Controlled Atmosphere Storage of Fruits and Vegetables, Second Edition

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To

Elara, Maya, Ciaran, Caitlin and Cameron,

to whom I owe much more than they will ever know

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About the Author

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Preface

Over the last 80 years or so, an enormous volume of literature has been published on the subject of controlled atmosphere storage of fruits and vegetables. It would be the work of a lifetime to begin to do those results justice in presenting a comprehensive and focused view, interpretation and digest for its application in commercial practice. Such a review is in demand to enable those engaged in the commerce of fruits and vegetables to be able to utilize this technology and reap its benefits in terms of the reduction of postharvest losses, and maintenance of their nutritive value and organoleptic characteristics. The potential use of controlled atmosphere storage as an alternative to the application of preservation and pesticide chemicals is of continuing interest.

In order to facilitate the task of reviewing the literature, I have had to rely on a combination of reviewing original publications and consulting reviews and learned books. The latter are not always entirely satisfactory since they may not give their source of information and I may have inadvertently quoted the same work more than once. Much reliance has been made on conference proceedings, especially the International Controlled Atmosphere Research Conference, held every few years in the USA; the European Co-operation in the Field of Scientific and Technical Research (COST 94), which held postharvest meetings throughout Europe between 1992 and 1995; and the International Society for Horticultural Science's regular international conferences; and, in particular, on CAB Abstracts.

Different views exist on the usefulness of controlled atmosphere storage. Blythman (1996) described controlled atmosphere storage as a system that 'amounts to deception' from the consumer's point of view. The reason behind this assertion seems to be that the consumer thinks that the fruits and vegetables that they purchase are fresh and that controlled atmosphere storage technology 'bestows a counterfeit freshness'. Also the consumer claims that storage may change produce in a detrimental way and cites changes in texture of apples, 'potatoes that seem watery and fall apart when cooked and bananas that have no flavour'. Some of these contentions are true and need addressing, but others are oversimplifications of the facts. Another view was expressed by David Sainsbury in 1995 and reported in the press as: 'These techniques [controlled atmosphere storage] could halve the cost of fruit to the customer. It also extends the season of availability, making good eating-quality fruit available for extended periods at reasonable costs'.

The purpose of this book is primarily to help the fresh produce industry in storage and transport of fruit and vegetables, but it provides an easily accessible reference source for those studying agriculture, horticulture, food science and technology, and food marketing. It will also be useful to researchers in this area, giving an overview of our present knowledge of controlled atmosphere storage, which will indicate areas where there is a need for further research.

Some criticisms can be made of the approach to controlled atmosphere storage and modified atmosphere packaging used in this book. Perhaps more interpretation or criticisms of the data in the literature should be made. The approach used in this book comes from my experience, starting in the 1970s on a 2-year assignment in the Sudan, 1 year in Korea and 2 years in Colombia. In all these three countries advice had to be given on postharvest aspects of a wide range of fruit and vegetables, most of which I had no first-hand experience of. Therefore I had to rely on the literature as a basis for that advice to farmers and those in the marketing chain. Conflicting information in the literature led me to the approach of accumulating as much information as possible, then giving advice based on the market situation and my own experience. So the objective of this book is to provide as much background information to provide a basis for informed decisions. Textbooks such as this are primarily used for reference and this structure admirably suits this use. There are controlled atmosphere storage recommendations for crops that perhaps would never be stored, and in some cases these are relevant to basic data on market situations related to modified atmosphere packaging.

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1 Introduction

The maintenance or improvement of the postharvest quality and the postharvest life of fresh fruits and vegetables is becoming increasingly important. This has been partly as a response to a free-market situation where the supply of good-quality fruits and vegetables constantly exceeds demand. Therefore to maintain or increase market share there is increasing emphasis on quality. Also consumer expectation in the supply of all types of fresh fruits and vegetables throughout the year is often taken for granted. This latter expectation is partly supplied by long-term storage of many crops but also by long-distance transport. With growing awareness and concern for climate change, long-distance transport of fruit and vegetables is being questioned.

