

QUALITY OF STRAWBERRY FRUIT AS AFFECTED
BY POST - HARVEST HANDLING

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ABSTRACT

QUALITY OF STRAWBERRY FRUIT AS AFFECTED BY POST-HARVEST HANDLING

By

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The purpose of this study was to summarize published studies on strawberries with particular reference to post-harvest life, and for Norwegian conditions, to recommend handling practices of the fruit that will minimize quality loss during the transit and marketing period.

Measurement and evaluation of quality factors, such as flavor, color and texture are considered for strawberries, as are the changes in these quality factors that take place during the ripening and post-harvest period.

The rate of the ripening processes, respiration and growth of decay, which all determine the life potential, are found to be closely related to the fruit temperature. Fruit at 10°C is considered to have about one third the life expectancy of fruit at 0°C. Handling practices for strawberries that maintain low temperature in each portion of the post-harvest period are therefore the best way to minimize quality loss.

The following are recommendations for improving post-harvest handling conditions of strawberries in Norway:

- 1) The growers should apply good "temperature" management in the field, which would include shading of the fruit as soon as possible after harvest and rapid hauling of the fruit from the field to precooling stations.
- 2) Precooling of strawberries by the forced air cooling method should be done either by the individual growers or by the shippers soon after harvest. Rapid cooling is important because the field heat should be removed rapidly and because the cooling operation should not delay the shipping significantly.
- 3) The transit equipments, such as trucks and railcars, used for transportation of the precooled strawberries should primarily be refrigerated in order to maintain the initial low temperature of the fruit.
- 4) When the temperature cannot be controlled satisfactorily during transit, high concentrations of carbon dioxide in the surrounding atmosphere will partially compensate for the lack of refrigeration. A high carbon dioxide

concentration can be built up by use of dry ice, if pallet covers are used. Pallet covers should provide an effective gas barrier and, in addition, also provide insulation, moisture resistance, and mechanical strength.

- 5) The maturity of the fruit does to a certain extent determine the life potential. Fruit for distant markets should be harvested before fully ripe and should be of uniform maturity. The proper stage of maturity at harvest is dependent on time in transit, temperature and atmospheres the fruit are expected to be exposed to during transit. The maturity should therefore be determined when these factors are estimated.

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By

Martin Nodenes

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INTRODUCTION

One of the main characteristics of agricultural practice in Norway is the smallness of the average holdings. Most farms are only about 5 hectares and there are very few holdings over 50 hectares. Many individuals are part time farmers and supplement their income in the fishing, forestry and other industries. In this situation, a crop such as strawberries, which can give a high income per acre, would be of distinct advantage. Strawberries do not require high temperature to give high yields and good quality, and can be produced in several areas of the country where other fruit cannot be grown. Because of this, strawberries have been considered an important crop, and the production has increased tremendously in recent years. However, the markets are a limiting factor for the potential production, and the perishable character of the fruit makes it difficult to expand into other European markets. Because of their perishable nature, it is generally considered, in Norway, that the crop should be in wholesale the morning after harvest and preferably be consumed the same day.

The handling practices for strawberries by Gartnerhallen (the main horticultural cooperative in Norway, by whom the author is employed) and its strawberry growing members, are normally as follow: The fruit is harvested during the day and kept by the growers until the evening when it is collected by Gartnerhallen trucks. Most of these growers do not have cooling facilities and the fruit may be kept in field sheds or a barn where they are held until collected. When the fruit from all the growers is collected at the local center of Gartnerhallen, it is reloaded for shipping to the terminal markets which seldom are more than twelve hours drive away.

Cooling is normally not applied during transit, neither in trucks nor in rail cars, although in recent years refrigerated rail cars and trucks have been used for transport over longer distances. Occasionally, strawberries may be transported by air, but mostly in small quantities because of the high cost and because of limited space on passenger planes.

Because of great variation in temperature from one location to another in Norway, the strawberry season is very long. It starts in late June in the earliest location (Southernmost Norway) and continues through September in the higher altitudes and latitudes. Because of the long season, there are indications that Norwegian strawberries could successfully be sold on other

European markets from late July to the end of the season, and in the early season, strawberries could be sold domestically to a greater extent, particularly in the northern part of the country. The extension of the market is, however, dependent on the fruit being capable of remaining in good condition two or three days in transit before they are in wholesale. Since the author is interested in the practical area of extending such markets, the particular subject of this thesis is chosen.

The main purpose of this thesis is to summarize published studies with strawberries with particular reference to post-harvest life. Initially, the quality factors that determine consumer decisions in the market place are considered in some detail. Some of the important changes which occur during ripening are also dealt with along with normal ripening changes that occur during the holding period under different environmental conditions. The potential post-harvest life of strawberries is considered in more detail as well as the factors such as rate of respiration and growth rate of decay organisms, which determine the rate of deterioration. Particular stress is placed on studies where the effect of artificial environments, which could be applied commercially during the post-harvest period, are studied. The potential post-harvest life is also considered in relation to the stage of maturity and the post-harvest ripening of the fruit.

The scope of the study also includes how post-harvest life of strawberry fruit is determined by different handling practices that may be applied during the different steps between harvest and consumption. Although the handling by growers, shippers and wholesalers is particularly studied, one should expect that the fruit is substantially affected by environment at the retail and consumer level.

QUALITY FACTORS OF STRAWBERRIES

Quality factors in strawberries are mainly judged by the consumer and are largely based on sensual perception. The consumer, in effect, evaluates the flavor, color, texture, appearance and to a lesser extent the nutritive values of the product. In this section, each of the quality factors will be considered in turn. We will deal with the problems of evaluating these quality factors and consider in some detail the changes which occur during the ripening process.

Flavor Constituents

Attributes of quality included in this group are largely those which the consumer evaluates with his senses of taste and smell. In addition to the sense of taste and smell, the senses of feel in the form of touch, pain, warm and cold may also be a part of the overall flavor (Kramer and Twigg, 1966).

Taste Constituents

Generally taste is considered to be a four dimensional phenomenon, consisting of sweet, sour, salt and

bitter sensations (Crocker, 1945). For fruit, including strawberries, the most accurate instrumental measures of consumer taste may be sugar content, acid and astringency (Kramer and Twigg, 1966); however, astringency is not recognized to be strictly a taste sensation, but more of a feeling factor (Joslyn and Goldstein, 1964). Culpepper et al. (1935) have pointed out the importance of a proper balance between both sugar, acid and astringency in determining the dessert quality of strawberries. The absolute amounts of these constituents were found to be of minor importance as compared with the ratios existing between them. The ratios between these taste constituents determined whether strawberries were subjectively judged as acid, sweet, tart, or properly balanced. For most fruit, however, the ratio between sugar and acid was found to be an adequate measurement and, not surprisingly, the ratio was a better measurement than the magnitude of each of the components (Mitchell and Kasmire, 1968). For quality evaluation of strawberry cultivars, the amount of sugar and acid and the ratio between them has been used by breeders as a practical guide to quality (Darrow, 1966; Zubeckis, 1964; Duewer and Zych, 1967).

Sugar and acid content of the fruit can also be relatively easily measured. Sweetness can be determined as percent soluble solids by the use of a refractometer. Sourness can be measured instrumentally by the use of a

pH meter, but the use of hydrogen ion concentration as a measure of sourness was not generally found to be as satisfactory as a measurement of total titratable acid (Kramer and Twigg, 1959).

In Table 1, some data on average composition of strawberries is given. It should be noted that the composition values in this table were obtained in different years, from different cultivars and locations which may account for some of the variation. Climate and environmental conditions indeed will influence the content of these constituents markedly. For instance, Zubeckis (1962) has shown variation in both sugar and acid in the same cultivar from one year to another, even when all other conditions were similar. Furthermore, Kimbrough (1931) showed that weather conditions, especially rainfall, had a great effect upon the composition of the fruit. He found that berries picked after a period with high rainfall, had high moisture and low sugar content, whereas the reverse conditions pertained after a period of no precipitation. Rootsi (1966) reported that dry weather caused a decrease in fruit weight and a higher percent of dry matter, whereas an increase in fruit weight and lower percent dry substance followed moist weather. Also the site of the field may influence sugar and acid content. It was reported that strawberries grown on the upper drier part of a Southeast slope were

TABLE 1.--Composition of strawberries. Factors which are related to taste. The data were obtained from analysis of a number of cultivars and conditions

	Total solids %	Soluble solids %	Sugars %	Insoluble solids %	Titratable acidity %	Soluble solids Titr. acidity %	Total astringency %	Tannin %	Non-tannin %
	10.16	6.87	5.00	3.29	0.705	9.74	0.319	0.178	0.141
Series I	8.24		5.59	--	--		--	--	--
Series II	7.70		4.97	--	0.815	9.44	--	--	--
	--	7.14	4.99	--	0.925	7.73	--	--	--

Sources: Culpepper et al., 1935.

Osborne, 1964.

Zubeckis, 1964.

smaller, but contained slightly more sugar and acid than berries produced on a lower wetter part of the same slope (Francuk and Scerbakova, 1965). Kusnip (1967) reported that strawberries grown at high altitude had nearly double the total sugar content and had higher acid than steppe grown fruit.

The effect of nitrogen fertilization upon sugar and acid content has been studied by a number of investigators (Kimbrough, 1931; Darrow, 1932; Haut et al., 1936). Although somewhat different results were obtained from one experiment to another, the plots with the high nitrogen have generally had slightly lower acidity and sugar than the control plots. It seems, however, as if soil moisture generally had a more pronounced effect than did fertilizer, upon content of sugar, acid and percent dry matter (Kimbrough, 1931).

Changes in Taste Constituents

Some very important changes take place in the taste constituent during the ripening process. Culpepper et al. (1935) studied very thoroughly the changes in composition which take place during the development of the fruit. From the whitening stage of the fruit to full ripeness, a general increase in total solids was observed. This increase was due to a rapid increase in total sugar, which more than compensated for the concomitant decrease

in insoluble solids. Sugars made up only 60 to 65 percent of the soluble solids and about 40 percent of the total solids during the whitening stage of the fruit, whereas in the ripe fruit, sugars constituted 70 to 80 percent of the soluble solids and 50 percent or more of the total solids. Increase in soluble solids upon ripening was also reported by Smith and Heinze (1958). The latter investigation also showed that this increase in soluble solids was paralleled by a decrease in acidity from the partly colored fruit to the fully ripe stage. Culpepper et al. (1935) also observed a rapid decline in titratable acidity from the whitening stage to full ripeness; when fruit was overripe a slight increase in acidity over the normal ripe stage was found.

The astringency constituents were found to undergo very little change during the actual ripening process (Caldwell, 1934; Culpepper et al., 1935). The total astringency showed a slight decline; an increase in the nontannin fraction partially counterbalancing the continued decrease in tannin observed.

Odor Constituents

The odor of food products has been defined as the combined effect of olfactory and gustatory sensation, the former being the most important (Kramer and Twigg, 1966). Fruit odor constituents are known to consist of volatile chemicals which often are in a complex mixture. Usually

the most significant organoleptic constituents are esters and/or oxygenated terpenes, but the aroma may also be modified by the presence of a large variety of hydrocarbons: alcohols, phenols, esters, aldehydes, ketones, and lactones (Nursten and Williams, 1967; Fidler, 1960). Since these volatile substances which cause olfactory sensation occur in extremely minute quantities (Fidler, 1960), their identification and quantitative estimation by the classic chemical methods is extremely difficult, and impractical for use in routine quality evaluation (Kramer and Twigg, 1966). With newer methods, particularly chromatographic and spectrophotometric separation, the determination of these compounds can be done more objectively. The gas chromatographic technique was utilized in order to examine flavor components in strawberries (Dimick and Makower, 1956). They prepared from 0.1 to 0.4 grams of oil (high boiling water insoluble) characteristic of strawberry aroma from 100 lbs of fruit. One to ten μg per kg fruit of methyl mercaptan was found in strawberries, with dimethyl disulphide in still smaller traces (Winter, 1963). Pribele and Vasatko (1967) found that, compared with other fruits, strawberries had a relatively high carbonyl content.

Some attempts have been made to obtain a flavor concentrate, but it was reported that not more than 1.0 ml of flavor concentrate was obtained from 44 lbs of

strawberry fruit (Bidmead and Welti, 1960). It was also reported that about 35 odorous substrates have been isolated, but it was still impossible to reconstitute a really fresh flavor (Darrow, 1966).

Changes in Odor Constituents

Anmed and Scott (1963) applied gas-liquid chromatography in order to examine the effect of maturity of the fruit, cultivars and storage duration on volatile emanation from strawberry fruits. Chromatograms from the different treatments were only related to each other, and the amount of each component was not determined. For the maturity examination, completely ripe and unripe (about three-quarter ripe) fruits of the cultivars 'Dixieland' and 'Fairfax' were used. The volatile profile (Figure 1) shows the results from the maturity test. It is obvious from Figure 1 that both cultivars have a much greater evolution both in number of compounds and concentration from the ripe fruits than from not fully ripe fruits. When the evolution of volatile compounds was determined by gas chromatography after the berries had been stored at room temperature for 0, 6, 24, 48, and 96 hours, there was a decrease in number and concentration of volatiles with increased time in storage. Winter (1963) also obtained results which showed that storage of strawberries rapidly reduced the volatile sulphur compounds markedly. When

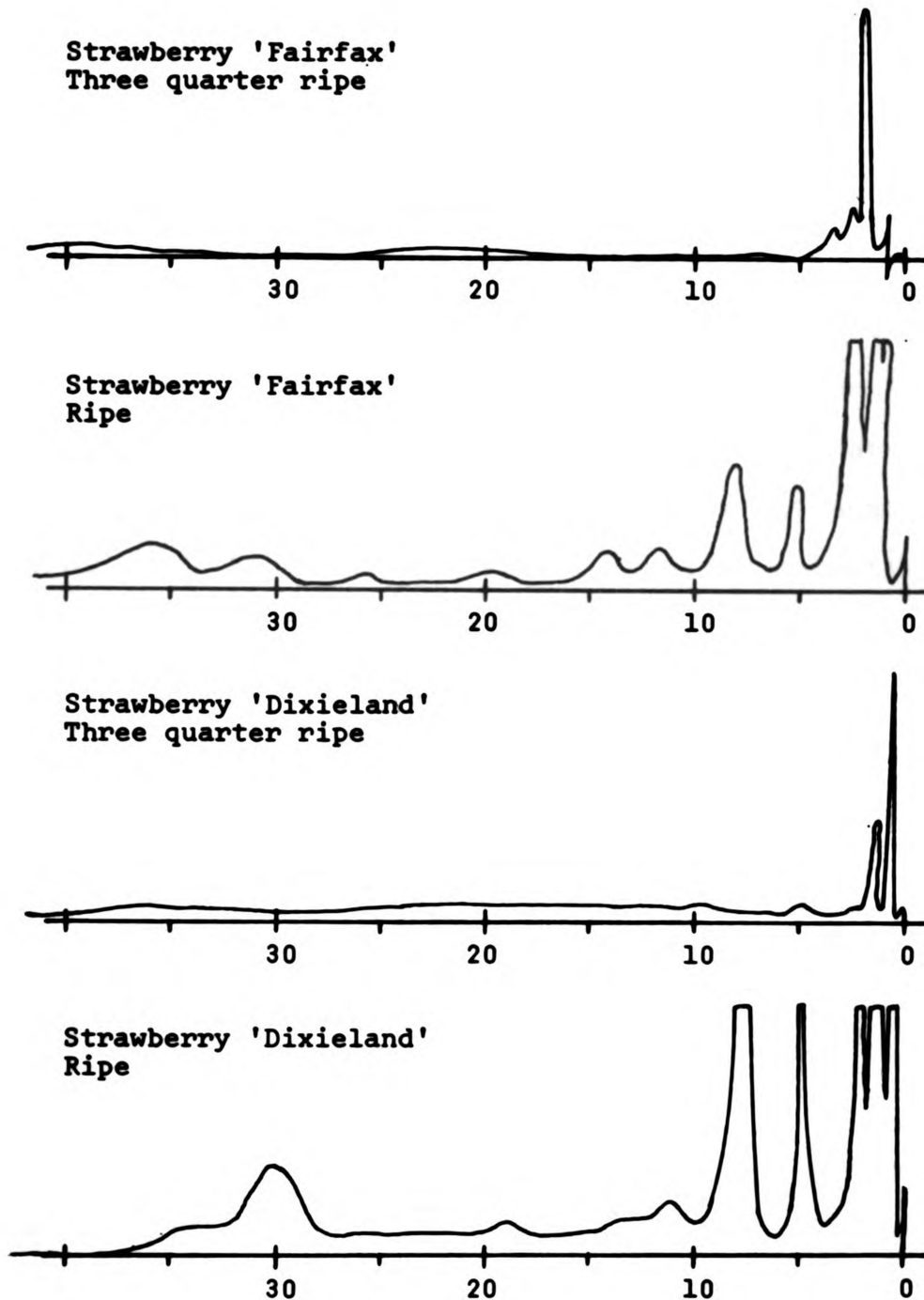


Fig. 1. Effect of ripeness on chromatograms obtained from vapor above fruits from two cultivars (Ahmed and Scott, 1963).

the fruit was somewhat deteriorated, no volatile sulphur compounds at all could be observed from some samples.

Nutritive Constituents

This characteristic of quality is one which the consumer cannot evaluate with his senses, yet it is of real importance to his health and economic welfare (Kramer and Twigg, 1966). Because the nutritive values cannot be sensed this aspect is rarely considered in the market place, with the possible exception of institutional buyers. Even the latter, however, consider nutritive values only when deciding which commodity to buy, rather than the specific lot which they are to purchase. Nutritive value is not, therefore, of great commercial importance, except when it is related to potential promotional activity. Even in this context more emphasis is placed on the general commodity than on specific lots. Promotion based on vitamin C content of oranges is an example of a commercially feasible project and one which has benefited the entire industry.

The nutritive figures in Table 2 may be considered as average values for strawberries, at least for the U.S. Because of the promotion factor mentioned above, it could be of some interest to compare some of the significant nutritive values with those for other fruits. According to Walt (1950) and Zubeckis (1963) strawberries

TABLE 2.--Nutritive composition of 100 grams edible portion of strawberry fruits.

