PREDICTION AND EVALUATION OF BARTLETT PEAR FRUIT MATURITY

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David R. Dilley
Major professor

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ABSTRACT

PREDICTION AND EVALUATION OF
BARTLETT PEAR FRUIT MATURITY

By

Timothy James Johnson

The time of maturation of Bartlett pear varies widely between years. This precludes the use of a fixed calendar date or a constant number of days from full bloom for determination of optimum harvest date.

Eleven orchards, representing the principal areas of pear production in Michigan, were selected for the study. Fruits were harvested at weekly intervals over approximately a 4-week period in each orchard. The harvest dates were chosen so as to obtain fruit both before and after the expected optimum date. Fruits were subjected to measurements of respiration, flesh firmness, size, skin color, juice soluble solids, starch content and the concentrations of ethylene in their internal atmospheres. Fruits from each harvest were also evaluated for storage performance, and assessments made of the value of each of the above parameters as a maturity index. Daily maximum and minimum temperatures were obtained from climatological stations operated by the National Weather Service at or near each orchard.

Variation in maturation could be accounted for largely by heat-unit accumulations in a 50-day period immediately following full bloom. This is the period of maximum cell-division frequency in the fruit cortical tissues. Daily mean temperatures between 40° and 80°F were employed for calculation of heat units, which were then adjusted to the mean day length to estimate the date of ideal maturation for harvest.

A significant linear correlation between corrected heat-unit accumulations and the number of days between full bloom and maturity allowed the use of the simple regression equation as a prediction formula. Accordingly, predictions of maturity were made up to 8 weeks in advance with a standard error of less than 4 days.

Late-season growing temperatures modified the predicted maturity dates. Temperature maxima above 80°F tended to retard maturity, while temperatures below 50°F caused premature ripening. It is, therefore, imperative that temperature extremes throughout the growing season be observed and employed to make the necessary adjustments in the early-season harvest predictions.

Pear fruits become increasingly sensitive to ethylene in terms of ripening response as they approach maturity. Harvested fruits that softened to a flesh firmness of 13 lbs. or less in 7 days at 20°C after a 12-hour treatment with a 1000 ppm ethylene were considered mature.

Subsequent harvests showed that the capacity of the fruits to produce ethylene increased until they were capable of softening to a flesh firmness of 13 lbs. or less in 7 days at 20°C without exogenous ethylene treatment. Such fruits were mature but often considerably past the optimum stage of harvest maturity suitable for long term storage. However, they had gained considerably in size since first reaching maturity.

The concept of a maturity period is proposed. The period begins when harvested fruits initially respond to an exogenous application of 1000 ppm ethylene and ends when non-treated fruits behave similarly. The period varies in length, and careful monitoring of internal fruit ethylene concentrations will assist in tracing its progress. Supplementary information may be gained from measurements of flesh firmness and the disappearance of starch from the flesh.

The decision as to proper time of harvest rests jointly with the grower and the processor. Gains in fruit size become incompatible with gains in length of storage life as the maturity period progresses. It is evident that fruits of potentially long storage life must command a premium price in order to compensate for the loss in potential size due to earlier picking. If shorter storage periods and earlier processing can be accommodated, pear fruits grown in Michigan can more frequently be permitted to reach the desirable size needed for premium packs.

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INTRODUCTION

Michigan is the principal pear-producing state in the central region of the United States. It is exceeded in production only by California, Oregon and Washington. The Bartlett variety is dominant, being the preferred variety for canning, for which the majority of the crop is grown.

Pear acreage in Michigan has declined in recent years because of an unprofitable economic return on investment to the grower. One major reason for this decline is the difficulty in producing fruit of the desirable large size without encountering serious loss of trees from fireblight (Erwinia amylovora) which is prevalent under high vigor culture required to attain large fruit. Fruits larger than 2-1/4 inch traverse diameter are desired by the canning industry and receive a premium price. Consequently, growers are reluctant to harvest pears until maximum size has been achieved and this occurs as fruits ripen on the tree. Such fruits must be processed soon after harvest. This has led to a conflict between the grower and the processor. The grower attempts to "hold" his fruit and to harvest them at maximum size; the

processor, although placing a premium on large size, demands fruits of high storage potential which is only possible if harvested at a relatively early maturity stage.