Controlled atmosphere (CA) storage has been shown to be a technology that can contribute to these consumer requirements, in that, in certain circumstances, with certain varieties of crop and appropriate treatment, the marketable life can be greatly extended. An enormous amount of interest and research has been reported on CA storage and modified atmosphere (MA) packaging of fruit and vegetables to prolong their availability and retain their quality for longer. For example the Tenth Controlled and Modified Atmosphere Research Conference in Antalya, Turkey in April 2009 had over 500 participants from 72 countries. Saltveit (2003) stated:

> … the natural variability in the raw material and its dynamic response to processing and storage conditions may render it impossible to identify a truly optimal storage atmosphere. Additional refinements in recommendations for the CA and MA storage of fruits and vegetables will continue to accrue through empirical observations derived from traditional experiments in which the six components of the storage environment (i.e. duration, temperature, relative humidity, O_2, CO_2 and ethylene levels) are varied in well-defined steps.

This book seeks to evaluate the history and current technology reported and used in CA storage and MA packaging and its applicability and restrictions for use in a variety of crops in different situations. While it is not exhaustive in reviewing the enormous quantity of science and technology which has been developed and published on the subject, it will provide an access into CA and MA for those applying the technology in commercial situations. The book can also be used as a basis for determination of researchable issues in the whole area of CA storage and MA packaging.

CA Storage History

The scientific basis for the application of CA technology to the storage of fresh fruit and vegetables has been the subject of considerable research, which seems to be progressively increasing. Some of the science on which it is based has been known for over 200 years, but was refined and applied commercially for the first time in the first half of the 20th century.

Early knowledge of the effects of gases on crops

The effects of gases on harvested crops have been known for centuries. In eastern countries, fruits were taken to temples where incense was burned to improve ripening. Bishop (1996) indicated that there was evidence that Egyptians and Samarians used sealed limestone crypts for crop storage in the 2nd century BC. He also quotes from the Bible, questioning whether the technology might have been used in Old Testament Egypt during the seven plagues wrought by God in order to facilitate the release of the children of Israel. Dilley (1990) mentioned the storage of fresh fruit and vegetables in tombs and crypts. This was combined with the gas-tight construction of the inner vault so that the fruit and vegetables would consume the oxygen (O_2) and thus help to preserve the corpse. An interpretation of this practice would indicate that knowledge of the respiration of fruit pre-dates the work described in the 19th century (Dalrymple, 1967). Wang (1990) quotes a Tang dynasty 8th century poem that described how litchis were shown to keep better during long-distance transport when they were sealed in the hollow centres of bamboo stems with some fresh leaves. Burying fruit and vegetables in the ground to preserve them is a centuries-old practice (Dilley, 1990). In Britain crops were stored in pits, which would have restricted ventilation and may have improved their storage life.

Currently CA research and commercial CA storage is used in many countries, and some background on this is given as follows.

France

The earliest-documented scientific study of CA storage was by Jacques Etienne Berard at the University of Montpellier in 1819 (Berard, 1821). He found that harvested fruit absorbed O_2 and gave out carbon dioxide (CO_2). He also showed that fruit stored in atmospheres containing no O_2 did not ripen, but if they were held for only a short period and then placed in air they continued to ripen. These experiments showed that storage in zero O_2 gave a life of about 1 month for peaches, prunes and apricots and about 3 months for apples and pears. Zero O_2 was achieved by placing a paste composed of water, lime and iron sulfate ($FeSO_4$) in a sealed jar, which, as Dalrymple (1967) pointed out, would also have absorbed CO_2. Considerable CA research has been carried out over the intervening period in France; however, Bishop (1996) reported that it was not until 1962 that commercial CA storage started in France.

USA

In 1856 Benjamin Nyce built a commercial cold store in Cleveland, USA, using ice to keep it below 1 °C (34 °F). In the 1860s he experimented with modifying the CO_2 and O_2 in the store by making it airtight. This was achieved by lining the store with casings made from iron sheets, thickly painting the edges of the metal and having tightly fitted doors. It was claimed that 4000 bushels of apples (a bushel is a volumetric measure where 1 US bushel = 2150.42 cubic inches = 35.24 l; 1 imperial bushel = 2219.36 cubic inches = 36.37 l) were kept in good condition in the store for 11 months. However, he mentioned that some fruit were injured in a way that Dalrymple (1967) interpreted as possibly being CO_2 injury. The carbonic acid level was so high in the store (or the O_2 level was so low) that a flame would not burn. He also used calcium chloride to control the moisture level in the mistaken belief that low humidity was necessary.