Food		Carbohydrate		Ash		Ca		P		Fe		Vit A		Thia- min		Ribo- flav		Nia- cin		A.A.	
Water	energy	Protein	Fat	Total	Fibers	Gram	Gm.	Gram	Gram	Mg	Mg	Mg	I.U.	Mg	Mg	Mg	Mg	Mg	Mg	Mg	Mg
89.9	37	0.8	0.5	8.3	1.4	0.5	28	27	0.8	60	0.03	0.07	0.3	60	0.03	0.07	0.3	60			

Source: Table 1, USDA Handbook No. 8 (Walt, 1950).

have a relatively high content of calcium and iron. Compared with other fruits, strawberries also have a high content of ascorbic acid. As Table 2 shows, strawberries have 60 mg/100 grams fresh weight of ascorbic acid whereas oranges have 49 mg/100 grams fresh weight (Walt, 1950).

Changes in Nutritive Value

The most significant change in nutritive value is the increase in the water content during ripening of strawberries (Culpepper et al., 1935).

Since ascorbic acid may play an important role in the most active metabolizing cells and since vitamin C has nutritive value, this compound has been studied also in strawberries (Mapson, 1958). When strawberries were harvested early (at the half red stage) the ascorbic acid content increased after harvesting, but it never did reach the same amount as if they were ripened on the plant (Darrow, 1966). Highest vitamin C was found in berries directly exposed to the sun during ripening on the plant. As the strawberries reached an over-ripe condition, the internal cell wall constituents started to leak, and the ascorbic acid content was found to decrease rapidly (Burkhart and Lineberry, 1942). This was due to rapid oxidation of ascorbic acid when the cell contents were mixed, similar to what occurs after bruising of the tissue (Burkhart and Lineberry, 1942).

Decline in ascorbic acid content was found to be relatively rapid in fruits like strawberries with a high respiratory activity compared with other fruits (Kopec, 1966). Lineberry and Burkhart (1943) studied the ascorbic acid content in strawberries after harvesting. A very small change in ascorbic acid was found after three days at 5°C or after 2 days at 25° C when the fruit was healthy and unbruised. Berries punctured to simulate bruising lost almost half the ascorbic acid content after one day, and all but a trace after the second day. Also after capping the berries (removal of calyx), a very rapid decline in ascorbic acid was found, but not as pronounced as after bruising. Capped berries were reported to lose between 10 and 15 percent vitamin C after being held at 24°C for twenty-four hours and between 85 and 90 percent after forty-eight hours (Darrow, 1966).

Texture (or Kinesthetics)

This characteristic deals with the sense of feel (Kramer and Twigg, 1966). The texture may be felt with the fingers of the consumers, but it is particularly and relevantly felt in the mouth. The texture is therefore considered an important quality factor.

Pressure testers have not come into practical use to determine proper harvest maturity of strawberries because the color is the factor which naturally determines the time of harvesting. However, objective

measurement of texture is needed to determine the maturity changes during the transit and display period, and also by breeders as an aid in the evaluation of cultivars and breeding material (Ourecky and Bourne, 1968). A firm flesh and tough skin are two important characteristics which strawberry breeders strive to incorporate into new cultivars. This is because firm fruits are less susceptible to bruising, hence they will have longer shelf life and will be more suitable for mechanical harvesting.

A number of methods have been devised to measure the firmness of strawberry fruits: a) by using plungers (Bourne et al., 1966; Burkhart, 1943; Clark, 1928; Darrow, 1932; Magness and Taylor, 1925); b) compressors (Bourne et al., 1966; Verner, 1931; Haller et al., 1933); and c) needles to penetrate the fruit (Hawkins and Sando, 1920). It has been difficult to obtain uniform results with these pressure testers because of the influence of factors which are difficult to control. Temperature of the berries was found to have some influence on fruit firmness (Haller et al., 1933; Hawkins and Sando, 1929, Rose et al., 1935 and Ourecky and Bourne, 1968). As the temperature increased, flesh firmness and skin toughness decreased. Large berries were reported to be more firm than the smaller berries (Burkhart, 1943). Darrow (1932) and Ourecky and Bourne (1968), however, reported

the small fruits to be more firm than the large ones. Culture methods also seem to influence the texture, e.g., fruits which ripened in the sun were found to be more firm than berries ripened in shade conditions (Burkhart, 1943).

Wide variation was also reported to occur among fruits within samples and within individual fruits (Burkhart, 1943). With improved measurement methods, however, real differences were observed between cultivars (Burkhart, 1943; Ourecky and Bourne, 1968). Ourecky and Bourne (1968) compared 64 different cultivars and selections with respect to flesh firmness and skin toughness. As far as skin toughness was concerned 'Marshall' was found to have least resistance to penetration through the skin (180 grams resistance) whereas a new selection, 'New York 1175' , had the toughest skin (468 grams resistance). For flesh firmness, 'Senga Precosa' was found to be the softest cultivar with 370 grams in resistance, whereas 'New York 844' had 1232 grams resistance. The new selections were generally found to be the toughest. 'Senga Sengana' which is the most important cultivar in northern Europe was found to be relatively soft both in skin and flesh firmness.

Changes in Texture

Softening of the flesh is obviously one of the most significant changes during ripening. It seems to be of

most interest, however, to find at which stage of ripening the softening occurs most rapidly and pinpoint bruising susceptibility at different stages. Microscopical examinations of sections and chemical analysis from fruit during maturation indicated that cell enlargement of the parenchyma cells of the cortex was accompanied by a decrease in the amount of cell wall material of the fruits (Neal, 1965). This process was most marked from the early pink stage where the fruit was still hard to a uniform red stage where the fruit was ripe but firm. Wade (1964) reported also the greatest textural change occurred from the early red stage to the uniform red stage. Culpepper et al. (1935) observed that the transition from the stage of whitening to full ripeness was accompanied by a very rapid decrease in resistance to puncture. Burkhart (1943) presented data (Figure 2) which showed that the berries softened more rapidly from the white stage to the pink than from pink to fully ripe. Ourecky and Bourne (1968) found the most rapid change from the under-ripe to the full-ripe stage, whereas no significant difference was observed between fully-ripe and slightly over-ripe. Interpretation of these data is somewhat complicated because the different investigators may have compared slightly different stages of maturity and have used many different cultivars. Also, different terminology for the same stage of maturity may have been

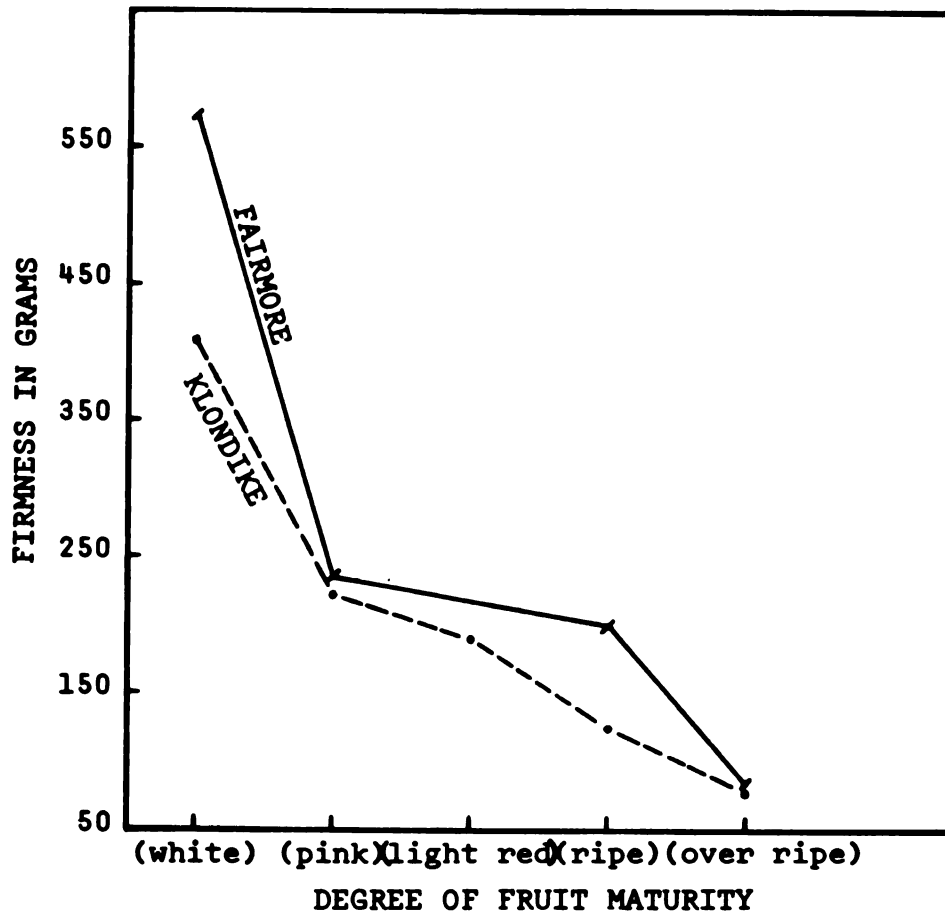


Fig. 2. Firmness of two cultivars of strawberries at five different stages of maturity (Burkhart, 1943).

employed. The data from Burkhart (1943) in Figure 2 indicates an "average" softening curve for strawberries. The relative softening is most rapid from the white to the early red (pink) stage and it proceeds more slowly from the red (pink) to the ripe stage. From the ripe to over-ripe stage there are differences between cultivars in the rate of softening. In conclusion, it should be obvious that strawberries should be harvested and handled at as early a stage as possible in order to prevent bruising of the fruit.

Color

Color is defined as an appearance characteristic properly attributed to the spectral distribution of light (Kramer and Twigg, 1966). Gloss is also an appearance characteristic which is considered to be important for strawberries (Kramer and Twigg, 1966). It is not easy to distinguish between color and gloss, but one lot of strawberries may appear more desirable than another because of a different "finish."

The terminology used to characterize cultivars of strawberries for color and gloss can be confusing for non-breeders. Darrow (1966) used terms such as 'bright red', 'glossy red', 'attractive appearance', 'beautiful red color', 'deep red', 'glossy light red', 'light red', and 'attractive bright red'. Breeders also use a

subjective measurement combined with a rating system from 1 to 10 for comparison of color of cultivars (Darrow, 1966). As a more accurate and objective measurement, color names can be related to wave length of light and used to evaluate color for strawberry cultivars (Darrow, 1966).

The major pigment in strawberries is an anthocyanin and was reported to be pelargonidin-3-glucoside (Lukton et al., 1955; Co and Markakis, 1966). Carotenoid content in strawberries was reported to be very low; ca 1.5 ppm on a fresh fruit basis (Galler and Mackinney, 1965). At such a low level, the carotenoid contribution to the color is negligible (Galler and MacKinney, 1965). Chromatographic analysis indicated that the red color anthocyanin in strawberries was attributed to a combination of 5 components (Habid and Brown, 1956).

Changes in Color

Changes in color during ripening in strawberries is obvious. Since the pigment is anthocyanin, the color changes will follow formation of this pigment. It is evident that the pigment is formed at the same rate as sugar content increases. Sugar is considered to be a precursor for anthocyanin (Thimann and Edmondson, 1949; Co and Markakis, 1966), but cinnamic acid and shikimic acid were found to be better precursors for anthocyanin in strawberry fruits (Co and Markakis, 1966). When

several labelled compounds were administered to detached strawberry fruits, and the incorporation of the label into anthocyanin was measured, cinnamic acid and shikimic acid were the most efficient precursors, but they were followed by glucose and fructose. Normally, light is considered to be necessary in formation of pigment (Thimann and Edmondson, 1949). As discussed in more detail later, light was found to have practically no influence on color formation when strawberries ripened detached from the plant (Austin et al., 1960). In that experiment, however, the fruit had some color when harvested. About 10 percent pink was the characteristic for the lowest colored treatment.

Discussion

In order to maintain and extend the demand, it is important that high-quality fruit be placed on the market. When the consumer receives the berries they should be at the stage where they have the characteristics of a ripe and healthy fruit. It is color development which mainly determines whether they are to be harvested or left for the next harvest. Because color is the main criterion of ripening, it is of interest to see if the other quality factors follow the same pattern of color development. Not surprisingly, it seems as if other significant ripening changes follow the color change very closely. The sugar content increases markedly when the color develops,

as does flavor. For example, the amount and number of volatiles from the slightly underripe to fully ripe stage increases dramatically. One aspect which is not clear is whether the fruit will obtain normal flavor constituents when harvested unripe and ripened detached from the plant. In the next section this problem will be discussed, but only in relation to subjective evaluation. It should also be kept in mind that there is a loss of volatiles during storage, and particularly in fruit which have started to deteriorate. Thus, the quality of any fruit cannot be expected to be as good some days after harvest, even if they have an unchanged appearance.

In order to breed cultivars which are suitable for mechanical harvesting and transportation over great distances, firm flesh and tough skin are two characteristics which breeders try to incorporate. Data presented shows that some of the new cultivars are much firmer than those used today, which indicates that strawberries will be tougher and firmer in the future.

FACTORS TERMINATING STORAGE LIFE

The life expectancy of strawberries is to a great extent dependent on the respiration rate, growth rate of decay organisms, transpiration loss and the stage of maturity at harvest. These factors will in turn be discussed in relation to the factors that affect them.

Respiration

Respiratory intensity can be considered as one measure of the rate at which plant metabolism is proceeding. Respiration rate has in fact been shown to parallel the rate of strawberry fruit metabolism and ripening and the rate of development of decay organisms (Maxie et al., 1959b). As such, this rate is often taken as an indication of the potential post-harvest life of the fruit. A high respiratory intensity is, for instance, associated with rapid fruit deterioration and a short storage life. Respiration rate is measured by the uptake of oxygen or evolution of carbon dioxide of the tissue, and is expressed as ml O₂ uptake or CO₂ evolution per kg of tissue per hour. Under normal aerobic conditions, the ml O₂ uptake and CO₂ evolution will be similar. Compared with other fruits,

strawberries have a high respiration rate. At 20°C, strawberries were found to evolve 65 ml CO₂/kg/hour, whereas grapes evolve 12 ml CO₂/kg/hour (Biale and Young, 1962). Pears evolve 33 ml CO₂/kg/hour at the climacteric peak. Respiration rate is affected by temperature, atmospheric composition, genetic background, stage of fruit development (maturity) and relative humidity. The influence of these factors is considered in turn below.

Influence of Temperature

Generally, respiration of plant tissues follows Vant Hoff's rule¹ which states that the rate of most chemical and bio-chemical reactions including respiration, increases two to three times with every 10°C rise in

¹Q₁₀.

Calculation of respiration rate from temperature coefficient (Q₁₀) by the van't Hoff's rule:

$$Q_{10} : \left(\frac{K_2}{K_1} \right)^{\frac{10}{t_2 - t_1}}$$

Where K₂ and K₁ are respiration rates at temperatures t₂ and t₁ given in °C.

temperature (Hardenburg and Lutz, 1968). For life processes in plant tissues, this will not be true below the freezing point and above about 30°C. Also, the Q_{10} may not be constant within this range.

Table 3 shows the effect of temperature on the respiration rate of strawberries found by measurement of CO_2 evolution (Haller et al., 1941; Maxie et al., 1959b). The data gives the rate in relation to respiration at 0°C which is unity.

In addition to the effect of temperature on respiration, it should be noted (Table 3) that the relative response (Q_{10}) was highest between 5°C and about 20°C. The respiration rate did not increase markedly at temperatures above 30°C.

The actual loss of sugar can be measured from the quantity of CO_2 evolved. Considering the data by Haller et al. (1941) above, it was reported that, on the average, 15.2 mg CO_2 per kg of fruit per hour was evolved at 0°C. Assuming that the CO_2 evolved resulted from the complete oxidation of hexose sugar, this rate would be equivalent to the loss of 0.025 grams of sugar per 100 grams of strawberries in 24 hours. Since the Q_{10} was found to be 3.4 between 0° and 10°C the loss would be 3.4 times as great at 10°C as at 0°C. The calculation indicates a considerable potential loss at high temperatures to which strawberries may be exposed during the post-harvest period.

TABLE 3.--The influence of temperature on respiration rate in strawberries and Q_{10} to each temperature range.

Temperature degree C	Respiration rate 0°C is unity	Q_{10}	Temperature degree C	Respiration rate 0°C is unity	Q_{10}
0	1		0	1	
4.5	1.7	3.2	5.0	1.4	2.0
10.0	3.4	3.6	20.0	7.2	3.4
15.6	5.3	2.3	30.0	19	2.6
21.1	8.6	2.4	38.8	19.6	1.0
26.7	13.0	2.0			

Source: Haller et al. (1941)

Source: Maxie et al. (1959b)

Figure 3 shows the influence of temperature on the respiration rate of the cultivar 'Shasta' (Maxie et al., 1959b). The profound effect of temperature on respiration is clearly shown in this graph. The authors also reported that at the high temperatures: 30° and 38.8°C, the berries were quickly destroyed. After about six hours, oily red droplets appeared on the surface of the berries, indicating skin damage, and this was followed by bleaching of the red in the berries, and still later by mushy breakdown of the tissue.

In relation to post-harvest life and temperature, it has been shown that the decay organisms on strawberries have a similar response to temperature as the life processes of the berries, a point which is considered in more detail below (Maxie et al., 1959b).