This basic problem is compounded by the lack of precise methods for determining optimum maturity. Errors in determination lead to considerable wastage. Immature fruits become excessively desiccated in storage and fail to ripen normally. Over-mature fruits develop senescent disorders if they are stored for long periods.

Fruits increase in size as long as they remain on the tree. If fruits of optimum quality and storage life are desired, however, they must be harvested during a relatively short period when fully mature, yet have not started to ripen. The longer the period of storage desired, the more important it is to recognize when this stage of development has been reached and harvest and store fruits accordingly.

Flesh firmness is the maturity index most commonly employed. The instrument generally used is the Magness-Taylor pressure tester. A rule-of-thumb criterion of maturity often used is a pressure of 18 lbs. registered on a pressure-tester fitted with a 5/16 inch diameter tip. Under Michigan conditions, this maturity index has not proven to be reliable. Fruit firmness varies with orchard conditions, notably soil-moisture availability and moisture

loss through transpiration. The pressure-tester itself is inadequate since results may vary considerably with the operator.

For most tree crops, it is the first one to two months of development following bloom that determine the ultimate time to maturity. This period varies with the crop but coincides well with the period of cell division in the fruit. It is during this period that environmental conditions influence the rate of attainment of fruit maturity.

This thesis is based on the dual hypotheses that fruit maturity can be predicted well in advance of the harvest period using information on environmental conditions during a relatively short period after bloom; and that assessment of maturity is better made on the basis of the physiological changes that occur in fruit at or about the time they reach optimum maturity.

A special advantage is afforded by an early prediction of maturity. Advance knowledge of the optimum harvest date aids in the efficient deployment of labor and storage facilities.

The terms "mature," "maturity," "maturation," "ripe," "ripeness" and "ripening" occur frequently in this dissertation. For the sake of clarity they are defined below.

A pear is mature when it is physiologically capable of ripening. This stage is reached when the pears are still green in color and have a flesh firmness within a range of approximately 17 to 24 lbs. Maturity is the state of being mature; maturation the process of attaining maturity.

A pear is ripe when it is suitable for eating. Ripe fruits are bright yellow in color and have a flesh firmness of 3 lbs. or less. Ripeness is the state of being ripe; ripening the process of attaining ripeness.

REVIEW OF LITERATURE

Methods for Early Prediction of Bartlett Pear Fruit Maturity

Phenological and Other Environmental Parameters

Descriptive and Historical

Phenology is concerned with the periodic phenomena of organisms insofar as they are influenced by climate. Réaumur (1735) first evolved the concept of definite heat equivalents for physiological processes in plants. He found that the sums of mean daily temperatures over the developmental periods of herbaceous plants were approximately constant for each specific plant from year to year. This constant sum was later termed the thermal constant, and it has a distinct value for each species. Boussingault (1834) demonstrated that the length of the period between germination and any given stage is inversely proportional to the sum of the daily temperatures above 0°C for that period. Edwards and Colin (1834) observed an upper limit in plant growth in relation to temperature. In 1861, Fritsch published the thermal constants for flowering and fruit maturation of 889 plant species.

Modern Applications of Phenology

The application of such findings to practical problems in food crop production did not occur until the twentieth century. In 1905, Abbe compiled an excellent review of the history of phenological theory. This work initiated a renewed interest in the field on the part of researchers in the United States. Lehenhauser (1914) measured the rate of growth of corn seedlings under various controlled temperatures. This led Livingston (1916) to devise a physiological index system which employed a scale of weighted temperature values between 40° and 90°F.

The remainder index method was developed during the twentieth century. The method is based on the premise that for each plant species (or, more specifically, for each physiological process in that species) there is a base temperature below which that process will not occur. Each physiological process has its own base temperature. The effective heat during the day is obtained by subtracting this base temperature from the daily mean. The remainder is expressed in degree-days or heat units. The daily heat units are summed for the duration of the physiological stage which is under study. The final total is termed the summation constant or remainder index. This figure is held to be approximately constant from season to season.