Dalrymple (1967) stated that R.W. Thatcher and N.O. Booth, working in Washington State University around 1903, studied fruit storage in several different gases. They found that 'the apples which had been in CO_2 were firm of flesh, possessed the characteristic apple color, although the gas in the jar had a slight odor of fermented apple juice, and were not noticeably injured in flavor'. The apples stored in hydrogen (H_2), nitrogen (N_2), O_2 and sulfur dioxide (SO_2) did not fare so well. They subsequently studied the effects of CO_2 on raspberries, blackberries and loganberries and 'found that berries which softened in three days in air would remain firm for from 7 to 10 days in carbon dioxid [*sic*]'.

Fulton (1907) observed that fruit could be damaged where large amounts of CO_2 were present in the store, but strawberries were 'damaged little, if any ... by the presence of a small amount of CO_2 in the air of the storage room'. Thatcher (1915) published a paper in which he described work in which he experimented with apples sealed in boxes containing different levels of gases, and concluded that CO_2 greatly inhibited ripening.

G.R. Hill Jr reported work carried out at Cornell University in 1913, in which the firmness of peaches had been retained by storage in inert gases or CO_2 (Hill, 1913). He also observed that the respiration rate of the fruit was reduced and did not return to normal for a few days after storage in a CO_2 atmosphere. C. Brooks and J.S. Cooley working for the US Department of Agriculture stored apples in sealed containers in which the air was replaced three times each week with air plus 5% CO_2. After 5 weeks' storage they noted that the fruits were green, firm and crisp, but were also slightly alcoholic and had 'a rigor or an inactive condition from which they do not entirely recover' (Brooks and Cooley, 1917). J.R. Magness and H.C. Diehl described a relationship between apple softening and CO_2 concentration, in that an atmosphere containing 5% CO_2 slowed the rate of softening, with a greater effect at higher concentrations, but at 20% CO_2 the flavour was impaired (Magness and Diehl, 1924). Work on CA storage which had been carried out at the University of California at Davis was reported by Overholser (1928). This work included a general review and some preliminary results on Fuerte avocados. In 1930 Overholser left the university and was replaced by F.W. Allen, who had been working on storage and transport of fresh fruits in artificial atmospheres. Allen began work on CA storage of Yellow Newtown apples. Yellow Newtown, like Cox's Orange Pippin and Bramley's Seedling grown in the UK, was subject to low temperature injury even at temperatures higher than 0 °C. These experiments (Allen and McKinnon, 1935) led to a successful commercial trial on Yellow Newtown apples in 1933 at the National Ice and Cold Storage Company in Watsonville. Thornton (1930) carried out trials where the concentration of CO_2 tolerated by selected fruit, vegetables and flowers was examined at six temperatures over the range from 0 to 25 °C (32 to 77 °F). To illustrate the commercial importance of this type of experiment, the project was financed by the Dry Ice Corporation of America.

From 1935 Robert M. Smock worked in the University of California at Davis on apples, pears, plums and peaches (Allen and Smock, 1938). In 1936 and 1937, F.W. Allen spent some time with Franklin Kidd and Cyril West at the Ditton laboratory in the UK and then continued his work at Davis, while in 1937 Smock moved to Cornell University. Smock and his PhD student Archie Van Doren conducted CA storage research on apples, pears and stone fruit (Smock, 1938; Smock and Van Doren, 1938, 1939). New England farmers in the USA were growing a number of apple varieties, particularly McIntosh. McIntosh is subject to chilling injury and cannot be stored at or below 0 °C (32 °F). It was thought that if the respiration rate could be slowed, storage life could be extended, lengthening the marketing period, and CA storage was investigated to address this problem (Smock and Van Doren, 1938). Sharples (1989a) credited Smock with the 'birth of CA storage technology to North America'. In fact it was apparently Smock who coined the term 'controlled atmosphere storage', as he felt it better described the technology than the term 'gas storage', which was used previously by Kidd and West. In the *Cornell Agricultural Experiment Station Bulletin*, Smock and Van Doren (1941) stated:

> There are a number of objections to the use of the term *gas storage* as the procedure is called by the English. The term *controlled atmosphere* has been substituted since control of the various constituents on the atmosphere is the predominant feature of this technique. A substitute term or synonym is *modified atmosphere*.