Influence of Modified Atmospheres

As discussed more thoroughly in the next section, oxygen and carbon dioxide concentration have both a qualitative and quantitative influence on the respiration. Haller et al. (1941) measured respiration rate on strawberries in air and in atmosphere of pure nitrogen at 0°C. Figure 4 shows the data they obtained with two cultivars over a period of 25 days. It may be seen that the respiration rate is markedly inhibited under anaerobic conditions for both cultivars. It should be noted,

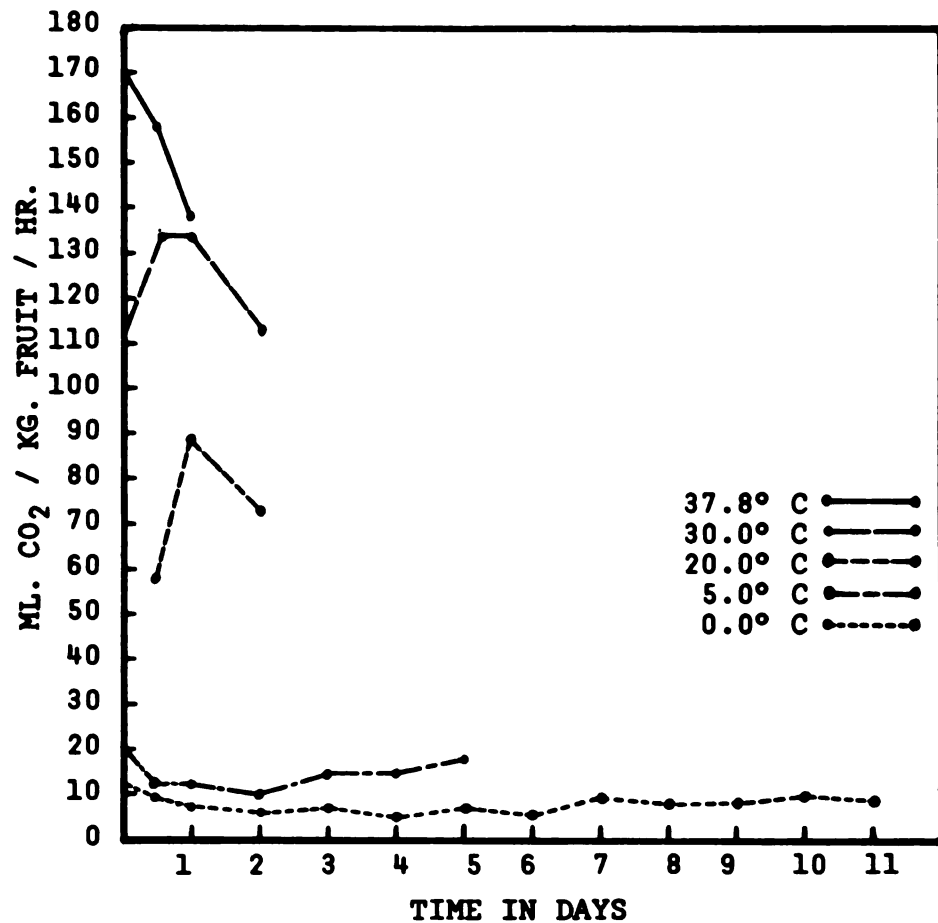


Fig. 3. The influence of temperature on the respiration rate of 'Shasta' strawberries (Maxie et al., 1959b).

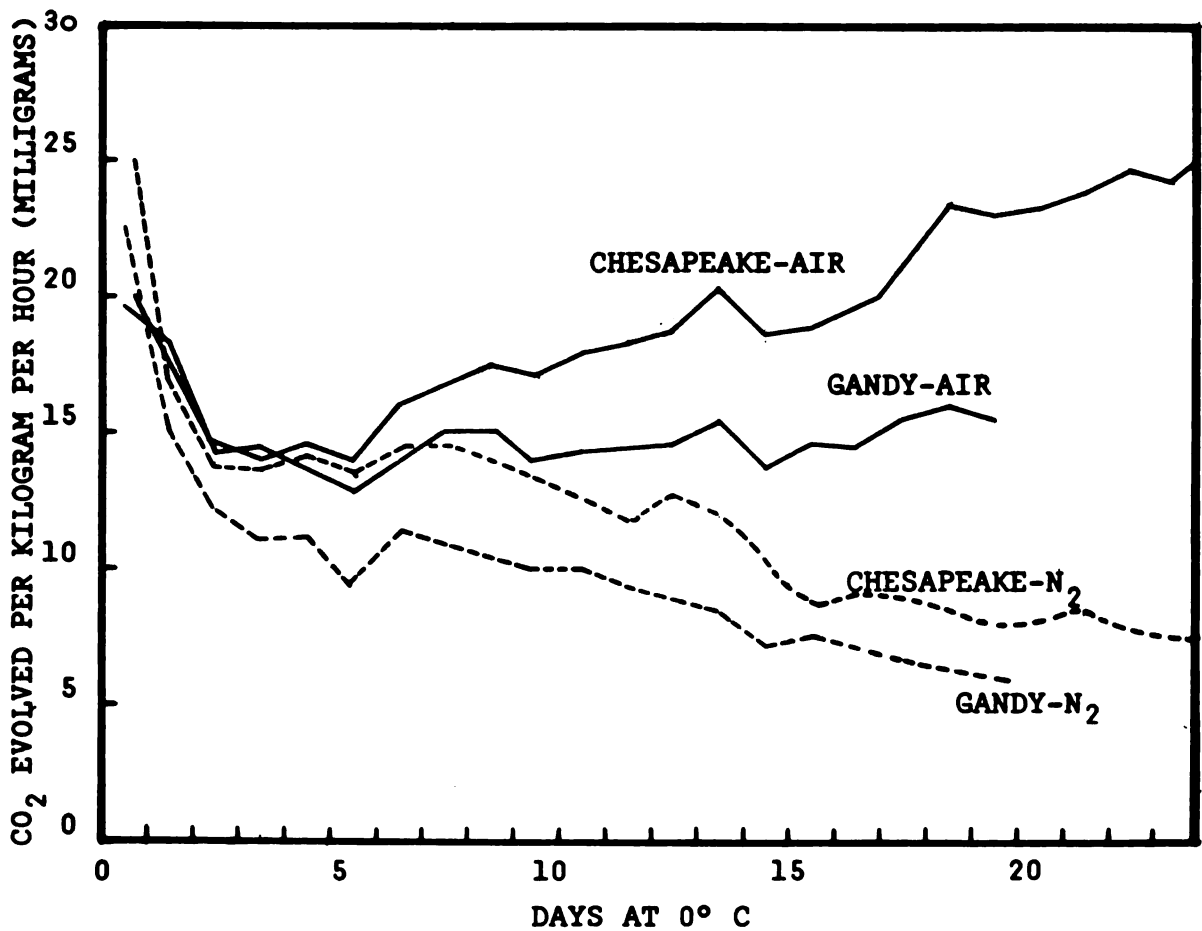


Fig. 4. The influence of the atmosphere on the respiration rate of two cultivars of strawberries held at 0° C. Carbon dioxide evolution of fruit held in air and in pure nitrogen was measured (Haller et al., 1941).

however, that under such anaerobic conditions only one-third as much CO_2 will be produced from the same amount of sugar as under aerobic conditions. The sugar loss will therefore be higher in anaerobic conditions, even if the CO_2 evolution is lower than under aerobic conditions. Analyses of the berries after holding in nitrogen showed that considerable amount of alcohol was formed (Haller et al., 1941). This caused undesirable flavor changes in the berries.

Influence of Relative Humidity

The relative humidity of the surrounding atmosphere is not likely to influence directly the respiration activity of fruit such as strawberries which have a high water content (Haller et al., 1941). These workers showed that there were no apparent differences in respiration rate in strawberries in various relative humidity at 15.6°C . Gerhard (1930) on the other hand, reported a temporary increase in respiration with low relative humidity.

Influence of Genotype and Stage of Maturity

It has been shown that the respiratory activity in strawberries is closely correlated with the dry matter content (Haller et al., 1941; Haller et al., 1933). It was also found that the percentage of dry matter in the fruit was correlated with the firmness of the fruit.

Haller et al., (1941) concluded that most of the cultivars with high respiratory activity had relatively firm berries that hold up well during shipment, and many of the cultivars with a low respiratory activity had soft berries of poor shipping quality. Overholser et al. (1931) also found the respiratory rate of several firm cultivars to be greater than those for several soft cultivars. Thus, strawberry cultivars with high sugar content and high respiration rate on a fresh weight basis, appear to be associated with good keeping and shipping quality. There are also changes in respiration rate of the same cultivar within a season and from one season to another. Measurements of respiration and the dry matter during certain seasons and several harvests of the same cultivar showed that both the percentage of dry matter and the respiratory activity increased later in the season (Haller et al., 1941). Overholser et al. (1931) also observed an increase in rate of respiration with advance of the season. As discussed previously, these changes in dry matter and respiration rate could be due to changes in the growing conditions. For example, the soil moisture could decrease as the season advances, which has been shown to give a higher percentage of dry matter and sugar (Kimbrough, 1931; Rootsi, 1966).

In many fruits, a rise in respiration is observed when the ripening process gets under way; such fruits are

termed climacteric (Biale, 1960). Biale (1960) has, however, classified strawberries as non-climacteric. This type of fruit is characterized by a gradual decline in respiration throughout maturation and into senescence. The changes characteristic of ripening often occur at a constant rate in non-climacteric fruits. Nonetheless, the differences between the two groups cannot be explained solely by the different rate of metabolism because fruits like strawberries and other perishable fruits respire as actively as, or more actively than, some fruits of the first class (Biale, 1960). There is evidence that the respiration rate of strawberries increases with maturity, although it may not have the same pattern as a typical climacteric fruit (Biale, 1960).

Overholser et al. (1931) reported a 50 percent increase in respiration rate from immature to mature strawberries. The respiratory activity of strawberries was measured at three stages of maturity (Haller et al., 1941); thus:

Stage of maturity:	Green	Half ripe	Ripe
Average ml CO ₂ evolution/kg fruit/hour:	35.6	42.5	50.8
Rate ripe fruit is unity:	0.70	0.84	1.0

The results show a rather consistent linear increase in respiratory activity with increase in ripeness. The half ripe berries evolved an average of 16% less CO_2 and the green berries 30% less than the fully ripe ones. No opinions were found as to whether this increase in respiration is necessary as an energy source for the ripening process or not.

Influence of Chemical Agents and Irradiation

N^6 -benzyladenine (Kinetin) has been shown to delay the symptoms of senescence of several vegetables during the storage period. Dayawon and Shutak (1967) applied 150 ppm N^6 -benzyladenine spray to strawberry plants three days before harvesting. Respiration rate of the harvested berries was observed at 21.1°C . Results of these respiration measurements are presented in Figure 5. The rate of CO_2 evolution was markedly depressed for berries treated with N^6 -benzyladenine compared with the control sample. It should also be observed that this difference in the rate of respiration persisted throughout the 30 hours duration of the experiment. Although no difference was observed in appearance of the treated and nontreated berries after the experiment, it was concluded that the inhibition of the respiration may be an indication that N^6 -benzyladenine may prolong the shelf life of strawberries, and that further evaluations of this and related

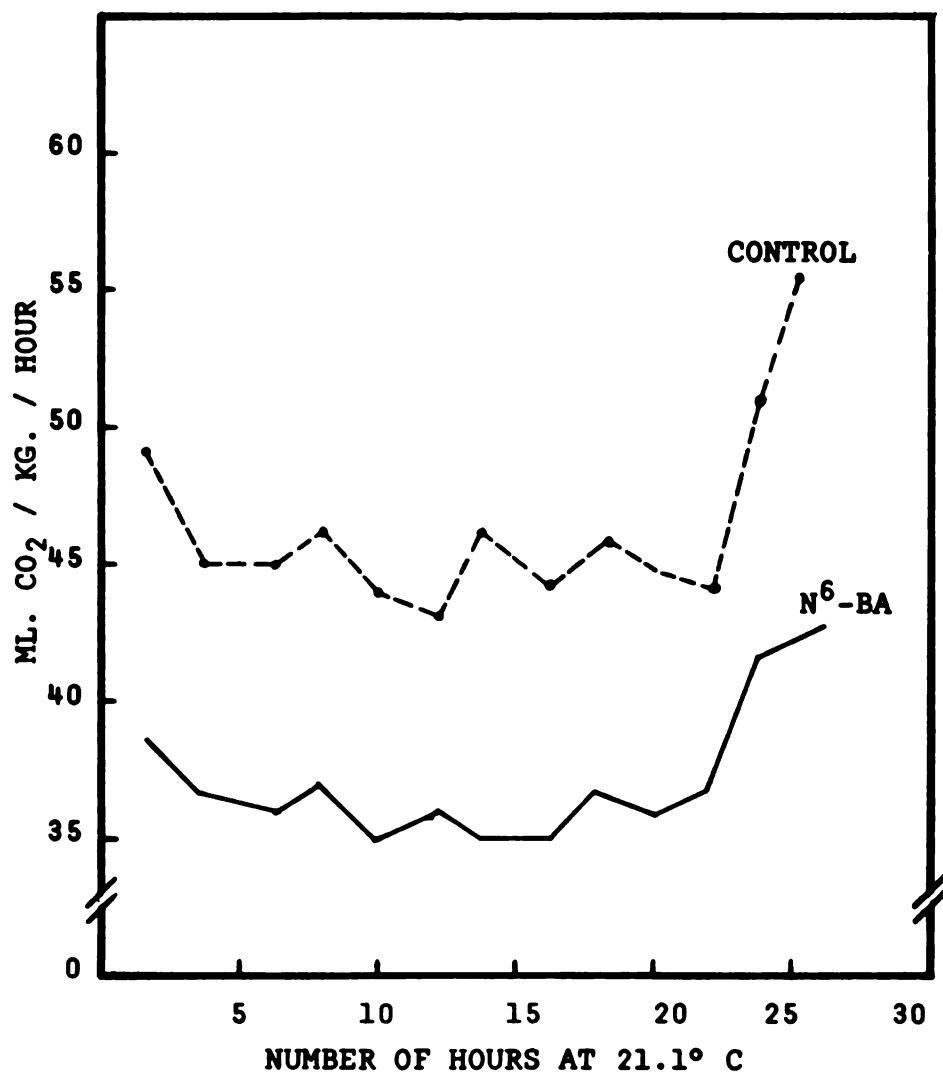


Fig. 5. The influence of N⁶-benzyladenine on the respiration rate of 'Geneva' strawberries at 21.1° C. The fruit was sprayed with 150 ppm N⁶-benzyladenine 3 days before harvest (Dayawon and Shutak, 1967).

compounds on the keeping quality of strawberries is desirable. Mercier and MacQueen (1965) found that irradiation of strawberries exhibited some beneficial effect upon decay control of strawberries. However, the respiration rate was found to increase after irradiation treatments (Maxie et al., 1964). When the respiration rate of irradiated 'Shasta' strawberries was measured at 5°C., berries subjected to 200 Krad, showed a 45 percent increase in carbon dioxide evolution 24 hours after treatment. By the end of 48 hours following treatment, the respiration rate of the irradiated berries was 12 percent above that of the control.

Decay Organisms (Pathological)

A considerable quantity of strawberries are lost due to the influence of decay organisms during the marketing period. In the U.S., spoilage losses in marketing fresh strawberries were estimated to be 15 percent (Droge, 1965). Of this loss, a large part was caused by decay organisms, mostly fungi. The main fungal diseases of harvested strawberries are described below. The influence of environmental conditions such as temperature, atmospheric composition and relative humidity on the growth rate of decay organisms is also discussed under the appropriate headings.

Principal Diseases of Harvested Strawberries

Gray mold rot.--Gray mold rot is the most serious fruit rot on strawberries all over the world (Darrow, 1966). It is most common, however, in the cooler producing regions (Harvey and Pentzer, 1960). It was also reported that this is the most important and prevalent post-harvest fungal disease on strawberries in Norway (Gjaerum, 1962). Gray mold rot is caused by the fungus, Botrytis cinerea, which is widespread in nature. Its spores, which are produced in great quantities, are wind-borne and, in wet weather, almost any senescent, dead or delicate strawberry plant tissue can be attacked. The fungus also attacks various parts of the strawberry flowers soon after the buds open and establishes a symptomless latent infection there (Jarvis and Borecka, 1968). The latent infection is usually quiescent throughout the flowering and green fruit stages, but under suitable conditions they develop gray mold on ripening berries. Harvey and Pentzer (1960) described gray mold rot on strawberries as follows: "Gray mold rot of strawberries is firm and fairly dry superficially. There is no marked collapse of the tissues and little leakage of juice. Affected areas on the berries are brown at first, but as the fungus spreads over the entire berry, powdery, gray fructifications are produced."

Leather rot.--Leather rot refers to the effect of the fungus, Phytophthora cactorum, a disease of strawberries that is characterized by a rather slight softening of affected tissues. It causes both external and internal discoloration and bitter taste (Harvey and Pentzer, 1960). Occasionally this disease can cause loss on the market. Louisiana strawberries on the Chicago market were damaged up to 100 percent by leather rot in the spring of 1964 (Wright et al., 1964).

Phizoctonia rot.--Rhizoctonia rot is caused by Rhizoctonia solani. Affected strawberry tissue is dry, spongy, and dark brown to black. There is usually a distinct margin between decayed and sound tissues (Harvey and Pentzer, 1960).

Rhizopus rot.--The fungus (Rhizopus stolonifer) has a wide distribution in nature (Harvey and Pentzer, 1960). The organism has been described as Rhizopus nigricans and R. stolonifer (Walker, 1957). In this thesis, it will be referred to as Rhizopus stolonifer. It causes a very soft rot of strawberries, breaks down the tissues and allows the juice to escape. In late stages there is almost always an odor of fermentation.

Others.--Gloesporium rot, stem-end rot, Sclerotinia rot and tan brown rot are also decay organisms which occasionally and locally may cause post-harvest rot on strawberries (Harvey and Pentzer, 1960).

Influence of Temperature

All the decay organisms that attack strawberries are by definition alive, and as such, temperature has a tremendous influence on the rate of their life processes (Maxie et al., 1959b). As discussed in the previous section on the influence of temperature on respiration and the other life processes of fruit, the growth of these organisms will also increase two- to fourfold for each 10°C increase in temperature (Maxie et al., 1959b; Mitchell et al., 1964). The different fungi do, however, have a minimum temperature which is required for significant growth. The following temperatures are considered to be those at which the different decay organisms do not grow, or grow very slowly (Harvey and Pentzer, 1960; Stephen, 1961):

Gray mold rot	-0.5°C
Leather rot	5 °C
<u>Rhizoctonia</u> rot	5 °C
<u>Rhizopus</u> rot	10 °C
Tan brown rot	5 °C

It will be noted from these figures that most of the decay organisms do not grow significantly if the fruit is cooled down to 5°C, although the gray mold rot organism does grow slowly even at the freezing point. Keeping strawberries at -1 to 0°C, the lowest temperature that

strawberries can be kept without freezing (Whiteman, 1957), will prevent the growth of most decay organisms.

High temperatures on the other hand will easily kill the spores of these fungi. Smith (1923) reported that most spores of Botrytis cinerea were killed after about 6 hours at 37°C. The effect of temperature was found to be a function of exposure time and temperature. At 50° C most of the spores were killed after exposure for about one hour. This range of temperatures is so low that the same temperatures may not injure the tissues, and heat treatment may be a method to control decay organisms in strawberries. Heat treatment of strawberries is discussed in more detail later.