Another major assumption in the remainder index method is that growth or development is essentially linear over the entire temperature range. This obvious flaw led workers such as Katz (1952) to incorporate the van't Hoff-Arrhenius principle into their indices. This principle states that, for each 10°C (18°F) rise within a stated temperature range, a developmental process will increase in rate by a constant factor. This factor, commonly known as the Q_{10}, has a specific value for each plant process. Livingston's (1916) physiological index was also an attempt to account for this non-linearity of response.

The remainder-index method makes no distinction between day and night temperatures. It merely uses the mean temperature. The mean obviously gives a very limited insight into the maximum and minimum temperatures and reflects none of the fluctuations that occur over the 24-hour period.

The remainder-index method has retained its popularity in spite of the simplified assumptions on which it is based. There seem to be two main reasons for this. Firstly, its extreme simplicity makes it a useful tool for farmer, processor, and researcher. Secondly, it is of acceptable accuracy for many crops in many locations.

Nuttonson (1948) modified the remainder-index method by incorporating day-length into heat-unit calculations. He reasoned that the value of heat units would

vary with day-length. He thus weighted each daily heat-unit amount with the day-length in hours.

Lindsey and Newman (1956) made an attempt to improve on the simple daily mean method of computing heat units. Their method was designed to reflect the approximate durations of different temperature levels during the day.

Arnold (1959) stated that the choice of base-temperature is extremely important. If it is wrong, then heat-unit summations will vary widely from year to year for a given developmental stage. He made a regression of rate of development on mean temperature. The correct base temperature was taken to be that obtained when the equation is solved with the rate of development set at zero.

Use of Phenology for Deciduous Fruits

Phenology has been applied extensively on crops used in the canning industry. Scheduling of plantings of peas, sweet corn, and snap beans is based on heat unit predictions. A description and review of work on these crops can be found in Holmes and Robertson (1959). The harvest of grapes is accurately predicted using heat summations during a short period following bloom. This literature review must, however, remain within the area of deciduous tree fruits when considering later work. A book

on agricultural meteorology by Wang (1967) is cited as a general reference on phenology.

Data presented by Magness, et al. (1926a) and Magness, et al. (1926b), indicated that the time interval between bloom and harvest for each apple variety in a number of areas varies little from season to season. Ellenwood (1941) showed much greater variations under Ohio conditions. For many varieties, a range of three weeks between longest and shortest seasons was observed. These results indicate that days from bloom to harvest is an inadequate prediction method for apples. Tukey (1942) compiled a table listing time intervals between full bloom and maturity for varieties of pear, apple, peach and cherry. Bartlett pears, in 11 seasons at Geneva, New York, took an average of 121 days from full bloom to maturity, with a range between 110 and 123 days. By contrast, Kieffer showed remarkable constancy, ranging in 12 seasons between 146 and 148 days. Ryall, et al. (1941) stated that the elapsed period from bloom was a much more reliable index of maturity for pears than the pressure test. Haller (1942) studied indices of maturity for four varieties of apple under middle Atlantic State conditions. He found that days from bloom to maturity was a more reliable index than any other.

Haller and Smith (1950) expressed a need for the re-evaluation of indices of maturity in apples. They

stated that the period from full bloom to maturity showed very little variation over a wide range of conditions. This period appeared to be influenced only slightly by growing season temperatures. Smock (1948) found the period between full bloom and harvest for McIntosh apples in New York varied between 123 and 157 days.

Thus, it can be seen that, for some workers, the period from full bloom to maturity is considered the most accurate index of maturity. In addition, it has a distinct advantage in that it is predictive. Once the full bloom date is recorded, then the harvest date can usually be predicted with reasonable accuracy. There remains, however, the problem that it is not always reliable. Consistency between seasons in the same area is good, yet the period of maturation differs widely between areas. Therefore, the inherent danger in adoption of such an index is that it will fail in an unusual season. Moreover, in an area with an extremely variable climate, errors may be of a more frequent nature.

Baker and Brooks (1944) examined the effect of temperature on the period between full bloom and maturity of apricots and prunes in California. They concluded that warm temperatures soon after bloom had the effect of shortening this period. This effect declined as the season progressed. They also noted that excessively high temperatures late in the season could actually retard ripening.