The term controlled atmosphere storage was not adopted in Britain until 1960 (Fidler *et al.*, 1973). Smock also spent time with Kidd and West at the Ditton laboratory. The CA storage work at Cornell included strawberries and cherries (Van Doren *et al.*, 1941). A detailed report of the findings of the Cornell group was presented in a comprehensive bulletin (Smock and Van Doren, 1941), which gave the results of research on atmospheres, temperatures and varietal responses of fruit, as well as store construction and operation. In addition to the research efforts in Davis and Cornell, several other groups in the USA were also carrying out research into CA storage. CA storage research on a variety of fruits and vegetables was described by Miller and Brooks (1932) and Miller and Dowd (1936). Work on apples was described by Fisher (1939) and Anon. (1941), work on citrus fruit by Stahl and Cain (1937) and Samisch (1937), and work on cranberries by Anon. (1941). Smock's work in New York State University was facilitated in 1953 with the completion of large new storage facilities designed specifically to accommodate studies on CA storage.

Commercial CA storage of apples in the USA began in New York State with McIntosh. The first three CA rooms with a total capacity of 24,000 bushels were put into operation in 1940, with Smock and Van Doren acting as consultants. This had been increased to 100,000 bushels by 1949, but the real expansion in the USA began in the early 1950s. In addition to a pronounced growth in commercial operations in New York State, CA stores were constructed in New England in 1951, in Michigan and New Jersey in 1956, in Washington, California and Oregon in 1958, and in Virginia in 1959 (Dalrymple, 1967). A CA store for Red Delicious was set up in Washington state in the late 1950s in a Mylar tent, where some 1000 bushels were stored with good results. By the 1955/1956 season the total CA storage holdings had grown to about 814,000 bushels, some 684,000 bushels in New York state and the rest in New England. In the spring of that year Dalrymple did a study of the industry in New York state and found that, typically, CA stores were owned by large and successful fruit farmers (Dalrymple, 1967). The average total CA storage holdings per farm were large, averaging 31,200 bushels and ranging from 7500 to 65,000 bushels. An average storage room held some 10,800 bushels. A little over three-quarters of the capacity represented new construction while the other quarter was remodelled from refrigerated stores. About 68% of the capacity was rented out to other farmers or speculators. In 2004 it was reported that some 75% of cold stores in USA had CA facilities (DGCL, 2004).

UK

Sharples (1989a), in his review in *Classical Papers in Horticultural Science*, stated that '[Franklin] Kidd and [Cyril] West can be described as the founders of modern CA storage'. Sharples described the background to their work and how it came about. Dalrymple (1967), in reviewing early work on the effects of gases on postharvest fruit and vegetables stated: 'The real start of CA storage had to await the later work of two British scientists [Kidd and West], who started from quite a different vantage point'.

During the First World War concern was expressed by the British government about food shortages. It was decided that one of the methods of addressing the problem should be through research, and the Food Investigation Organisation was formed at Cambridge in 1917 under the direction of W.B. Hardy, who was later to be knighted and awarded the fellowship of the Royal Society (Sharples, 1989a). In 1918 the work being carried out at Cambridge was described as:

> a study of the normal physiology, at low temperatures, of those parts of plants which are used as food. The influence of the surrounding atmosphere, of its content of O_2, CO_2 and water vapour was the obvious point to begin at, and such work has been taken up by Dr. F. Kidd. The composition of the air in fruit stores has been suspected of being of importance and this calls for thorough elucidation. Interesting results in stopping sprouting of potatoes have been obtained, and a number of data with various fruits proving the importance of the composition of the air.
>
> (Anon., 1919)