Influence of Modified Atmospheres

Oxygen.--Brown (1922) studied the growth of various fruit-decay fungi at different concentrations of oxygen. The lowest concentration applied was about 1 percent oxygen, but even this low concentration was reported to have very little or no retarding effect upon growth of Botrytis cinerea. Similar results were obtained when the following fungi were studied in regard to growth at low oxygen concentrations in the atmosphere: Botrytis cinerea, Alternaria tenuis, Cladosporium herbarum and Rhizopus stolonifer (Follstad, 1966). The growth rate was tested in the following concentrations of oxygen: 0%, 0.25%, 0.50%, 0.75%, 1.0%, and 21% (air). The results

from this experiment are presented in Figure 6. It should be noted that only about 20 percent inhibition of growth was found at 1 percent oxygen, and that the growth response for lower concentrations was relatively linear for all fungi tested.

It was also reported that Botrytis cinerea produced abundant aerial mycelia when grown in 1 percent oxygen or in air. Most isolations produced spores in 5 days in air, but no spores developed in 1 percent oxygen or below. Alteraria tenuis and Cladosporium herbarum, however, sporulated in all atmospheres tested except 0 percent oxygen, in which no mycelial growth was observed. Couey et al. (1966) studied the effect of oxygen concentrations of 0, 0.25, 0.50 and 1 percent oxygen on the decay of five cultivars of strawberries under simulated commercial conditions. Half of the berries in each treatment were examined after 5 days at 3°C in the indicated atmospheres (examination 1), and the other half after an additional 2 days in air at 15°C (examination 2). Most of the decay observed was caused by Botrytis cinerea, but in some experiments, Rhizopus stolonifer was also found. The percentage of decay in the five cultivars of strawberries was low at examination 1 and no difference in decay of berries held in different atmospheres could be detected. At examination 2, less decay had developed in berries previously held in 0.50% or less than in air or 1%

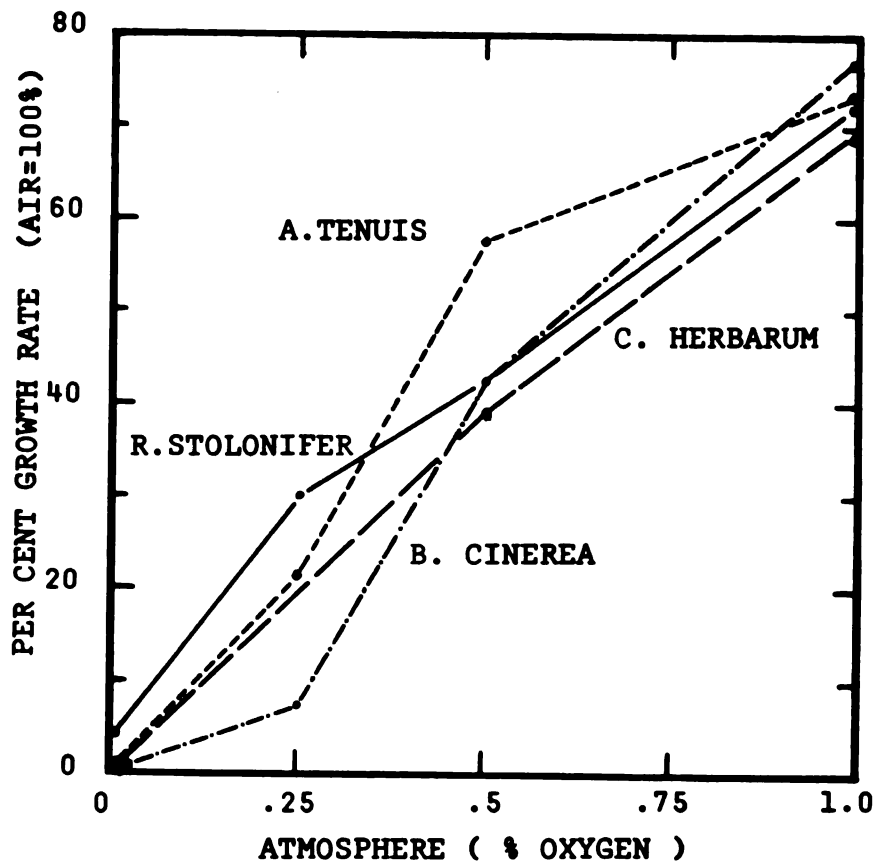


Fig. 6. Average growth response of Alternaria tenuis, Rhizopus stolonifer, Cladosporium herbarum, and Botrytis cinerea cultured on two agar media at 15° C in atmospheres containing 1% oxygen or less (Follstad, 1966).

oxygen. The results are presented in Table 4. Most of the visible decay development occurred at 15°C after the berries were removed from the modified atmospheres. The reduction in decay of berries in the low oxygen atmosphere found in this experiment, corresponds closely to the linear growth reduction of decay organisms presented in Figure 6.

Similar results were obtained by Parson et al. (1964) when they kept strawberries in atmospheres containing 0, 1% and 21% O₂ (air) at 0.5°C for 7 and 10 days. They were examined for decay after an additional 3 days in air at 12.8°C. The mold growth was retarded on berries previously held in 1% and 0% oxygen in relation to those held in air. Hansen (1967) studied the effect of low oxygen concentration on the following cultivars of strawberries: 'Senga Sengana', 'Gorella', and 'Red Gauntlet'. In one experiment, the berries were stored for 7 days at 4°C in 1% oxygen and in 21% (air). When the fruit was examined after removal from the modified atmospheres, 54% was decayed after keeping in air, whereas only 8.5% decayed from the 1% oxygen treatment. Berries stored for 7 days at 15°C in an atmosphere maintained between 0.5% and 1% oxygen, had 66% less decay (breakdown) than berries stored in air under similar conditions. It was also reported that berries stored in low oxygen atmospheres had better color and appearance than the control.

TABLE 4.--Decay of strawberries after storage in low-oxygen atmospheres^a

Examination ^b	Decay at indicated oxygen conc (%)				
	21	1	0.5	0.25	0
	%	%	%	%	%
1	0.8 a ^c	0.8 a	0.8 a	0.8 a	0.7 a
2	10.3 c	8.3 c	4.0 b	4.6 b	2.5 b

^aCombined data from tests with five different cultivars.

^bBerries were examined after 5 days in indicated atmosphere at 3°C (examination 1) and after an additional 2 days in air at 15°C (examination 2).

^cAdjusted geometric means. Means not followed by the same letter are significantly different at the 5% level. There was no significant difference among the cultivars.

Source: Couey et al., 1966.

It should be noted that in this experiment there was more retardation of growth of decay organisms in 1% oxygen than in the other experiments. Hansen (1967) concluded that 0.5% to 1% oxygen in the atmosphere was an adequate concentration for strawberries, whereas Couey et al. (1966) reported that the oxygen concentration had to be maintained between 0.25% and 0.50% before decay was retarded markedly, or before it could be applied economically and commercially.

Carbon dioxide.--Atmospheres high in carbon dioxide have been reported to reduce the activity of decay organisms which attack strawberries (Harvey and Pentzer, 1960). Brown (1922) studied the effect of carbon dioxide concentration on the germination and growth of decay organisms which attack fruits. It was found that fungi vary in their response to high carbon dioxide atmospheres, the variation depending on temperature, concentration of nutrients and on the stage of fungi development. The following figures give the concentrations of carbon dioxide which were found to stop germination of Botrytis cinerea and Rhizopus stolonifer spores at 15-18°C (over a period of seven days):

	Spores sown in water
<u>Botrytis cinerea</u>	20-30% CO ₂
<u>Rhizopus stolonifer</u>	20% CO ₂

The following figures give percent growth (air : 100) of Botrytis cinerea on an apple gelatin substrate at given temperatures and CO₂ concentrations (Brown, 1922):

	air (0.03% CO ₂)	10% CO ₂	20% CO ₂
at 15°C	100	69%	37.5%
at 5°C	100	54%	14 %

Brooks et al. (1932) found that 10-13 percent CO₂ had little effect on growth of Botrytis cinerea and Rhizopus stolonifer on strawberry fruit, 17-19 percent CO₂ had an effect equivalent to a drop of 10°C in the temperature (about 60 percent reduction in decay), 23 percent CO₂ almost completely inhibited the growth of both fungi and 37 percent CO₂ kept them completely in check. Other experiments (Winter et al., 1938; Smith, 1957; Winter et al., 1940) have also shown that carbon dioxide has a greater retarding effect on decay growth the higher the concentration. Relatively low inhibition was found in concentrations below about 15 percent carbon dioxide. Harvey et al. (1966a) reported that strawberries held for 24 hours at 15.6°C or 2.9°C in atmospheres with 20, 30, or 40 percent carbon dioxide had significantly less decay than those held in air, when observed after being held an additional 48 hours in air at 15.6°C. Differences in decay among berries held in 20, 30, or 40 percent carbon

dioxide were not statistically significant, indicating very low benefit of higher concentrations than 20%.

It has been previously shown that low temperature has a great retarding effect on decay. Brown (1922) reported that temperature is a more important inhibitor of decay organisms than high carbon dioxide. If high carbon dioxide atmospheres are to be utilized commercially, it is reported to be valuable only when the temperature cannot be controlled at a satisfactory low level (Harvey et al., 1966a, 1966b, 1967). This is because the low temperature has a greater retarding effect both on decay and respiration rate than high carbon dioxide concentration. Harvey et al. (1966a) found no differences in decay after experimental shipment in high carbon dioxide atmospheres and air when the temperatures were about 5°C, or below, during the transit period. Figure 7 shows the effect of transit temperature and carbon dioxide together on decay of air shipped California strawberries during marketing on Eastern U.S. markets (Harvey et al., 1966a).

When high carbon dioxide concentration was maintained (above about 20%) by help of polyethylene liners, decay did not increase significantly with increase in temperature during transit. The regression curve in

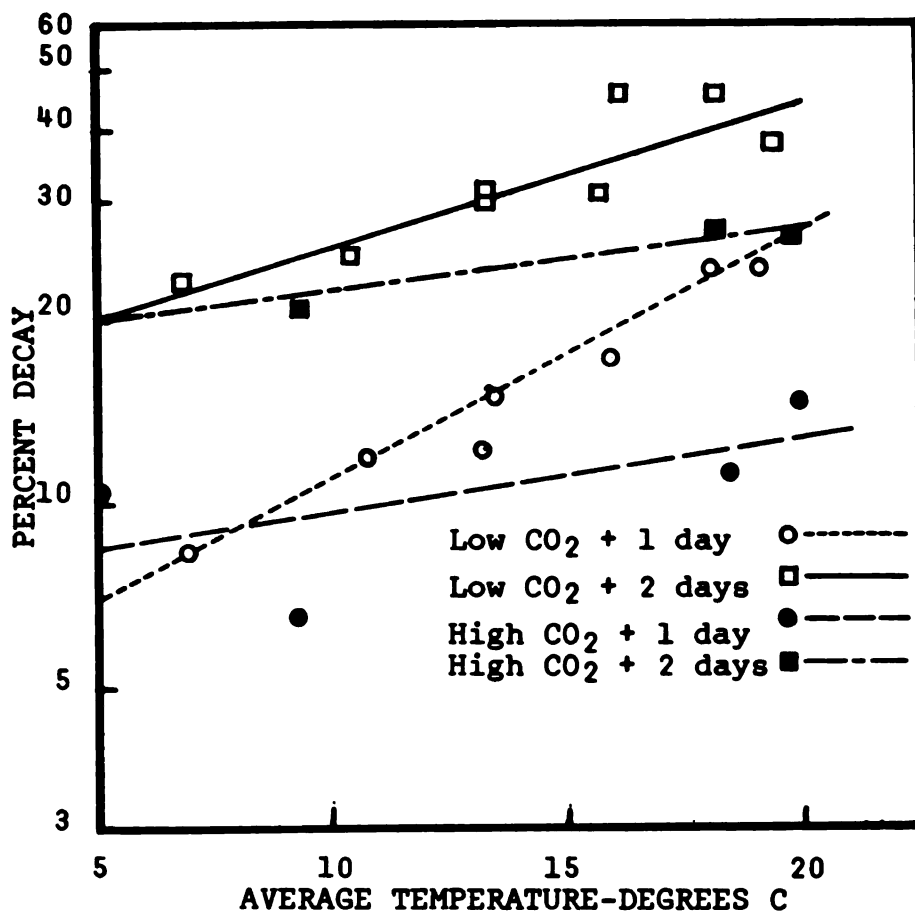


Fig. 7. The effect of transit temperature and carbon dioxide concentration (dry ice) on decay of air-shipped California strawberries during marketing. Fruit was held one and two days at 15.6° C after transit. Decay percentages are plotted on a logarithmic scale (Harvey et al., 1966a).

Figure 7 indicates that at 5°C or below, high carbon dioxide concentration had no significant effect on decay. Similar relationships between temperatures and carbon dioxide atmospheres on decay organisms of strawberries were found in practical air shipping experiments (Harvey et al., 1968). Figure 7 also demonstrates the importance of temperature during transit in normal atmosphere (air). The logarithm of percent decay of fruit in a normal atmosphere was linearly related to the average transit temperature. After 1 day at 15.6°C on the market, the amount of decay doubled for each 8.3°C increase in transit temperature. After two days at 15.6°C the amount of decay doubled for each 12.8°C increase in transit temperature.

Influence of Relative Humidity

The relative humidity per se does not seem to have a considerable effect on growth of decay organisms (Hardenbury and Lutz, 1968). However, if the relative humidity reaches 100% by decreasing the temperature, condensation occurs and the growth is normally considered to be favored. This is discussed in the next section. Condensation on the berries also occurs when the berries are removed to higher temperature.

Influence of Chemicals and Irradiation

Spores of fungi can effectively be killed or inhibited by a number of chemicals (fungicides, etc.) and by irradiation. Such treatments are discussed in

more detail in the next section. There are two basic problems with treatments like these on strawberries. First, they may be harmful or undesirable to human beings; second, they may injure the berries, or cause undesirable quality changes.

Stage of Maturity

The significant ripening changes were discussed earlier. It was shown that the berries are firmer when not fully ripe, hence they reach the market without as much bruising and can be shipped over longer distances if they can be harvested and transported before fully ripe. In this section, changes which occur during ripening of fruit detached from the parent plant and during normal post-harvest handling will be considered. Color development, fruit texture and flavor are the main factors affected by the stage at which strawberries are harvested and they will be considered in that order below.

Color Development as Influenced by Maturity

The color of the fruit was previously shown to be a very important appearance factor for strawberries, and they should have as good color as possible when they reach the market. The brightest and best color will be obtained when they are ripened fully on the plant and sold directly, but satisfactory color will also develop

on the fruit when detached from the plant, provided they have reached a partially colored stage (Rose and Gorman, 1936). Smith and Heinze (1958), studied color development in five cultivars of strawberries (in addition, other quality factors, such as texture, flavor, sugar and acidity were considered) in relation to stage of maturity at harvest. The berries were harvested at the following stage of ripening: a) quarter-colored, b) half-colored, c) three-quarter colored, and d) fully-colored. These were all ripened to the fully ripe stage at 21.1°C and evaluated by a team for color, texture, and flavor. The results are shown in Table 5.

No significant differences were found between color in the post-harvest ripened berries regardless of the color of the berries at picking. The time from picking to full color development varied with the stage of maturity and was approximately two days for three-quarter colored fruit, two to three days for half-colored fruit, and three to four days for quarter-colored fruit.

Sobczykiewicz (1965) studied the color development in 'Senga Sengana' and 'Talisman' strawberries. The fruit were harvested at three stages of ripeness: a) greenish white with 25% pink color, b) pinkish white with 50% pink color, and c) berries with 75% pink color. Each group was ripened at each of the temperatures, 18°, 21°, and 25°C. The time to full color development varied from

TABLE 5.--Average color, texture, and flavor ratings^a of strawberries harvested at different stages of color development

Quality rated and cultivar or selection	Number of tests	Fully colored freshly picked	Fully colored stored at 0°C	Three- quarters colored ^b	Half- colored ^b	Quarter- colored ^b
Color:						
Blakemore	3	---	8.2	8.1	8.2	7.9
U.S. 3763	3	8.7	8.6	8.6	8.4	8.3
Pocahontas	2	8.7	8.7	8.8	8.6	8.5
Fairfax	1	7.7	7.6	7.8	8.1	8.2
Redstar	1	8.2	8.4	7.6	7.7	7.7
Texture:						
Blakemore	3	---	8.8	7.6	7.4	6.4
U.S. 3763	3	7.8	7.6	7.6	7.3	6.9
Pocahontas	2	8.0	8.0	7.9	8.0	7.4
Fairfax	1	7.4	6.5	6.9	6.9	6.5
Redstar	1	7.3	8.1	7.2	7.2	6.8
Flavor:						
Blakemore	3	---	7.1	6.6	6.3	5.4
U.S. 3763	3	8.0	6.6	6.9	6.1	5.3
Pocahontas	2	7.4	6.7	6.2	6.5	5.1
Fairfax	1	7.3	5.6	6.0	5.8	5.5
Redstar	1	7.0	7.9	6.3	5.5	5.4

^aAverage rating by 12 judges on strawberries; 10 equals highest rating, 0 the lowest, and ratings of 3 and below unacceptable.

^bBerries ripened to full color at 21°C.

Source: Smith and Heinze, 1958.