This paper was one of the first to observe the early-season influence of temperature. Heat unit summations for the whole season had been collected by earlier workers and little or no relationship was noted between them and the maturation periods. Weinberger (1948) found a similar relationship for the Elberta peach in Georgia. Temperatures during the first 50 days following bloom accounted for 93% of the variability in the length of the bloom-harvest period. Brown (1953) calculated the relative efficiencies of different temperatures in promoting apricot fruit development. He found a minimum efficiency at 42.5°F and an optimum at 72.5°F. Eggert (1960), using a 0°F base temperature, examined the relationship between heat-unit summations and the period between full bloom and maturity of McIntosh apples in Maine. Summations from bloom to bloom + 40 days were highly correlated with the length of the maturation period.

Holmes and Robertson (1959) adopted a general base temperature of 42°F for all crops. The choice of the base temperature is probably more critical, however, and will vary between crops. Arnold (1959) described methods of arriving at the true base temperature for the crop or development phase under study.

Fisher (1962) reviewed the work on heat units and maturity of tree fruits. He also examined data from nine widely separated areas of the United States, comparing

total heat unit summations with maturation period for several pome and stone fruits. He observed wide variations in heat summations, but failed to find a close relationship with maturation. Blanpied (1964) noted that Fisher's data for Delicious apple showed a strong negative relationship between bloom date and length of growing season. The earlier that bloom occurred, the longer the fruit took to mature. This confirmed earlier work by Blanpied (1960a, 1960b, 1962) with McIntosh apples in New York. Like Fisher, Blanpied used a base temperature of 50°F when re-analyzing the former's Delicious apple data. He found a negative relationship between days from bloom to harvest and heat-unit summations from full bloom to full bloom + 30 days. The correlation coefficient was not significant, probably due to wide variation between areas. This would have the result of introducing many other variables (e.g., photoperiod, rainfall, nutrition) which would remain relatively constant if data from a single area were used.

Zimmerman (1965) correlated heat unit accumulations (base temperature 45°F) for a period of eight weeks following bloom with the period from bloom to maturity of Oregon Bartlett pears. A correlation coefficient of -0.96 was obtained with a standard error of the estimate of 1.5 days. Mellenthin (1966) demonstrated similar results with Oregon Anjou pears. He also examined the effect of

late-season ambient temperatures on premature ripening of the fruit. It was found that abnormally low temperatures in the month preceding harvest unexpectedly hastened fruit ripening.

Environmental factors other than temperature cannot be ignored when examining influences on maturity. Moisture availability and loss through transpiration may be considered as phenological examples. Nutritional status, rootstock type, age of tree, crop load and tree vigor are non-phenological examples.

Aldrich and Work (1934) showed that high rates of transpiration markedly reduced pear fruit growth. Ryall and Aldrich (1938) demonstrated an influence by moisture status on pear fruit firmness and quality. Hendrickson and Viehmeyer (1941) recommended wetting of the leaves to reduce transpiration on hot days and thus to avoid a slowing of pear growth rate.

An effect of rootstock type on maturity of pears was noted by Allen (1929). Trees on Japanese stock had much firmer fruit than those on French stock. Griggs and Iwakiri (1969) noted no difference in bloom period of Bartlett pear trees on six different rootstocks. Since a difference at this stage is likely to carry over to the harvest period, this conclusion is significant to the present study. Badran (1963) found that the effects on fruit maturity of seven East Malling apple rootstocks were only slightly different.

Fisher, et al. (1959) found that high potassium levels retarded pear maturity as measured by fruit firmness. They also noted a statistically significant reduction in soluble solids as a result of nitrogen treatment. More extensive work with apples has not shown tree nutrition to be very important as far as maturity is concerned (Stiles and Childers, 1961).

Physical Parameters

Under this heading are discussed morphological and anatomical parameters that may be indicators of the stage of pear fruit development. There is a large body of literature pertaining to the morphology and anatomy of developing pomaceous fruits. No references, however, will be made to studies unless they either (1) relate data obtained to ultimate maturity or (2) present data that are relevant to the present author's study. The latter's purpose in reviewing the literature is to find discrete, discernible stages in early fruit development which can be closely related to ultimate fruit maturity.