One problem that was identified by the Food Investigation Organisation was the high levels of wastage which occurred during the storage of apples. Kidd and West were working at that time at the Botany School in the University of Cambridge on the effects on seeds of CO_2 levels in the atmosphere (Kidd and West, 1917), and Kidd was also working on the effects of CO_2 and O_2 on sprouting of potatoes (Kidd, 1919). Kidd and West transferred to the Low Temperature Laboratory for Research in Biochemistry and Biophysics (later called the Low Temperature Research Station) at Cambridge in 1918 and conducted experiments on what they termed 'gas storage' of apples (Sharples, 1986). By 1920 they were able to set up semi-commercial trials at a farm at Histon in Cambridgeshire to test their laboratory findings in small-scale commercial practice. In 1929 a commercial gas store for apples was built by a grower near Canterbury in Kent. From this work they published a series of papers on various aspects of storage of apples in mixtures of CO_2, O_2 and N_2. The publications included Kidd and West, 1925, 1934, 1935a,b 1938, 1939 and 1949. They also worked on pears, plums and soft fruit (Kidd and West, 1930). In 1927 Kidd toured Australia, Canada, the USA, South Africa and New Zealand, discussing gas storage. By 1938 there were over 200 commercial gas stores for apples in the UK.

The Food Investigation Organisation was subsequently renamed. 'The first step towards the formation of the [Food Investigation] Board was taken by the Council of the Cold Storage and Ice Association' (Anon., 1919). The committee given the task of setting up the Food Investigation Board consisted of Mr W.B. Hardy, Professor F.G. Hopkins, Professor J.B. Farmer FRS and Professor W.M. Bayliss 'to prepare a memorandum surveying the field of research in connection with cold storage'. The establishment of a 'Cold Storage Research Board' was approved. Since the title did not describe fully the many agents used in food preservation, it was renamed the Food Investigation Board with the following term of reference: 'To organise and control research into the preparation and preservation of food'.

Work carried out by the Food Investigation Board at Cambridge under Dr F.F. Blackman FRS consisted of experiments on CA storage of strawberries at various temperatures by Kidd and West at the Botany School (Anon., 1920). Results were summarized as follows:

> Strawberries picked ripe may be held in cold store (temperature 1 °C to 2 °C) in a good marketable condition for six to seven days. Unripe strawberries do not ripen normally in cold storage; neither do they ripen when transferred to normal temperatures after a period of cold storage. The employment of certain artificial atmospheres in the storage chambers has been found to extend the storage life of strawberries. For example, strawberries when picked ripe can be kept in excellent condition for the market for three to four weeks at 1 °C to 2 °C if maintained:
>
> 1. in atmospheres of O_2, soda lime being used to absorb the CO_2 given off in respiration;
> 2. in atmospheres containing reduced amounts of O_2 and moderate amounts of CO_2 obtained by keeping the berries in a closed vessel fitted with an adjustable diffusion leak.
>
> Under both these conditions of storage the growth of parasitic and saprophytic fungi is markedly inhibited, but in each case the calyces of the berries lose their green after two weeks.

CA storage at low temperature of plums, apples and pears was described as 'has been continuing' by Anon. (1920), with large-scale gas storage tests on apples and pears. It was reported that storage of plums in total N_2 almost completely inhibited ripening. Plums can tolerate, for a considerable period, an almost complete absence of O_2 without being killed or developing an alcoholic or unpleasant flavour.

Anon. (1920) describes work by Kidd and West at the John Street store of the Port of London Authority on Worcester Pearmain and Bramley's Seedling apples at 1 °C and 85% relative humidity (rh), 3 °C and 85% rh and 5 °C and approximately 60% rh. Sterling Castle apples were stored in about 14% CO_2 and 8% O_2 from 17 September 1919 to 12 May 1920. Ten per cent of the fruit were considered unmarketable at the end of November for the controls, whereas the gas-stored fruit had the same level of wastage 3 months later (by the end of February). The Covent Garden laboratory was set up as part of the Empire Marketing Board in 1925. It was situated in London, close to the wholesale fruit market, with R.G. Tomkins as superintendent. Anon. (1958) describes some of their work on pineapples and bananas, as well as pre-packaging work on tomatoes, grapes, carrots and rhubarb.