12 hours for the 75% pink berries at 25°C to 84 hours for the 25% pink berries at 18°C. Austin et al. (1960) also studied color development in relation to temperature. A range of fruits of the 'Sparkle' cultivar were harvested from greenish white up to approximately 10% pink. To study the color change, the unripe berries were kept in darkness at four different temperatures: 12.8°, 18.3°, 23.8°, and 29.4°C. They devised a subjective index to express rate and degree of coloring. A value of 0] represented a berry ranging from a greenish white up to 10% pink, 1] a fruit 11% to 35% pink to red, 2] one 36% to 70% pink to red, 3] for 71% to 100% pink and red coloration, and 4] for a completely red berry. Since 25 berry samples were used, a value of 100 would indicate that all fruits were completely red. The result of this investigation is presented in Figure 8. Berries colored completely in 48 hours at 29.4°C; at 23.8°C coloration was completed after 96 hours, and was almost completed after 72 hours. It should also be noted that color development was much slower at 18.3° and 12.3°C. Full color was not reached in either of these latter temperatures after 96 hours. At 18.3°C an index of 90 was finally reached, at 12.8°C an index of only 58 was finally reached. In the same experiment, the influence of incandescent light (25 foot candles at berry level) on post-harvest color development was investigated. At 23.8°C, light slightly

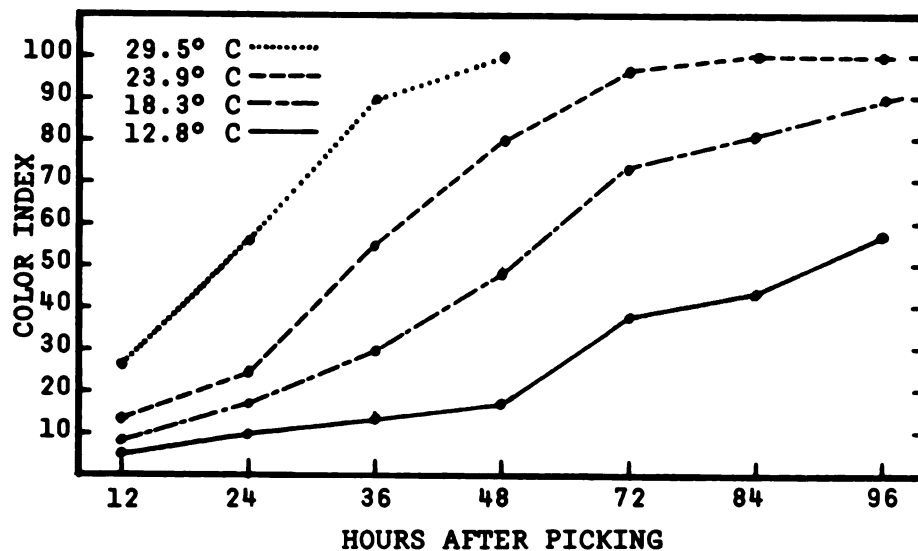


Fig. 8. The influence of temperature on color changes of strawberry fruit (cultivar, 'Sparkle') stored in darkness. The fruit was harvested when showing a color from greenish white to approximately 10 percent pink (Austin et al., 1960).

increased the amount and speed of color development and at 12.8°C the influence of light was negligible.

Pratella and Paltrinieri (1964) harvested strawberries when they were nearly completely unripe or when the first tinge of red was observed. They were ripened for 30 to 40 hours at 28-30°C either immediately or after a week's storage at 0°C. It was reported that the berries ripened satisfactorily and that the method was also promising as a means of control of Botrytis rot. However, if field spraying is done properly, gray mold rot can be controlled satisfactorily before harvest. Nonetheless the method could be of some significance as a means of market regulation.

Texture as Influenced by Maturity

Firmness (or softness) is an important quality factor of strawberries. In order to be of high quality at the time of consumption, the berries should not be too firm, too tough, or too soft or overripe. It was previously shown that one of the important changes which takes place during ripening is the softening of the berries. Of paramount importance, if strawberries are to be picked unripe for distant markets, is the question whether the texture change is similar when the berries ripen attached or detached from the parent plant. Smith and Heinze (1958) subjectively evaluated the texture, using the same team that examined color development. The

fruit was harvested at the same stages of maturity as when color development was studied and ripened at 21.1°C to the fully ripe stage. The results of this study are presented in Table 5. It shows that fruit which ripened detached from the plant attained approximately the same score for texture as the samples which ripened attached to the plant. This was not the case for the least mature samples (quarter-colored fruit) which scored slightly lower for texture when evaluated. This indicates that strawberries should not be harvested earlier than about half-colored if the berries are to obtain a naturally ripened texture.

Flavor as Influenced by Maturity

A number of volatile constituents, soluble solids and acids were previously shown to be the most important agents which contribute to the flavor of strawberries. Smith and Heinze (1958) reported that when subjective differences in flavor were obtained, the flavor differences were almost completely removed by the addition of sugar, thus emphasizing the importance of soluble solids (sugar) as a flavor constituent. The stage of maturity as reflected by flavor was studied by Sobczykiewicz (1965). He reported that strawberries harvested when 50% ripe or 75% ripe obtained almost as high a score for flavor as fruit harvested field ripe when subjectively evaluated. The soluble solids, however, were found to

be higher in berries harvested field ripe than in berries ripened detached from the plant. Austin et al. (1960) found no differences in soluble solids between berries ripened detached from the plant and those ripened on the plant. The soluble solids determinations in this experiment were all done when the berries had reached an index of 4, which was the fully ripe stage. The keeping temperature during ripening was found to have no influence on the soluble solids content, but the fruit needed more time to ripen at the lower temperature. When the judges used by Smith and Heinze (1958) evaluated flavor (Table 5), freshly picked berries were almost always given the highest rating and the quarter-colored the lowest rating for flavor. The differences between the half-colored, three-quarter colored and fully-colored fruits were very small. None of the samples in the experiment were considered to have unacceptable flavor.

The chemical analysis of the ripened fruit of the various stages of color development are summarized in Table 6. These data indicate that the fruit picked with less color contained less sugar and more acid than fruit picked when fully ripe. The higher flavor ratings of the fully- and three-quarter-colored berries appeared to be related to the higher sugar and lower acid content.

TABLE 6.--Sugar content and titratable acidity^a of strawberries harvested at different stages of color development

Cultivar or Selection	Fully colored		Three-quarter-colored ^b		Half-colored ^b		Quarter-colored ^b	
	Total sugar	Acidity	Total sugar	Acidity	Total sugar	Acidity	Total sugar	Acidity
	percent	ml	percent	ml	percent	ml	percent	ml
Pocahontas	3.62	----	3.50	----	3.27	----	3.17	----
Fairfax	5.42	73.6	4.83	92.1	4.55	114.0	4.22	109.2
U.S. 3763	5.54	112.0	5.13	120.0	4.58	132.0	4.33	137.6
Average	4.86	92.8	4.48	106.0	4.13	123	3.90	123.4

^aml of N/10 NaOH per 100 gm of pulp.

^bBerries were analyzed after they had ripened to full color at 21°C.

Source: Smith and Heinze, 1958.

Transpiration

Strawberries do lose appearance and weight by loss of water in the vapor state, or transpiration loss. Shrinking of the berries may occur after holding some days, but the calyxes are likely to appear shrivelled first. Water loss in unit time is dependent on temperature and relative humidity in the surrounding atmosphere. This can be expressed as vapor pressure deficit (Hardenburg and Lutz, 1968). The relative humidity in the internal atmosphere in the tissues is then considered to be 100 percent. The lower the relative humidity in the surrounding atmosphere and the higher the temperature the greater the vapor pressure deficit and hence water loss. Mann (1955) reported that strawberries were found to lose 0.29 percent of the fresh weight per day per mm Hg vapor pressure deficit in still air. When the air was moving rapidly the loss was 0.57 percent per day per mm Hg pressure deficit. At 10°C and 90% relative humidity the vapor pressure deficit is 0.92 mm Hg (Hardenburg and Lutz, 1968). Under these conditions strawberries would lose 0.27 percent weight per day. Under practical handling conditions, the relative humidity may often be lower than 90 percent, the temperature may be higher than 10°C, and a cooling period may be involved which also, initially, will increase water loss. Goble and Cooler

(1962) reported a loss of 1.6 percent weight of strawberries in 16 hours at about 7°C. Relative humidity was not measured.

Discussion

Duration of the post-harvest life is determined by the following factors: respiration rate, growth rate of decay organisms, stage of maturity and to some extent the transpiration intensity. Respiration rate and growth of decay organisms will vary greatly with temperature, atmosphere composition, several chemicals and other treatments. Since the practical aspects of respiration rate and decay will be discussed later (next section), this discussion will be confined to the importance of the stage of maturity in determining post-harvest life. Because the berries are firmer at an early stage of maturity, they are less susceptible to mechanical damage during the marketing period (Rose and Gorman, 1936; Fisher and Luts, 1939). There is also evidence that they are less susceptible to post-harvest decay when harvested at an early stage of maturity than fully ripe (Fisher and Luts, 1939). The quality, however, may be affected by harvesting unripe fruit. It has been shown that factors such as color and texture develop satisfactorily after harvesting if the berries were only slightly colored when harvested, but the flavor may be affected adversely. One definite disadvantage of early harvesting

Is the loss in size of berries. Smith and Heinze (1958) found that when the berries were harvested three-quarters colored, about 16% less than theoretical size was attained, half-colored berries lost about 18%, and quarter-colored lost about 38% of the theoretical maximum. Although there are disadvantages with harvesting unripe fruit, several growing areas use maturity manuals which call for unripe fruit in order to avoid the incidence of overripe berries on the market.

Morrison (1928) published a maturity manual used in Florida and most of the shipping associations in Florida have picking instructions that call for berries ranging from about three-quarter-colored to a full red color. For the local market, more fully ripened berries are recommended. Mitchell et al. (1964) also recommended ripe and firm berries for the local market and pink or three-quarter-colored berries for long distance shipment. Nodenes (1968) published a manual which called for three different maturities dependent upon the estimated time from picking to consumption under shipping conditions in Norway. Stage I: fully ripe strawberries which are to be consumed the day of picking. Stage II: three-quarter-colored, or a uniform pink fruit, which should be in wholesale the day after picking and may be in retail for one to two more days. Stage III: fruit about half to quarter-colored which are to be shipped over

distances which will take at least three days before they are in wholesale.

Before the berries are harvested ideally, one should consider which market they are going to, or what time is to elapse before they can be consumed. Also to be considered is the handling they will receive between harvesting and consumption, such as, temperature and modified atmospheres. Because these factors will determine the rate of the ripening process, it should be theoretically possible to determine the stage at which they should be harvested if the keeping conditions are to be predicted. This is difficult, however, because in most cases, a number of factors are uncertain, such as time in wholesale, retail, and in the consumer's home.

METHODS OF PRESERVING QUALITY

In this section the influence of a) temperature, b) modified atmospheres, c) chemicals, d) heat treatment and e) irradiation on strawberry keeping quality during transit and storage will be considered.

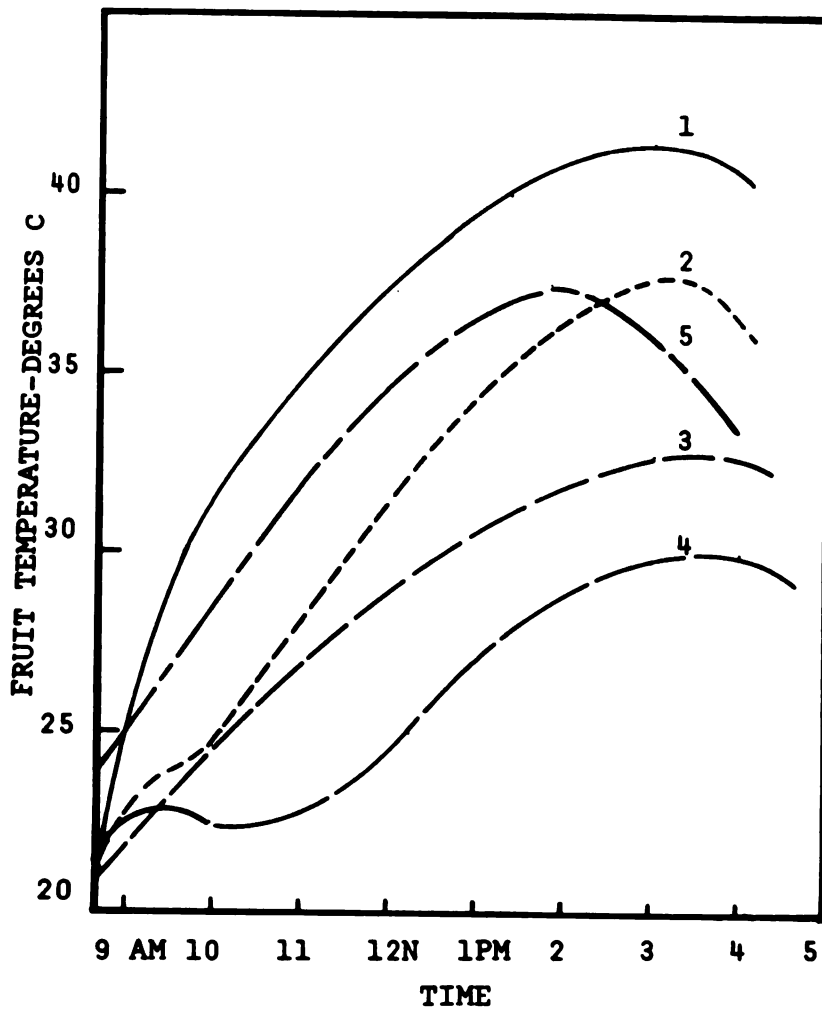
Temperature

In the second section the effect of temperature on the respiration, growth rate of decay organisms and on the ripening process was discussed. It was shown that the rate of activity of these life processes increased about threefold for each 10°C increase in temperature, which implies that fruit at 10° has a life expectancy of a third that of fruit at 0°C . Furthermore, it has been shown that about twice as much decay occurred on strawberries held at 12°C than at 1°C during a 24 hour period, and about four times as much decay occurred at 21°C than at 1°C (Harvey, 1961). The moisture loss from the berries was also previously shown to be directly related to temperature. The vapor pressure deficit is about four times as high at 20°C as at 0° at the same relative humidity (Hardenburg and Lutz, 1968). Indeed, there are

several reports that strawberries will store best at 0°C. Harvey et al. (1966b) reported that the nearer the fruit was to 0°C in all phases of handling and transportation, the smaller the loss of quality. Mitchell et al. (1964) also considered 0°C to be the best temperature for maximum post-harvest life, but that when holding for one or two days, 5°C may be sufficient. Below will be discussed the interrelationship of the temperature and the handling practices in the context of keeping quality of the fruit. This is followed by a discussion of the main methods of cooling the fruit and a consideration of the physical factors determining rate of cooling.

Influence of Handling on Temperature and Fruit Quality

Handling in the field.--Normally the temperature is rather high during the growing season and consequently the initial temperature of the harvested fruit is high. Experiments have shown that exposing harvested berries to high temperatures for even a short time reduced their storage life (Maxie et al., 1959a; 1959b; Moore and Brown, 1967). Shading of the berries soon after harvesting is one of the factors which would influence the fruit temperature. The graph (Figure 9) shows the temperatures of strawberries in different positions in the crate and in shaded and sunny locations. Strawberries exposed directly to the sun quickly reached temperatures



KEY:

- 1-Fruit, top of basket in sun;
- 2-Fruit, bottom of basket in sun;
- 3-Fruit, top of covered basket;
- 4-Fruit, bottom of covered basket;
- 5-Air, in sun.

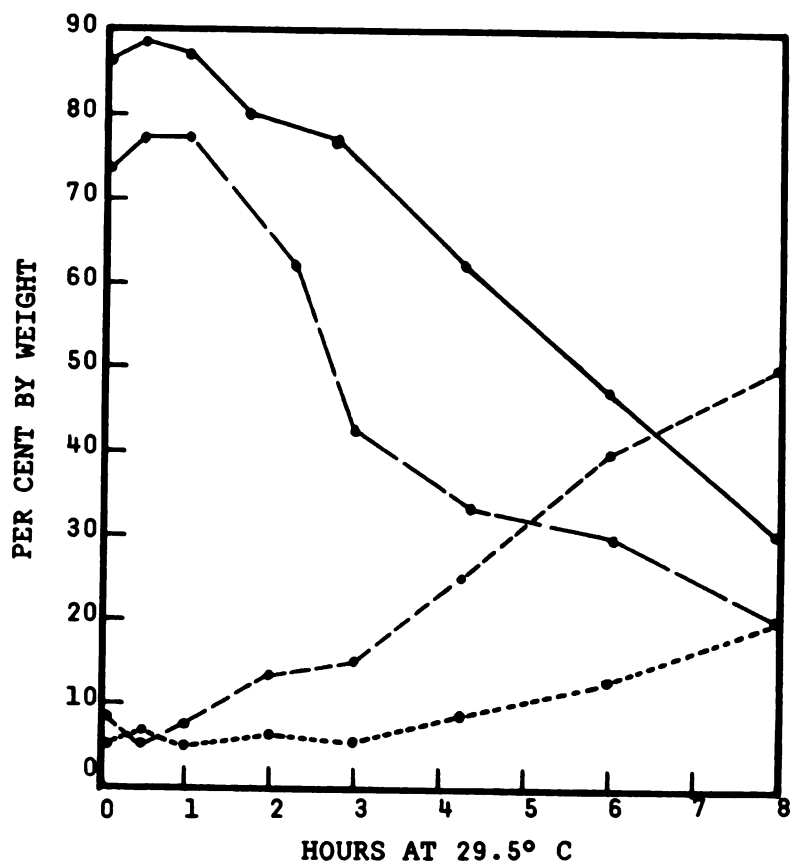
Fig. 9. The influence of shading on the temperature in harvested strawberries left in the field (Maxie et al., 1959a).

considerably above air temperature because their dark color readily absorbs heat from the sun (Mitchell et al., 1964). Nodenes et al. (1968) reported that the temperature was 10°C higher in the berries directly exposed to the sun than in shaded berries within 30 minutes. During long exposure (Figure 9), even berries in shaded positions ultimately reached temperatures approaching that of the air. Wind velocity also has an effect on the heating of berries even if they are shaded. Mitchell et al. (1964) observed about 10°C higher temperature in shaded berries when the air velocity was 5 miles per hour than with no wind.

The effect of delays in hauling the berries from the field to cooling facilities or prolonged exposure to this high temperature has been examined. Moore and Brown (1967) harvested strawberries in the morning when the temperature was relatively low. One lot was placed immediately in cold storage for cooling. One lot was left in crates in the fieldshed for 4 hours, and another for 8 hours, before cooling and holding in cold storage for observation of fruit deterioration. They found that strawberries placed in cold storage immediately after harvest did not deteriorate in storage as rapidly as fruit held in the field for 4 or 8 hours. This difference was most apparent after 6 and 8 days of storage. Maxie et al. (1959b) also studied the effect of delayed cooling

on the keeping quality of strawberries. Berries kept at 29.5°C were cooled to 5°C after one half, one, two, three, four, six, or eight hours. All fruit was quickly cooled using the forced air principle (see later) and then held for seven days at 5°C. Each lot was then removed and sorted immediately into four classes: a) sound or undamaged, b) badly bruised but not decayed, c) slightly decayed, and d) severely decayed. Sound fruit and bruised, but not decayed berries were considered marketable. The results of this work are shown in Figure 10, where it is strikingly apparent that the overall quality drops sharply after two hours at 29.5° before cooling. Another important trend shown is the tendency of an increase in decay with the longer retention period at high temperature. It was also observed that berries retained for more than three hours would have been completely useless for retailing after a 24 hour period. These experiments clearly indicate that strawberries must be cooled very soon after harvest if satisfactory quality is to be maintained.

