For flushing and external scrubbing methods, the process can be activated by a solenoid valve, which allows circulation of gas through the scrubber.

Automated systems can simplify the control of low-oxygen atmosphere storages, but they should not become excuses for neglecting the proper function of all components. It is recommended that the gas levels be checked regularly to minimize error of the automated system as a result of faulty sampling lines or calibrations.

SAFETY

CA storage facilities are dangerous because of the low-oxygen content of the atmosphere. Accidents are often fatal. No one should enter or place their head inside an operating CA room. All CA storage facilities should be clearly labeled with warning signs and the access doors must be kept locked. At oxygen levels less than 6%, loss of consciousness occurs in less than 30 seconds, followed by death.

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