Besides defining the appropriate gas mixture required to extend the storage life of selected apple cultivars, Kidd and West were able to demonstrate an interaction. They showed that the effects of the gases in extending storage life varied with temperature, in that at 10 °C gas storage increased the storage life of fruit by 1.5–1.9 times longer than those stored in air, while at 15 °C the storage life was the same in both gas storage or in air. They also showed that apples were more susceptible to low-temperature breakdown when stored in controlled atmospheres than in air (Kidd and West, 1927a).

In 1929 the Ditton laboratory (Fig. 1.1) was established by the Empire Marketing Board, close to the East Malling Research Station in Kent, with J.K. Hardy as superintendent. At that time it was an outstation of the Low Temperature Research Station at Cambridge. The research facilities were comprehensive and novel, with part of the station designed to simulate the refrigerated holds of ships in order to carry out experiments on sea freight transport of fruit. Cyril West was appointed superintendent of the Ditton laboratory in 1931. West retired in 1948 and R.G. Tomkins was appointed superintendent (later the title was changed to director) until his retirement in 1969. At that time the Ditton laboratory was incorporated into the East Malling Research Station as the fruit storage section (later the storage department), with J.C. Fidler as head. When the Low Temperature Research Station had to move out of its Downing Street laboratories in Cambridge in the mid-1960s, part of it was used to form the Food Research Institute in Norwich. Subsequently it was reorganized in November 1986 as the Institute of Food Research. Most of the staff of the Ditton laboratory were transferred elsewhere, mainly to the new Food Research Institute. The UK government's Agricultural Research Council had decided in the mid- to late 1960s that it should reorganize its research institutes on a crop basis, rather than by

Fig. 1.1. The Ditton laboratory at East Malling in Kent. The photograph was taken in June 1996 after the controlled atmosphere storage work had been transferred to the adjacent Horticulture Research International.

discipline. For example, Dr W.G. Burton, who worked on postharvest and CA storage of potatoes at the Low Temperature Research Station at Cambridge and subsequently at the Ditton laboratory, was appointed deputy director at the Food Research Institute. Some of the Ditton laboratory staff thought this government action was just a ploy to dismember the laboratory as it had got out of control. Apparently at one time visitors from Agricultural Research Council's headquarters were not met off the train nor offered refreshment (John Stow, personal communication).

B.G. Wilkinson, R.O. Sharples and D.S. Johnson were subsequent successors to the post of head of the storage department at East Malling Research Station. The laboratory continued to function as a centre for CA storage research until 1992, when new facilities were constructed in the adjacent East Malling Research Station, and the research activities were transferred to the Jim Mount Building. In 1990 East Malling Research Station had become part of Horticulture Research International, and subsequently it became 'privatized' to East Malling Research. In an interview on 24 July 2009, D.S. Johnson indicated that the team of scientists and engineers he joined at East Malling in 1972 'has come down to me', and he was about to retire (Abbott, 2009).

Although Kidd and West collaborated on 46 papers during their lifetimes, they rarely met outside the laboratory. Kidd was an avid walker, a naturalist, gardener and beekeeper. He also wrote poetry and painted. West was interested in systematic botany and was honoured for his contribution to that field (Kupferman, 1989). West retained an office in the Ditton laboratory until the 1970s, from which he continued to pursue his interests in systematic botany (John Stow, personal communication).

Australia

In 1926 G.B. Tindale was appointed by the state of Victoria to carry out research in postharvest of fruit. He collaborated with Kidd during his visit there in 1927. The Council for Scientific and Industrial Research Organization was formed about the same time, and F.E. Huelin and S. Trout from the CSIRO worked with Tindale on gas storage of apples and pears. For example, in one study in 1940 they used 5% CO_2 + 16% O_2 for storage of Jonathan apples by controlled ventilation with air and no CO_2 scrubbing. Huelin and Tindale (1947) reported on gas storage research of apples, and CA work was subsequently started on bananas (McGlasson and Wills, 1972), but the work was not applied commercially until the early 1990s. In Australia most commercial fruit storage until 1968 was in air, and in 1972 CA generators were introduced. So the reality was that commercial CA storage was probably not used before 1968 and presumably not to any significant extent until after 1972. It seems the real problem of introducing CA storage technology was that the old cold stores were leaky (Little *et al.*, 2000; John Faragher, personal communication) and therefore not easily adapted to CA.