Handling before and during shipping.--The time factor in shipping a perishable product like strawberries is very important. A few hours delay may hold back the product for one whole day on the terminal market. This delay in marketing may cause price changes, and the benefit of time consuming precooling on quality may also



- [—•—] Marketable fruit
- [---•---] Sound fruit
- [- - -•- - -] Fruit showing slight decay
- [.....•.....] Fruit showing severe decay

Fig. 10. The influence of delayed cooling on keeping quality of 'Shasta' strawberries (Maxie et al., 1959b).

be lost. Redit and Hamer (1959) reported that insufficient time was one of the major difficulties in pre-cooling of strawberries. Many transit cars were pre-cooled (see later for a discussion of precooling) only 2 to 3 hours and a minimum of 4 hours of continuous operation was considered desirable under these conditions. Sainsbury (1955) stated that because of a day's delay in shipment due to precooling, many shippers of perishable fruits had desisted from a systematic pre-cooling routine. Such shippers have felt that one day delay occasioned by precooling was more hazardous than high temperature experienced during the transit period. Smith (1957) compared precooling, which delayed marketing, with noncooling (shipped immediately). Both lots of fruit travelled by road. The advance of ripening and rotting was delayed by precooling, but there was not a great deal gained when the condition of the precooled fruit on arrival at the terminal market was compared with the condition of noncooled fruit which had arrived 24 hours earlier.

Harvey et al. (1966b) compared the two practices for cooling of strawberries which have been used commercially in Southern California. These are either to pre-cool berries overnight in a normal cold room and ship them the day after harvest, or to partially precool them and ship on the day harvested. In a test concerning European

markets where the crop was shipped by air (in the spring when the temperature was relatively low), the overnight precooling showed no advantages over partial precooling in reducing decay. The temperature differences between the two precooling practices were, however, not great: 6°C for precooled vs. 10°C for partly precooled berries. The slightly lower temperature in the berries held overnight compared with those partially cooled and shipped the day of harvest, apparently did not compensate for the longer time between harvest and reaching market.

The same practices were compared (Harvey et al., 1966a) in shipment in the summer when the temperature was higher. In this latter test, the difference in temperature during transit between the two precooling practices was much greater. It varied from 4.5 to 10°C in precooled berries, whereas partially cooled berries varied between 15.6° and 21°C. In this experiment, precooled berries had significantly less decay than noncooled berries after 1 or 2 days exposure to a temperature of 15.6°C, but not on arrival at the wholesale market. On arrival, 9.3 percent of precooled berries had decayed and 8.8 percent of noncooled; after one further day at 15.6°C, 10.4 percent of precooled fruit and 18.5 percent of noncooled had decay and after 2 days at 15.6°C, 25.5 percent of precooled and 35.3 percent of noncooled had decay. These data are average figures for a number of shipping

tests. These experiments indicate that delay in shipment and slow precooling may be valuable when the temperature in the berries is high and when the temperature can be lowered markedly.

Methods for cooling of strawberries have been developed which are more rapid. Cold air can be forced through the mass and it is possible to cool the berries in a few hours and ship them without much or any delay (Guillou, 1960). This will be discussed in more detail later. The effect of rapid and immediate cooling was studied in shipping tests during two seasons (Mitchell et al., 1961). After harvesting and shipping in California, the fruit quality was examined in several Eastern markets after transcontinental transit. In all the 6 shipping tests, rapid cooling of the fruit was compared to what was called normal handling of the fruit. In all cases the fast-cooled fruit was moved into the cooler promptly after harvest and an effort was made to limit the field-to-cooler time to one hour. The delay for normally handled fruit varied according to the practices of the growers. The strawberries were shipped with refrigerated railroad cars and traveled by express. The elapsed time from harvest to arrival in the terminal market ranged from five to six days. Test conditions and results at time of arrival of the six experimental shipments are recorded in Table 7. The results favored fast-cooling above

TABLE 7.--Effect of cooling treatment on fruit marketability

Trial No.	Cultivar	Origin	Desti- nation	Pulp Temp. at Harvest	Normal Handling*			% Marketable at Arrival		% Increase due to rapid cooling
					Hours Delay Before Cooling Started	Estimated Hours from Harvest to 4.5°C	Days from Harvest to Arrival	% Marketable at Arrival		
								Rapid cooled	Normal Han- dling	
1	Shasta	San Jose	New York	26.7°	4	9	5 1/2	94	74	20
2	Shasta	Watsonville	Boston	29	7	10	6	60	52	8
3	Shasta	Salinas	Cleveland	28.5	5	9	5	71	60	11
4	Shasta	Salinas	Cleveland	25.5	4	8	6	73	52	21
5	Lassen	Orange	Toronto	25	9	14	6	86	78	8
6	Lassen	Irvine	New York	27.2	6	11	5 1/2	99	88	11

*All fast-cooled lots into cooler within 1 hour and cooled to 4.5°C within approximately 2 hours after harvest.

Source: Mitchell et al., 1961.

normally handled fruit in each case. However, the difference among the six shipments ranged from 8 percent to 21 percent. Samples of the test fruit were graded at the time of arrival and at 24 hour intervals thereafter for various periods ranging from two to five days following arrival. The composite results of all tests, expressed in terms of percent marketable fruit, are shown in Figure 11. The fast-cooled fruit showed a higher percentage of marketability on arrival than normally-cooled berries. This difference increased slightly with holding time after arrival. The normally-cooled fruit showed approximately the same percentage of marketable fruit the day of arrival as the fast-cooled lot did the second day. When the lines in the graph are extended, they indicate that normally-cooled fruit would have completely deteriorated about four days after arrival, whereas the fast-cooled fruit would have reached the same point in about six days.

In the same experiment, the importance of holding the fruit refrigerated after arrival to the terminal market was tested (Mitchell et al., 1961). The results from this test are shown in Figure 12. With refrigeration in the market, deterioration was less rapid than without. The percent marketable fruit was only about 60 percent when this part of the experiment started, but with refrigeration after arrival, more than 50 percent of the fruit

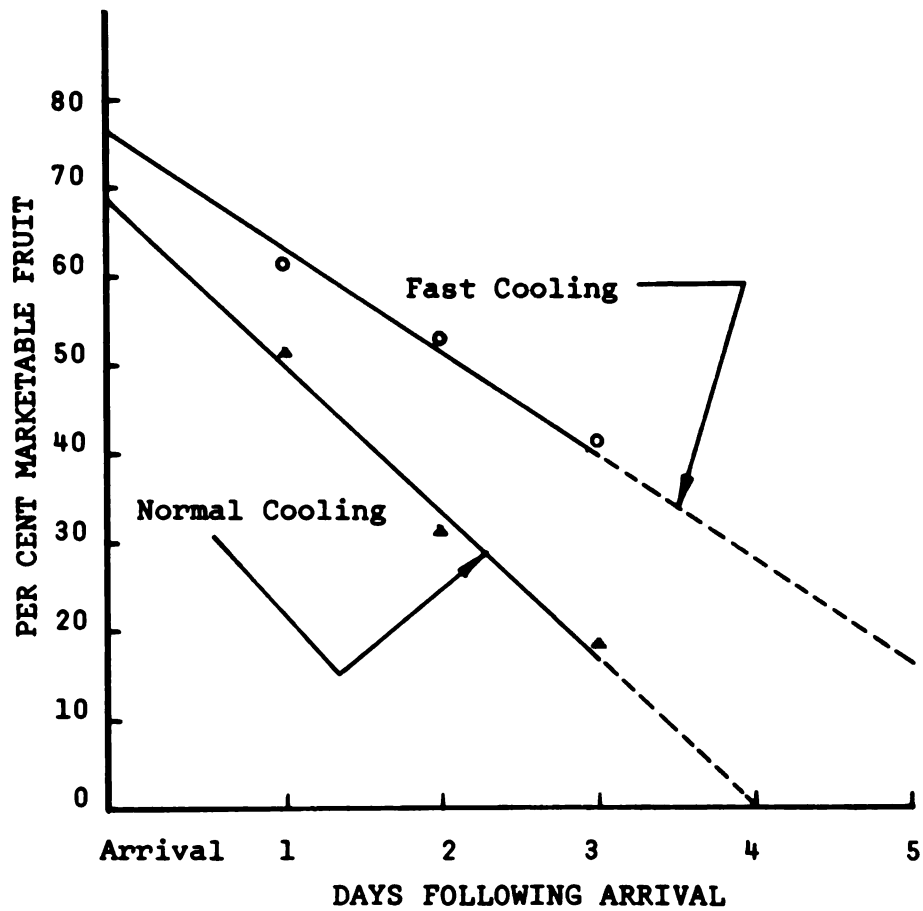


Fig. 11. The effect of rapid handling and cooling on the keeping quality of 'Shasta' strawberries (Mitchell et al., 1961).

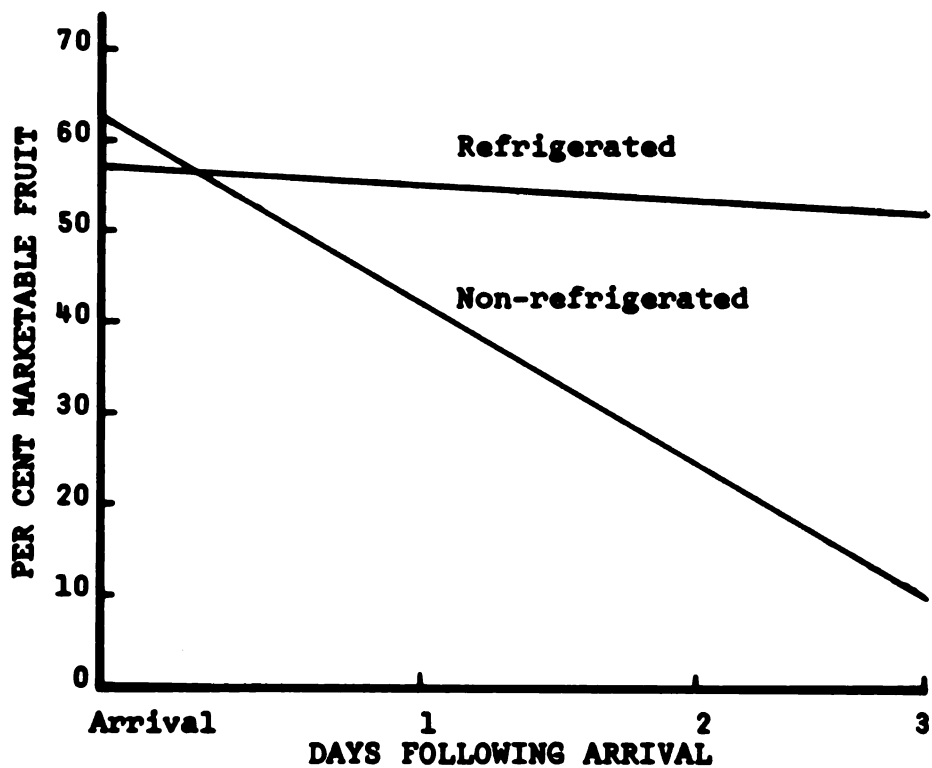


Fig. 12. The influence of refrigeration at the terminal market on the keeping quality of strawberries. The fruit had been in transit 5 days before the test started (Mitchell et al., 1961).

was marketable at the end of three days on the terminal market. Without refrigeration after arrival, only about 10 percent was marketable at the end of three days.

Methods of Precooling Strawberries

As concluded above, strawberries should be moved as soon as possible after picking to precooling equipment before shipping. Precooling refers to the rapid removal of field heat before shipment (Hardenburg and Lutz, 1968). Precooling is accomplished commercially by several methods. All involve the rapid transfer of heat from the commodity to the cooling medium (air, water, or ice). The main methods are hydrocooling, contact icing, vacuum cooling and air cooling and are considered under separate headings below.

Hydrocooling

Hydrocooling depends on water being moved about or through containers or through a bulk layer of the product, carrying heat from the product to ice or refrigerated surfaces (Guillou, 1960). This is a rapid precooling method because water has a large heat capacity and a high rate of heat transfer. Goble and Cooler (1962) applied hydrocooling to strawberries, and compared the treatment with noncooled conditions; the time needed to reduce the temperature in treated berries to 5°C was only 8 to 12 minutes. Less decay was found in the hydrocooled

berries than in noncooled and such cooling significantly affected the weight change of the fruit during transit; nonhydrocooled strawberries lost 1.6% in weight during 16 hours in transit, whereas hydrocooled berries had gains of about 3% in weight. Evaluation of the quality by a test panel, showed no differences in flavor, texture, brightness and color between hydrocooled and nonpre-cooling. It was reported, however, that hydrocooling appeared to wash the color from bruised berries, producing areas light in color, which may be one reason why hydrocooling has not been applied commercially on a large scale.

Contact Icing

In this method, finely chopped ice is packed within containers of the berries. Morrison (1928) reported that this method ("Pony refrigerators") was extensively used in Florida for strawberries. The main problem with this method was that because of sweating on the ice pan, water was allowed to drop on the berries, causing injury (Morrison, 1928).

Vacuum Cooling

Commodities to be precooled by this method are placed in a large steel chamber that can be hermetically sealed and rapidly evacuated (Guillou, 1960). The pressure is reduced to 4.6 mm of mercury which is the

boiling point of water at 0°. Water from the commodity will evaporate and this process removes heat directly from the crop to be precooled. A commodity temperature of about 0°C will be reached if evaporation continues for a sufficient time at that low pressure. Commodities such as strawberries, with a small evaporation surface in proportion to volume, are considered to be poorly cooled by vacuum cooling (Friedman and Radspinner, 1956). However, vacuum cooling of strawberries was reported to be sufficient when the berries were moist from rain, heavy dew, from being washed or from application of fungicides in water (Friedman and Radspinner, 1956). Under such circumstances, vacuum cooling would also serve to dry the fruit, and loss of water would be low from the fruit.

Air Cooling

Exposure of the products to cold air is a common method of precooling produce (Hardenburg and Lutz, 1968). Moving air is not an ideal refrigerating medium because it has a drying effect on the products, but for many crops, for example, strawberries, this is the most suitable method. Since air cooling is the only method which is used commercially in large scale for strawberries this method will be discussed in more detail in relation to precooling of this product.

Methods of Air Cooling

Cooling with air can be applied to refrigerated rooms, rail cars, trucks or conveyor tunnels. Cold air either from mechanical refrigeration or ice is necessary for all kinds of air cooling.

In Ordinary Cold Storage

Cooling in ordinary cold storage is accomplished by passing the air past the crates or pallets with little air passing through the containers. As already mentioned, this is a slow method of cooling. Delays in shipment for at least one night often occur and this is too long in many cases.

In Rail Cars and Trucks

When strawberries are to be shipped by rail or truck, transportable fans can be utilized in combination with refrigeration in the cars; alternatively, on a stationary set-up, the fruit can be precooled after the car is loaded (Rose and Gorman, 1936; Redit and Hamer, 1959). About 4 hours after loading was needed in one shipping test to lower the berry temperature to 4.5°C (which was required before they could be shipped) (Redit and Hamer, 1959). With this method, the cooling will normally be delayed somewhat after harvesting because of the transport time of fruit from the growers to the shipping point. The shipping will also be delayed

somewhat, which has already been discussed. An advantage with this method is that it requires hardly any extra labor or handling of the product.

Forced Air Cooling

Forced air cooling is a method whereby the air is forced to pass rapidly through containers and around the fruit (Guillou, 1960; Sainsbury, 1951). With forced air cooling, the time required to lower the temperature for transit is reduced considerably. Figure 13 shows a comparison in a test between room cooling and forced air cooling (Mitchell et al., 1964). In this test, the air temperature was 2.2°C and the berries were on pallets and in cartons. The airflow on the forced air treatment was about 3 cubic feet per minute (cfm) per lb of berries. The graph indicates that under this condition, the half cooling time² in a room was about 2 1/2 hours, whereas it was about 20 minutes in the forced air treatment.

²Half cooling time

Cooling rate is normally measure by half cooling time, used in Figure 13 (Guillou, 1960). The half cooling time is the time required to reduce the difference in temperature between the commodity and cooling medium by one half. Half cooling time is easily measured and is the same for a given set-up regardless of the initial temperature of the product (Guillou, 1960). The temperature that will be reached at a given time or the time to reach a given temperature may be roughly estimated from the

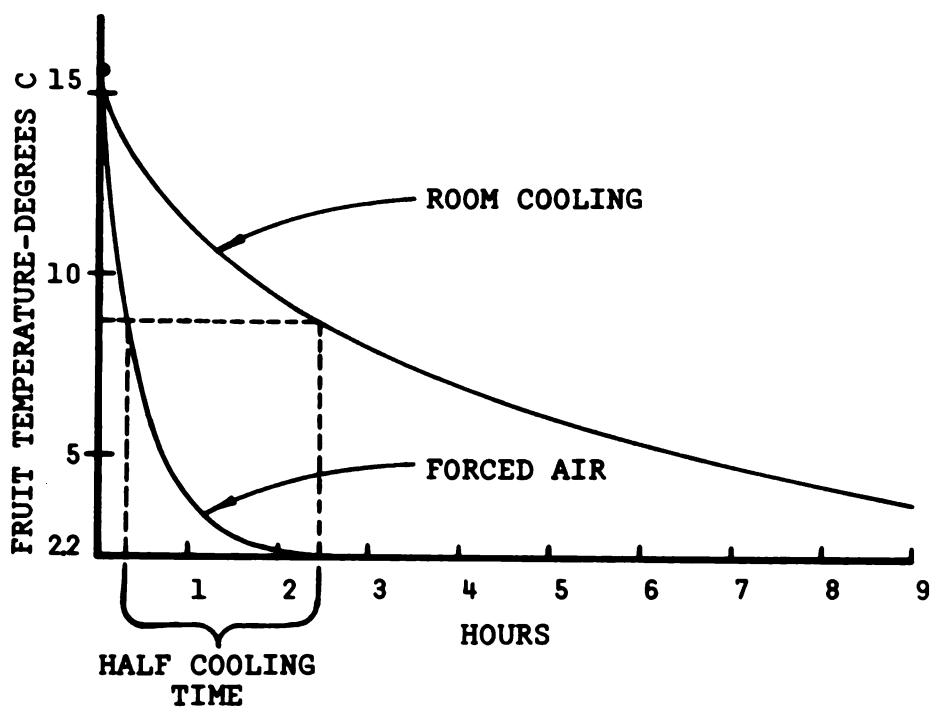


Fig. 13. Cooling rate of strawberries at two air cooling methods. Air flow in the forced air cooler was estimated to be 3.0 cfm/lb berries and the air temperature was a constant 2.2° C in both methods. The cartons were placed on the pallets in six stacks and the pallets were in a single layer in the coolers (Mitchell et al., 1964).