Canada

Hoehn *et al.* (2009) reported that Charles Eaves worked on fruit and vegetable storage in Nova Scotia and initiated the construction of the first commercial CA store in Canada in 1939 at Port Williams in Nova Scotia. Eaves was born in England but studied and worked in Nova Scotia and then spent a year in England with Kidd and West at the Low Temperature Research Station in Cambridge in 1932–1933. On returning to Canada he was active in the introduction of CA technology (Eaves, 1934). The use of hydrated lime for removing CO_2 in CA stores was also first developed by him in the 1940s. He was involved, with others, in the development of a propane burner to reduce rapidly the O_2 concentration in CA stores. He retired in 1972. CA is important in Canada, especially for apples, and in November 2009 there were 398,324 t of apples in CA storage, 157,334 t in refrigerated storage and 8 t in common storage (Anon., 2010).

China and South-east Asia

It was reported that, in 1986, the first CA store was established in Yingchengzi in China, to contain some 1000 t of fruit (DGCL, 2004). In Thailand some CA research is currently carried out at Kasetsart in Bangkok, most of it on rambutan, but there is no commercial CA storage (Ratiporn Haruenkit, personal communication). In the Philippines CA transport trials by the Central Luzon State University were reported for mango exports by Angelito T. Carpio, Freshplaza, 12 September 2005, but results were not published.

Netherlands

A considerable amount of CA research was carried out by the Sprenger Institute, which was part of the Ministry of Agriculture and Fisheries, and eventually was incorporated within Wageningen University. Although the effects of CA on flowers dates back to work in the USA in the late 1920s (Thornton, 1930), much of the research that has been applied commercially was done by the Sprenger Institute, which started in the mid-1950s (Staden, 1986). From 1955 to 1960 research was carried out at the Sprenger Institute on 'normal' CA storage of apples, which meant that only the CO_2 concentration was measured and regulated. Also at this time the first commercial CA stores were developed and used with good results. From 1960 both O_2 and CO_2 were measured and controlled, and several types of CO_2 scrubbers were tested, including those using lime, molecular sieves, sodium hydroxide (NaOH) and potassium hydroxide (KOH). For practical situations lime scrubbers were mainly used and gave good results. From 1967 to 1975 active carbon scrubbers were used, which gave the opportunity to develop central scrubber systems for multiple rooms. From 1975 to 1980 the first pull-down equipment was used in practice, mainly using the system of ammonia cracking called 'Oxydrain', which produced N_2 and H_2 gases. The N_2 gas was used to displace storage air to lower O_2 levels. At this time most apple varieties were stored in 3% CO_2 + 3% O_2. From 1980 to 1990 an enormous development in CA storage occurred, with much attention on low O_2 storage (1.2%), sometimes in combination with low CO_2. In this system the quality of the stored apples improved significantly (Schouten, 1997). There was also improvement in active CO_2 scrubbers; gas-tight rooms; much better pull-down systems for O_2, including membrane systems; pressure-swing adsorption; and centralized measurement and controlling systems for CO_2 and O_2. From 1990 to 2000 there was further improvement of the different systems and the measurement of defrosting water. During 2000 to 2009 there was further development of the dynamic control system, using the measurement of ethanol as the control method for the O_2 concentration. This enables the level to be lowered sometimes down to 0.4% in commercial storage. A lot of sophisticated ultra-low oxygen (ULO) storage rooms use this technique with very promising results. At the same time the use of 1-methylcyclopropene (1-MCP) was introduced in combination with ULO storage (Alex van Schaik, personal communication).

India

Originally established in 1905, the Indian Agricultural Research Institute initiated a coordinated project on postharvest technology of fruits and vegetables in late 1970. Currently the head is Dr R.K. Pa, and a considerable amount of research has been carried out on several fruit species, including work on CA. Jog (2004) reported that there were a large number of cold storages in India and some of the old ones had been revamped and generators added, and that the availability CA and MA facilities was increasing, but CA stores remained rare.