Physical Factors Affecting Cooling Rate

The rate of cooling of any commodity is primarily dependent upon four factors: 1) the accessibility of the product to the refrigerating medium, 2) the difference in temperature between the product and the refrigerating medium, 3) the velocity of the refrigerating medium, and 4) the kind of cooling medium (Hardenburg and Lutz, 1968).

Since air velocity is one factor which is dependent on the fan capacity, the determination of fan type and capacity is important (Guillou, 1960). Figure 14 (lower curve) shows the air flow needed to cool strawberries half-way to air temperature in a given time (Guillou, 1960). If three-quarter cooling is needed, it will take twice as long a time. It should be noted that this curve is based on constant temperature of air blast. The air flow per pound of product to produce a given half

number of half cooling times as follows (Guillou, 1960):

Number of half cooling times	Remaining fraction of initial temperature difference
1	1/2
2	1/4
3	1/8
4	1/16

It should be noted that the consistency in half cooling time is dependent on constant air temperature.

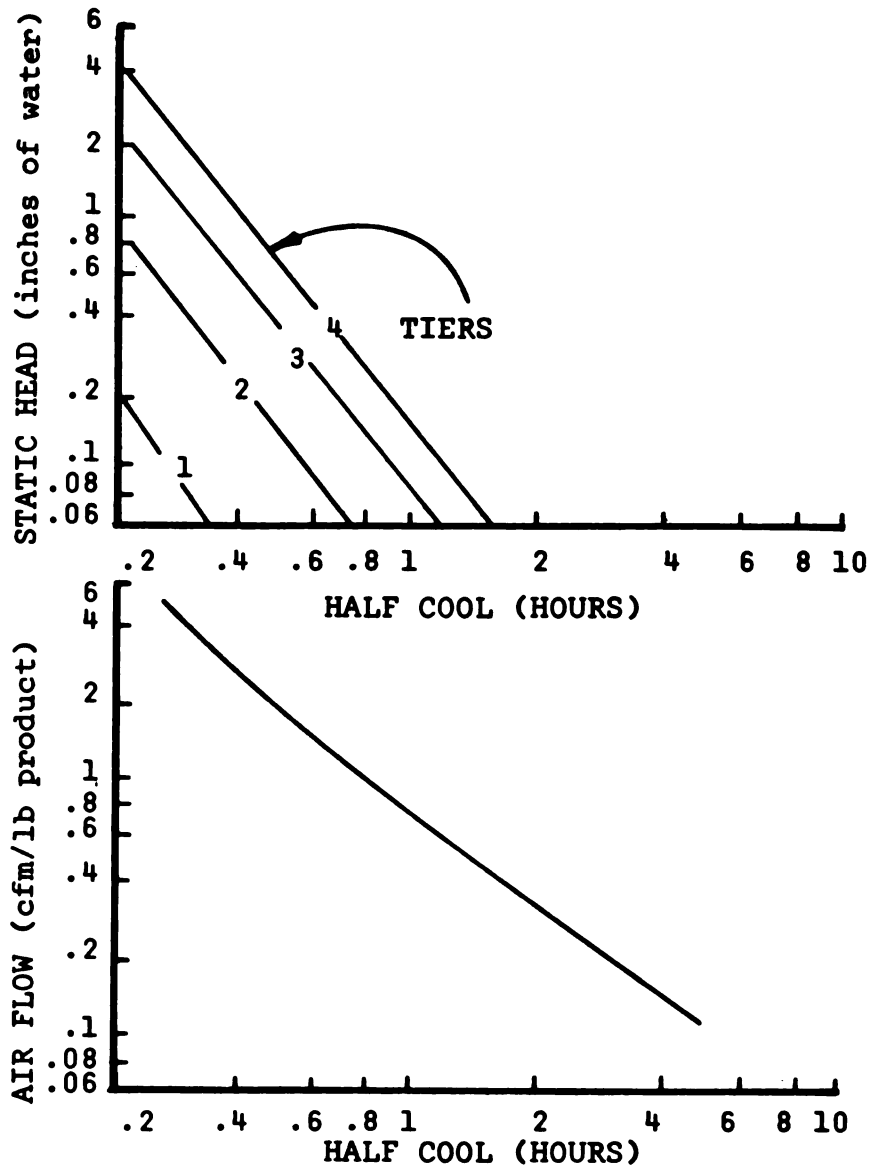


Fig. 14. Upper curves. The influence of the thickness of stack or layer on the static head needed to produce a given half-cooling time. Lower curve. The air flow needed to cool strawberries half-way to air temperature in given times. The fruit was placed in open cartons and temperature was constant (Guillou, 1960).

cooling time is not significantly affected by the thickness of the stack or layer of produce through which air passes. The static head to produce a given half cooling time is, however, drastically affected by the thickness of the stack or layer, as shown by the upper curves in Figure 14.

Redit and Hamer (1959) tested three different containers, two types of fiberboard trays and one wirebound crate, using forced air cooling in rail cars. All containers appeared to cool adequately when they were properly spaced to provide air circulation. Cooling with one of the fiberboard containers was slow because the load was tight against the bulkhead and had no lengthwise vertical channels to allow air to move through the load. A space provided between the bulkhead and the trays was sufficient to provide adequate air movement and then cooling was satisfactory. Kushman and Ballinger (1962) studied forced air cooling of blueberries packed in corrugated fiber containers. Forced air cooling reduced the half-cooling time considerably. In the corrugated fiberboard containers, air flow of 0.9 cfm per pint of fruit gave a half cooling time of about 110 minutes. By increasing the air flow to 1.7 and 3.5 cfm per pint, the half cooling times were reduced to approximately 62 and 43 minutes respectively. Cooling rates were increased by increasing the number of holes in the sides from three

to five, which provided more channels for air to pass through. It was also found that use of plastic mesh pint boxes provided better air circulation and shorter half cooling time than the wooden pint boxes. Kushman and Ballinger (1968) compared cooling of packed blueberries in a fiberboard and a wooden master container in a forced air cooler. They found that when master containers were used that allow air to pass through without much pressure difference, the palletized containers may be stacked 2 and probably 3 pallets deep along the cooling tunnel. With the other container that restricts air movement, the palletized containers may be placed along the tunnel in a single row of pallets. In other words, the capacity increased 2 to 3 times by providing air circulation through containers.

Modified Atmospheres

The influences of oxygen and carbon dioxide concentration in the atmosphere has already been discussed in relation to respiration rate and growth rate of decay organisms. Below will be discussed how low oxygen and high carbon dioxide concentration in the atmosphere affect the fruit and how a modified atmosphere can be utilized during transit and holding periods as a possible substitute for refrigeration.

Oxygen Concentration

Liquid nitrogen is a possible source of refrigeration during transit, and it is utilized for some perishable vegetables, for example, lettuce. When liquid nitrogen expands to a gas in a fairly air tight room, the oxygen concentration may approach zero since it is displaced by the nitrogen. In this way, the atmosphere can rapidly be modified. Decay rate, flavor and texture are all influenced by oxygen concentration, and the influence of concentration on each of these in turn will be discussed under separate headings below.

Influence on decay.--In the previous section, it was shown that oxygen concentration needs to be very low--less than 1 percent and probably below 0.5 percent--to give effective decay control of harvested strawberries. Under practical transit conditions of strawberries, it is difficult to maintain such low concentrations without getting too low a concentration which will cause injury of the fruit (Couey et al., 1966).

Influence on flavor.--Even if decay organisms could be controlled effectively by low oxygen atmospheres, there are several reports of undesirable flavor changes in strawberries held in such atmospheres. Eaves (1935) reported that storage of strawberries in a pure nitrogen atmosphere at 7.7° had a very deleterious effect upon the fruit, although the growth of Botrytis was retarded.

Parson et al. (1964) on the other hand, found no flavor difference between strawberries held in a pure nitrogen atmosphere and those held in air for periods of up to 10 days. The flavor of the fruits held in 1% oxygen was also generally the same as the control, but the strawberries held for 7 days in this concentration had a significantly different flavor; however, there was great variation from one member of the test panel to another. The temperature in this experiment was 0.5°C and it seems as if this low temperature could be the reason for the lack of flavor change. When Hansen (1967) kept strawberries in 1% oxygen, some flavor change was detected, but the flavor in the low oxygen treatment was preferred by the test panel over that in air and 2% oxygen. The temperature in this experiment was 4°C and they were kept for up to 10 days before they were examined. Cultivars used in this experiment were 'Senga Sengana', 'Red Gauntlet', and 'Gorella' in contrast to the other experiments referred to where other cultivars had been used. Couey et al. (1966) studied flavor change in the cultivars 'Solana', 'Shasta', 'Fresno', 'Torrey' and 'Z5A' after holding them in 0, 0.25, 0.50, 1% oxygen and in air at 3°C. The test panel found objectional off-flavor in the berries held in 0.25% and 0% oxygen for five days at 3°C. The berries were also examined after a display period of 2 days in air at 15°C, but there was

no significant difference between the two examinations, which indicates that the flavor change is not reversible at least within a normal display time.

There were also cultivar differences in the degree of off-flavor when they were compared between air and 0.25% oxygen. In Table 8, it can be seen that the off-flavor was more readily detected in 'Solana' than in 'Torrey' and 'Z5A'. Test shipments of strawberries by rail from California to New York were reported by Harvey et al. (1967). The transit period was about 6 days, the average temperature in the berries was about 10.5°C. The rail car atmospheres contained about 2% oxygen and 0% CO₂ initially and averaged 6% oxygen and 4% CO₂ at destination. In this case, no off-flavor was reported, but when the berries were enclosed in 5 mil polyethylene bags and the oxygen concentration was very low and CO₂ concentration high, the berries had undesirable off-flavors on arrival. Decay in this treatment was negligible. The polyethylene bags used were tightly sealed, allowing no leakage of gases into or out of the pallet load of berries, and most of the oxygen in the bags was consumed by respiration of the berries.

If one assumes that the flavor changes that occur in strawberries held in low oxygen atmospheres, are caused by anaerobic respiration and formation of alcohol, one should expect the flavor changes to be a function of

TABLE 8.--Flavor preferences for five cultivars of strawberries held in air compared with those held in 0 or 0.25% oxygen

Cultivar	No. of judgments	Percent judgments favoring berries held in air ^a
Solana	72	96
Shasta	46	80
Fresno	78	76
Torrey	72	72
Z5A	36	71

^aThe chi-square value for percentages is 13.5, which is significant at the 1% level.

Source: Couey et al., 1966.

concentration of oxygen, and time exposed to the atmosphere and temperature. Haller et al. (1941) reported that alcohol formation in strawberries increased with temperature when stored in zero percent oxygen.

Influence on texture.--Even if low oxygen concentration causes a lower respiration rate, it does not seem to inhibit the particular ripening process involved in texture change or softening. Indeed, it has been shown that strawberries will soften more rapidly when held in a low oxygen atmosphere than in air. Parson et al. (1964) found that after the berries were removed from the modified atmospheres at 0.5°C and displayed at 12.8°C for 3 days the berries previously held in 1% oxygen and pure nitrogen softened more rapidly than those held continuously in air. Grunig (1963) also reported that the fruit softened more rapidly after holding in 1% and 0% oxygen than in air. Harvey et al. (1968) also observed an increase in softening when strawberries were shipped in low oxygen atmospheres. The fruits shipped in a liquid nitrogen refrigerated container with a low oxygen atmosphere had more than twice as many soft berries (9.35%) as fruit shipped in a high CO₂ atmosphere (4.30%). Slightly more softening occurred in the berries shipped in the nitrogen containers than in those shipped in regular pallets with a normal atmosphere.

Carbon Dioxide Concentration

Carbon dioxide is an end product of respiratory metabolism. During a transit period, high carbon dioxide can be built up by respiration and by use of dry ice in a fairly gas tight room. Strawberries have been found to be very tolerant of relatively high carbon dioxide atmospheres and CO₂ gas from dry ice has been used commercially for many years to extend the market life for this crop (Harvey et al., 1967; Smith, 1963).

The effect of carbon dioxide concentration will be discussed under similar headings to that considered above for oxygen with the addition of a methodology section on the maintenance of carbon dioxide concentration during transit.

Influence on Decay.--It has been previously shown that the fungi causing decay on strawberries are retarded by high concentrations of carbon dioxide. It was concluded that high CO₂ concentration can be an effective substitute to low temperature for strawberries during a transit period of one to two days. The concentration of carbon dioxide will have to be maintained at about 20 percent in order to be effective. However, no benefit of high carbon dioxide can be expected if the temperature is below about 5°C in the fruit (Harvey et al., 1966a).

Influence on flavor.--Since CO₂ affects the metabolism of the fruit, undesirable as well as desirable

changes may conceivably occur after exposure to higher concentrations than normal. If certain limits of concentration and duration of exposure are exceeded, then this gas proves toxic. The first signs of damage from high CO₂ atmospheres are off-flavors and these are followed by discoloration (Smith, 1963). Brooks et al. (1932) examined the effect of CO₂ on strawberries in relation to temperature and duration of treatment. They found that the first effect was a slight loss of aroma while more prolonged treatment produced further loss of flavor, and finally fermentation.

Examination of the fruit in transit showed that concentrations in excess of 25%, falling to 10% in 24 hours adversely affected the flavor of the fruit. Thornton (1931) found that firm ripe strawberries were not noticeably injured by exposure for 3 days at 15% CO₂ at 0°C, 4°C and 10°C. Winter et al. (1940) used higher concentrations of CO₂, 35% initially falling to 20% in 6 to 10 hours and to 15% after 16-20 hours; the temperature was also relatively high and varied from 13.9 to 15.6°C. Under these circumstances, no loss of flavor occurred. A very slight off-flavor was, however, noted after 11 hours when the berries were exposed to an initial concentration of 45% CO₂. A marked off-flavor was observed after 18 hours at the same initial concentration of CO₂, but in this latter case, the temperature was

higher (20°C). When they held the fruit in constantly maintained 25% CO₂ at 15.5°C, a slight off-flavor appeared after 28 hours at 15.5°C. Smith (1963) exposed strawberries to concentrations of CO₂ ranging from 0 to 40% for periods up to six days at 10°C and kept them under observation on removal to room temperature. Under these conditions no off-flavors were detected.

Harvey et al. (1966a) kept berries for 24 hours in atmospheres with 20%, 30%, or 40% CO₂ at 15.6°C and 2.5°C. In this laboratory experiment, off-flavors could only be detected in fruit exposed to the highest concentration (40%). Commercial shipping experiments in refrigerated railcars from California to New York were done with strawberries in atmospheres of high CO₂ (20.2% CO₂ average) (Harvey et al., 1967). The fruit was in transit about 6 days. Decay was greatly reduced in berries that were exposed to this high CO₂ atmosphere, maintained with dry ice, but the advantage in decay control was nullified because of off-flavor. The temperature in the fruit during transit averaged 5.8°C.

Although the observations on flavor change caused by CO₂, discussed above, have clearly been done under different conditions and may not be directly comparable, it is clear that off-flavors occur after exposures to high CO₂ atmospheres. As concluded for low oxygen atmospheres, it seems as if flavor change caused by high CO₂

atmospheres is a function of concentration, temperature and time. Harvey et al. (1967) concluded after a number of commercial shipments of strawberries in modified atmospheres, that strawberries can tolerate a relatively high CO₂ concentration during a short time in air transit, but not during longer times in rail freight transit.

No conclusion can be made which will be useful for all cultivars of strawberries and under all conditions, but it seems as if strawberries can be safely exposed for 24 to 48 hours to CO₂ concentrations of 20 to 30% in the atmospheres at relatively high temperatures, about 15°C, without developing an off-flavor (Harvey et al., 1967).

Influence on Texture.--In addition to the retardation of decay organisms, the use of high CO₂ atmospheres is also found to slow down the ripening process, particularly softening. Brooks et al. (1932) found that fruit in high carbon dioxide concentrations (at about 20°C) were firmer than untreated (air), and the difference between these treatments was maintained for some time after the fruit was removed from the atmospheres. Smith (1963) reported similar results and indicated that the ripening process was retarded when a high CO₂ atmosphere was applied. Most inhibition of the softening process was found at CO₂ concentrations of 30

to 40 percent. Duvekot (1958) also reported that strawberries exposed to high CO₂ atmospheres were firmer than untreated. Harvey et al. (1968) observed after air shipment in modified atmospheres in 1966 and 1967 that high CO₂ atmospheres had an effect upon the softening of the fruit. About a third more berries were soft and over-ripe, when shipped in the regular pallet covers with normal atmospheres, than those shipped in coated covers or covers with polyethylene liners with high CO₂ atmospheres. The softening, in the normal atmospheres, was accompanied by a darkening of the fruit surface and sunken areas that moistened when touched. Such fruit was also easily bruised when handled. Thornton (1931), however, obtained somewhat different results. In his experiment, the fruit softened rapidly after exposure to 25% CO₂ atmospheres.

Maintenance of high CO₂ atmospheres.--As pointed out above, CO₂ atmospheres must be maintained at about 20% if they are to actively retard decay organisms on strawberries. These high CO₂ atmospheres can be obtained by supplementing the respiratory CO₂ evolution with gas from dry ice. It has been demonstrated, however, that transport units are insufficiently gas tight, especially when in motion and it is difficult to achieve concentrations of a desired order without some sort of gas tight materials to cover the commodity (Smith, 1963). Smith

(1959) demonstrated special containers in which it was possible to obtain 20% CO₂ initially by use of dry ice. Harvey et al. (1966a, 1966b, 1967, and 1968) have developed sealed pallet covers for strawberries in transit, which have given desirable CO₂ concentrations when dry ice was used. They were not completely sealed because some gas exchange was needed in order to give the desirable concentration (Harvey, et al., 1966a). The sealing system developed was polyethylene liners or fiber board coated with a mixture of wax and polyethylene. Both the coated, taped pallet covers and the covers with polyethylene liners were effective in maintaining the CO₂ atmospheres in the shipping experiments.

The dry ice needed within each pallet cover was found to be 8-10 lbs per pallet which consisted of 72 flats with berries (Harvey et al., 1966a, 1966b). The dry ice was wrapped in a heavy paper and placed in an empty strawberry flat. An additional empty flat was placed below the one containing dry ice, and paper or fiberboard was used in the latter to help insulate the berries in the surrounding flats from the dry ice. The pair of flats (with dry ice and insulation) were placed in the top layers of the sealed pallet loads just before shipment.