Mexico

In countries like Mexico, crops are not widely stored, partly because of long harvesting seasons. However, CA storage is increasingly used, for example in Chihuahua and Coahuila for apples. It was estimated by Yahia (1995) that there were about 50 CA rooms there, storing about 33,000 t of apples each year.

New Zealand

Research work for the Department of Industrial and Scientific Research on gas storage of apples between 1937 and 1949 was summarized in a series of papers, for example Mandeno and Padfield (1953). The first experimental CA shipments of Cox's Orange Pippin apples were carried out to Netherlands and the UK in the early 1980s, supervised by Stella McCloud. These were in reefer containers at 3.5–4.0 °C, and a small bag of lime was placed in each box to absorb CO_2, although this presented a problem with the Dutch customs, who needed to be convinced that the white powder was in fact lime. O_2 was probably controlled by N_2 injection. Before that time apples were shipped only in reefer containers or reefer ships, and the use of CA was in response to the apples developing 'bitter pit', which was controlled by the increased CO_2 levels (John Stow, personal communication). Subsequently the Department of Scientific and Industrial Research developed predictive levels of fruit calcium needed for Cox's Orange Pippin apples free of bitter pit.

South Africa

Kidd and West (1923) investigated the levels of CO_2 and O_2 in the holds of ships carrying stone fruit and citrus fruit to the UK from South Africa. However, the first commercial CA storage facilities in South Africa were installed near Cape Town in 1935 (Dilley, 2006). Others were commissioned in 1978, and by 1989 the CA storage volume had increased to a total of 230,000 bulk bins, catering for >40% of the annual apple and pear crop (Eksteen *et al.*, 1989).

Turkey

In Turkey CA research started in Yalova Central Horticultural Research Institute in 1979, initially on apples, and subsequently at TÜBİTAK and various Turkish universities. Commercial CA storage also started near Yalova, and one private company was reported to have some 5000 t CA capacity. Currently there are perhaps 25 commercial CA stores,

Fig. 1.2. New laboratories at the Low Temperature Research Station in St Augustine, Trinidad in 1937. Photo: Tucker Picture Production Ltd (Wardlaw and Leonard, 1938).

with a total capacity of approximately 35,000 t (Kenan Kaynaş, personal communication).

West Indies

In 1928 the Low Temperature Research Station was established in St Augustine in Trinidad at the Imperial College of Tropical Agriculture, at a cost of £5800. The initial work was confined to '… improving storage technique as applied to Gros Michel [bananas] … for investigating the storage behaviour of other varieties and hybrids which might be used as substitutes for Gros Michel in the event of that variety being eliminated by the epidemic spread of Panama Disease'. Due to demand the work was extended to include '… tomatoes, limes, grapefruit, oranges, avocados, mangoes, pawpaws, egg-plant fruit, cucurbits of several kinds and to the assortment of vegetables that can be grown in the tropics' (Wardlaw and Leonard, 1938). An extension to the building was completed in 1937 (Fig. 1.2), at a cost of £4625. 'Dr F. Kidd and Members of the Low Temperature Research Station at Cambridge gave assistance and advice in technical and scientific matters', and CA storage work was carried out using imported cylinders of mixtures of N_2, O_2 and CO_2. Professor C.W. Wardlaw was officer-in-charge, and a considerable amount of work was carried out by him and his staff on fresh fruit and vegetables, including work on CA storage (Wardlaw, 1938).

With the formation of the University of the West Indies in the 1960s, work in Trinidad continued mainly under the supervision of Professor L.A. Wilson, and subsequently by Dr Lynda Wickham, on postharvest of fruit and vegetables. There has been considerable work on MA packaging but limited work on CA storage. Dr Errol Reid carried out experiments in 1997 on CA transport of bananas in reefer containers from the Windward Islands and subsequently supervised the use of CA reefer ships in 1998. CA reefer ships are still being used today for transport of bananas from the Windward Islands to the UK (50,000–60,000 t year^{-1}), often combined with bananas from the Dominican Republic to reduce the risk of dead-freight.