The concentration obtained when this procedure was used varied somewhat from one shipment to another and

seemed to be correlated with the temperature. Table 9 is data from Harvey et al. (1966a, 1968). They are from different shipment experiments, and are average figures.

The difference in concentration obtained may be due to a number of factors, but since it obviously is correlated with the temperature, the higher concentration of CO₂ in the high temperature is probably due to a higher respiration rate and hence more CO₂ evolution and more oxygen uptake. At the lowest temperature, 4.5°C, the concentration maintained was low, but at this temperature very little benefit of high CO₂ atmospheres could be expected (Harvey et al., 1966a).

Table 9 also shows that atmosphere modification with dry ice in sealed pallet covers is characterized by relatively high CO₂ levels and only slightly lowered oxygen levels. No effect of this slightly lowered oxygen atmosphere could be expected on decay organisms (Brown, 1922; Couey et al., 1966).

Influences of Volatiles

Stadelbacher and Shaw (1969) reported that ethyl acetate and acetaldehyde (volatiles which also were shown to be evolved from ripening strawberry fruit) when applied in additional quantities reduced decay caused by Botrytis cinerea and Rhizopus stolonifer. Strawberries were kept at 15.6°C for 5 days in various atmospheres of

TABLE 9.--CO₂ and O₂ concentrations during transit in
sealed pallet covers

$\bar{X}$ temperature	10°		4.4°		18.3°		12.8°	
Gas measured	CO ₂	O ₂	CO ₂	O ₂	CO ₂	O ₂	CO ₂	O ₂
Origin airport	23	13	8	16	29.8	10.6	20.5	14.9
New York	27	12	17	13	--	--	--	--
Destination	21	14	15	13	40.4	--	29.8	11.0
Sources:	Harvey <u>et al.</u> , 1968				Harvey <u>et al.</u> , 1966a			

oxygen and carbon dioxide and ethyl acetate and acetaldehyde individually or in combination were added to part of the modified atmospheres maintained; concentrations used were 0.5%, 1% and 2%. Examination of the fruit for decay after the storage period, showed that both ethyl acetate and acetaldehyde at all concentrations significantly reduced both of the decay organisms. After keeping the berries for an additional 2 days in a simulated "supermarket" atmosphere and temperature, the examination gave similar results.

It was also observed that strawberries in high carbon dioxide atmospheres altered metabolism, and caused an increase in the production of ethyl acetate and acetaldehyde in the strawberries. Control of B. cinerea and R. stolonifer was in all treatments related to the levels of ethyl acetate and acetaldehyde in the atmospheres, which indicates that build up of these volatiles may be the direct effect of high carbon dioxide. Acetaldehyde at high levels in the atmospheres was reported to cause the fruit to darken (Stadelbacher and Shaw, 1969). High levels of both ethyl acetate and acetaldehyde also increased the pH in the fruit.

Relative Humidity and Condensation

Under field conditions the amount of infection and growth of decay organisms is favored by wet weather, or

conditions which allow a high degree of condensation on flowers and fruits. It does not seem to be well understood just how condensation, caused by temperature changes, affects decay on harvested strawberries. Nevertheless, it is generally accepted that cooling the fruit for short periods is not beneficial because condensation on the berries when removed from the cold temperature will result in rapid growth of gray mold on the berries (Smith, 1959; VanDoren et al., 1941). There is evidence, however, that water itself on the fruit does not increase infection and growth of gray mold, since Goble and Cooler (1962) reported that hydrocooling of strawberries did not increase the mold count on the berries. In addition, Dedolph and Dewey (1964) studied the effect of moisture on development of decay on stored strawberries. They used three storage temperatures: 4.4°C, 12.8°C, and 21.1°C. One subtreatment within each temperature was stored dry, and another was kept constantly wet by drenching it in water once a day during storage. Every day one lot of berries from each treatment was removed and frozen for comparison on completion of the experiment. No differences in amount of decay were found between the dry and the wet treatments, regardless of storage temperature.

Although the berries may or may not generally deteriorate more rapidly after water condensation on the

surface, they will under all conditions, at least temporarily, lose their brightness and hence market value. To avoid this, Smith (1959) and Van Doren et al. (1941) suggest keeping the fruit at about 10°C just prior to selling.

Chemical Treatments

Gray mold can now be effectively controlled in the field by applications of prophylactic fungicidal sprays during flowering, a procedure which is now a part of the standard spraying program in strawberries in Europe (Jarvis and Borecka, 1968). The chemical used is primarily diclofluanid. Control of decay in the field with chemicals is obviously of great significance for the post-harvest life of the fruit. Experiments with post-harvest treatment with chemicals known to have some inhibitory effects have also been done. Thompson (1958) applied several chemicals as post-harvest dips and captan and dehydro-acetic acid were the only materials which had some effect in controlling fruit rots of strawberries produced by Botrytis cinerea and Rhizopus stolonifer. The Sodium salt of dehydro-acetic acid was the most effective of these two materials. Later experiments have proven that dehydro-acetic acid effectively reduces post-harvest decay on strawberries (Thompson, 1961 and 1964; Smith and Worthington, 1965; Tuli et al., 1962). Dipping the fruit

for 15 seconds in a concentration of 0.5% dehydro-acetic acid was found to give adequate control of decay (Smith and Worthington, 1965). However, dehydro-acetic acid has been reported to cause injury on the fruit (Thompson, 1958; Smith and Worthington, 1965). A dip of berries in 0.5% dehydro-acetic acid causes some bleaching of the berries; and after dipping in a 1% solution, the berries were hardly marketable (Smith and Worthington, 1965).

N⁶-benzyladenine has been shown to have a retarding effect on the respiration rate of harvested strawberries (Dayawon and Shutak, 1967). It was also suggested that the effect upon the keeping quality might be desirable. Post-harvest treatment of strawberries with 10 ppm N⁶-benzyladenine was found to have no beneficial effect on retention of chlorophyll in the strawberry fruit calyxes after storage for 7 days. Decay of treated berries was as high or higher than those untreated.

Ozone (O₃) is an unstable gas with strong oxidizing properties. It has been used to suppress mold growth in rooms with high relative humidity (Cook, 1964). Spalding (1966) studied development of decay on strawberries held in ozone enriched atmospheres at 12.8° and 15.5°C and 95% relative humidity. Ozone of any concentration did not reduce gray mold rot of strawberries in this test. Ozone at concentrations of 2ppm and above almost completely inhibited the development of aerial

mycelia. These berries were blackened in appearance, and gray mold decay of the berries occurred rapidly after removal from the ozone atmosphere. The flesh of the berries did not appear injured by ozone concentrations up to 10 ppm administered for 5 days. However, at concentrations of 0.5 ppm to 10 ppm, ozone caused shriveling and drying of the caps.

Fumigation with 0.25% sulphur dioxide was shown to control gray mold on strawberries, but not Rhizopus rot (Jarvis, 1968). Although gray mold was controlled, treatment of wet and bruised fruit was less satisfactory as it damaged such berries.

Heat Treatment

It has been shown that Botrytis cinerea will be killed or inhibited when exposed to temperature from 37°C and above (Smith, 1923). At 50°C most of the spores were killed after exposure for one hour. At lower temperatures, the time needed to kill the spores would increase.

Smith and Worthington (1965) exposed strawberries to air at 43°C for 1/2 hour. This treatment did not reduce decay when the relative humidity was low (50%, 60% and 70%) whereas at 98% relative humidity the decay (Botrytis and Rhizopus) was significantly reduced. This difference was found to be due to more rapid heating of the berries at the high relative humidity than at low.

Dipping for 15 seconds at 43°C water injured the berries and only slightly reduced decay. Couey and Follstad (1966) applied H₂O saturated air at 44°C to straw-berries for various times and studied the development of decay organisms and possible changes in quality factors. The berries were examined after 5 days at 3°C (examination 1) and after an additional 2 days at 15°C (examination 2). When the berries were heated for 40 and 60 minutes at 44°C, decay at examination 2 was sharply reduced, but a 20 minute exposure was relatively ineffective. Results from this experiment are shown in Table 10. When the berries were exposed to the hot air of 42°, 44° and 46°C for one hour, the decay was reduced at examination 2 in all treatments. Decay was most reduced at 44°C and 46°C but the berries become bleached and softened at the latter temperature. The data from the experiment indicate that decay control by heat treatments are a function of exposure time and temperature.

The test panel conducted for quality evaluation (Couey and Follstad, 1966) could not detect consistent differences in flavor or texture due to heat treatments.

Heat injury occurred in only two tests in berries heated at 44°C, and was reported to consist of a slight darkening of previously bruised areas on the berries, usually located at the top of the flat. No unusual drying or other injury of the calyx was observed.

TABLE 10.--Decay of strawberries after exposure to 44°C for various times

Exam ^a	Exp. No.	Replica- tions	Decay after indicated exposure time (min)			
			0	20	40	60
			%	%	%	%
1	1 ^b	18	3.4ab ^d	1.8c	1.7c	1.9bc
	2 ^c	12	1.5a			1.1a
2	1	18	14.3a	9.9a	6.2b	4.4b
	2	12	28.9a			3.7b

^aBerries were examined after 5 days at 3°C (examination 1) and after an additional 2 days at 15°C (examination 2).

^bFresno, Solana and Lassen from the Fresno area, 1964 and 1965. Shasta from the Watsonville area.

^cFresno from the Fresno area, Shasta and Z5A from the Watsonville area, 1965.

^dGeometric means, adjusted for blocks in experiment 1. Means in any row not followed by the same letter are significantly different at the 5% level.

Source: Couey and Follstad, 1966.

Irradiation

Several researchers have shown that irradiation of strawberries does extend the market life through reduction of decay (Mercier, 1964; Mercier and MacQueen, 1965; Johnson et al., 1965; Maxie et al., 1964; Bramlage and Couey, 1965). However, undesirable quality changes may occur after irradiation, such as softening (Johnson et al., 1965; Kuhn and Merkley, 1966), adverse flavor (Johnson et al., 1965) and color changes (Mercier, 1964). The dosage which is found to be somewhat promising for reducing decay in strawberries without accompanying large quality changes was found to be about 200 krad (Maxie et al., 1964; Mercier and MacQueen, 1965). In a shipment study of irradiated strawberries from California to Chicago for 6 days at about 5°C plus 1 day at 20°C on the terminal market, 19% decay was found in untreated berries whereas 7% was found in berries irradiated in 200 krad; 5% of the berries were soft in the untreated vs 9% in 200 krad treated berries (Maxie et al., 1964). Great differences were found in responses to irradiation and quality changes from one year to another (Maxie et al., 1964) and between cultivars (Staden and Van Laar, 1965) and also between temperatures in storage (Kuhn and Merkley, 1965).

Discussion

It was demonstrated in this chapter that temperature control and rapid handling are the key factors which determine the condition in which the fruit reaches the consumer. Mitchell et al. (1966) also concluded that constant low temperature provided the greatest protection of strawberries, and that any warming was detrimental to fruit quality. Total deterioration was related to the total length of time fruit was exposed to the warm temperature, regardless of the pattern of exposure. Because strawberries ripen in the warm season, it is very difficult to fulfill the temperature requirement of the fruit. The individual growers may not make enough effort to maintain good temperature management in the field. The shippers may not have the equipment for rapid pre-cooling, or may not cool them properly even if the equipment is available, because they wish to ship to a particular market with no delay. In the cases where the temperature is not satisfactory in the fruit during transit, modified atmospheres can be applied.

Strawberries, as living tissues, use oxygen and give off carbon dioxide and heat, as a result of their metabolic activity. In a closed space, this process in itself causes a modification in the proportion of each gas in the atmosphere. However, the modification of the atmosphere will not be rapid enough by this process

only. Liquid nitrogen may be used as a refrigerant. When it is used in a tightly closed space, it displaces the oxygen in the air and reduces this gas from a normal 21% to levels approaching zero. Experiments have shown that oxygen must be lowered to at least 0.5% to reduce decay of strawberries significantly and that lowering it below 0.25% causes off-flavors under certain conditions of time and temperature (Couey et al., 1966). Maintaining oxygen within this very narrow range is difficult to achieve commercially, and it is impossible with the present refrigeration equipment (Couey et al., 1966). Hansen (1967) concluded from his experiments that liquid nitrogen would be useful in modifying the atmosphere for strawberries, and that 1% oxygen in the atmosphere would be adequate. More experiments using low oxygen concentration for storage of strawberries may therefore be needed.

The use of high carbon dioxide atmospheres, maintained with dry ice, was found to offer advantages of reducing decay, reducing the number of soft or overripe berries and improving the overall quality. Since the ripening process is retarded, the berries may be harvested in the more ripe stage which also may improve the overall quality of the fruit. Use of high carbon dioxide atmospheres was found to be beneficial only when the temperature cannot be maintained at a level below about 5°C.

Also, high carbon dioxide atmospheres may not be used safely during transit over periods of more than one to two days, because of development of off-flavors. The effective concentration of carbon dioxide in the atmospheres should reach at least 20%, and should be maintained between 20% and 30%. An effective level of carbon dioxide can be obtained by using dry ice and sealed, coated fiberboard pallet covers or polyethylene liners. A system like this has been developed for shipment of strawberries from California to the eastern U.S. markets, and to Europe, by jetliners (Harvey et al., 1966a, 1968). Since a high carbon dioxide atmosphere reduces decay when the temperature is relatively high, it can be used as a substitute to low temperature, and can be valuable when the temperature cannot be controlled satisfactorily during transit.

Because of ineffectiveness or undesirable quality changes, or high cost, post-harvest treatment with chemicals and irradiation have not yet been applied commercially in large scale. Heat pasteurization has also not been applied commercially, but results from the experiments referred, shows that moist heat greatly reduces decay of strawberries without altering the appearance, flavor or texture of the berries when handled under simulated commercial conditions. The effectiveness of decay control, safety from the consumer standpoint, and

probable low cost make heat pasteurization of strawberries an attractive commercial possibility. However, the range of safe and effective exposure times and temperatures is relatively narrow and requires precise control (Couey and Follstad, 1966). Further studies seem to be needed in this area.

CONCLUSIONS

The primary aim of this study was to investigate how strawberries should be handled in order to obtain maximum post-harvest life. There are indications that new markets could be developed for strawberries from some of the growing areas in Norway if they could be shipped over distances which require two to three days in transit and still have a quality potential to withstand the normal marketing period on the terminal markets. In the U.S., strawberries are successfully shipped over distances which require considerable time in transit and the reason for this seems to be primarily due to better handling practices. However, the cultivars used in the U.S. seem to be more firm than those used in Europe, which may be a further factor that determines differences in keeping quality.

The conclusions and recommendations made below are primarily seen in relation to improvements of the handling practices which are applied in Norway. Most of the improved handling practices are applied somewhere in the U.S., but not necessarily in all the states, particularly

not in states where the market is fairly close to the growing areas.

The Norwegian growers are responsible for the first post-harvest operations on the fruit, and the importance of rapid shading of the fruit in the field and rapid hauling has been discussed here. It is obvious that successful shipping and marketing is dependent on proper grower handling. Hence, the growers that shall take part in shipping of strawberries to distant markets should have to prove that they are capable of applying management to deliver fruit at a reasonable temperature with a relatively low percentage of bruising and other damage.

Precooling the fruit before transit has been shown here to be of great importance, and should be done without delay. Ideally the individual growers should have their own forced air cooling equipment whereby the fruit may be cooled rapidly after hauling from the field. However, it seems as if one precooling plant at the shipping point will be the most realistic alternative, because it will be too expensive for each grower to have his own, particularly when the farms are relatively small. If the precooling is done at the shipping point, the fruit will have to be collected from the growers and transported to the precooling plant several times a day so that the fruit will remain on the farms a

minimum amount of time. If the precooling operation could be done fairly soon after harvest, all the fruit could be shipped the same day as harvested because precooling with forced air can be done in a few hours.

For shipments to markets where trucks or rail may be most convenient for transport, mechanical refrigerated transport equipment should be used for the precooled strawberries. When the fruit is at a low initial temperature, the respiration rate is low and so is the heat evolution and thus the refrigeration needed during transport need only be sufficient to maintain that temperature. For shipments to markets where planes or boats are necessary, it may be more difficult to control the temperature during transit. Shipping studies on strawberries by air from California to the Eastern markets or Europe have shown that the fruit spent only about 32% of the total transit time in the air, and 18 percent in truck to and from airports, and 50 percent at airports (Harvey et al., 1966b). The temperature was often high in the airports, no cooling facilities were available and hence the temperature increased. The same situation will probably also occur during shipments with boats, where little protection against both high temperature and rain could normally be expected.

When the temperature cannot be controlled during transit, as in the cases mentioned, attention should be

paid to the system developed in California for shipment of strawberries by jet liners. Pallets with berries are covered with a fiberboard sleeve and the latter coated with a mixture of wax and polyethylene (or only polyethylene). This pallet cover will result in a high carbon dioxide atmosphere, particularly when supplemented with dry ice cooling. This atmosphere will give better control of decay and ripening when the temperature cannot be controlled satisfactorily. The pallet covers have also been shown to retain low temperature when the ambient temperature was high during transit, partly because of insulation by the fiberboard and partly because of the dry ice (Harvey et al., 1966b). Pallet covers should also be considered seriously for the mechanical protection they afford and their role in maintaining the vertical alignment of flats, preventing pilferage, and protecting the berries from rainfall. During handling in various phases of transit, pallet loads of berries are subjected to a considerable amount of tugging, pushing and compression and a fiberboard sleeve tends to reduce damage from these forces (Harvey et al., 1966b). Pallet covers will have to be developed for the size of flats and pallets used. The amount of dry ice used will have to be estimated and tested during test shipments, but the results obtained with the shipments from California will be of great help in the estimation.

Refrigerated containers with liquid nitrogen and low oxygen concentration is a further possible way to retard decay during transit when the temperature cannot be controlled mechanically, but since conflicting results have been obtained, further experiments are needed in Norway before it can be applied safely.

In order to market a high quality fruit, strawberries should not be harvested more unripe than necessary to have enough post-harvest potential. The stage at which the fruit should be harvested should be determined concomitantly with the handling practices which will be applied to the fruit. Since the ripening process is dependent on temperature, atmospheric composition and time, the stage of ripening at harvest must be determined when these factors are known.

Strawberry cultivars with firm fruit have been shown to keep better and to be less susceptible to bruising during transit than soft fruit cultivars. It will therefore be a goal for breeders of strawberries in Norway to develop new cultivars which are firmer, and which could be grown for shipment to distant markets.

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