Tukey and Young (1944) mention earlier work by Tukey (1933a, 1933b, 1934, 1936) as evidence that in the developing peach and cherry fruit there are three definite growth stages. The middle stage is a period of slow fruit growth but is the time of rapid embryo growth. The authors found no such stages of fruit growth in the apple. There

is, however, a short but rapid burst of growth in the embryo 30-40 days after bloom. On the other hand, Mitchell (1950) found a definite double sigmoid curve in developing Bartlett pear fruits. Moreover, the mid-season halt in whole fruit growth coincided with a rapid spurt in embryo growth. Between 56 and 84 days after full bloom, the embryo grew from 0.3 mm to 6.9 mm, 93% of its final length. Between the 63rd and the 77th days after bloom; i.e., in the middle of this growth spurt, whole fruit size remained almost constant. Previous work by Hendrickson and Viehmeyer (1941) had not shown such a temporary cessation of Bartlett fruit growth.

Cell division in the cortex ceased 56 days after bloom in Mitchell's (1950) study of Bartlett pear fruit growth. This cessation coincided exactly with the onset of rapid embryo growth. Cell division in apple cortex ceases relatively early, at approximately 21 days (Tukey and Young, 1944, Bain and Robertson, 1951a). Subsequent growth of the cortex takes place, therefore, primarily as the result of cell expansion.

Griggs and Iwakiri (1956) compared methods of obtaining growth curves of Bartlett pears. They obtained more uniform curves by measuring the same fruit than by picking a random sample of different fruit at each measurement. This increase in accuracy was small and the latter method was less time-consuming. It also allowed cutting of the fruit and counting the seed.

Bain (1961) has made the latest and most comprehensive study of morphological and anatomical development of the Bartlett pear fruit. She divided fruit development into two distinct stages. Stage I occupies the first 42-56 days after bloom and is the period of cell division and slow physiological change. Stage II is the remainder of the period on the tree and is the stage of cell expansion and rapid physiological change. Stage I is also one of more marked morphological changes. Cell division in the cortex and pith ceases at the end of Stage I, but the rate of growth of the fruit increases, due to rapid cell expansion. The author makes a strong point that the transition point between Stage I and Stage II is one of great developmental significance. However, data are lacking around this point in her paper.

Stoll (1968) noted that the growth of the apple stem cavity provides a precise measure of a developmental stage. As the young apple grows it changes from a convex shape at the stem end to a concave shape. At the transition point the stem end is flat and the plane it occupies forms a T-shape with the stem. Hence, it is called the T-stage and predictions of maturity can be made by adding a constant number of days to the date on which it is reached. The period between this stage and harvest maturity is almost constant from year to year. The T-stage can be determined by direct observation or by

extrapolating back when two later measurements of stem cavity depth have been recorded (growth of the fruit is essentially linear at this stage).

Sclereid or stone-cell formation in pear fruit has been studied by Crist and Batjer (1931), Smith (1935), Mitchell (1950), Sterling (1954) and Bain (1961). The last author states that lignification of cells in the cortex starts approximately 14 days after bloom. The rate of sclereid formation starts to decline after the 28th day but continues at a somewhat slower rate to the end of Stage I. In the outer cortex, sclereids first appear at about 21 days after bloom and continue to form during Stage II.

Biochemical and Physiological Parameters

Hulme (1958) reviewed the work to date on the biochemistry of apple and pear fruits. Workers in Australia have done extensive studies on nitrogen and organic acid metabolism of Granny Smith apples (Robertson and Turner, 1951; Pearson and Robertson, 1953). They note that starch content of the fruit rises steeply until about 160 days after bloom (30 days before commercial harvest) when it begins to decline. Respiration rate at bloom was 330 mg. CO_2/kg./hr. and it declined to 11 mg./kg./hr. at 160 days. The climacteric rise occurred at about 190 days after bloom (commercial maturity). Ulrich and Thaler (1957)

traced changes in carbohydrates, organic acids and nitrogenous compounds in the Bartlett pear throughout its development.

Changes in mineral content of apples during development have also been measured (Wilkinson and Perring, 1964). The most remarkable change that occurs in early apple fruit development is for calcium. Whereas potassium uptake continues at a high level throughout growth, calcium uptake falls appreciably after the initial cell-division period.

Of all the organic and inorganic chemical changes that occur in the young fruit, only one suggests itself as a means of predicting ultimate maturity. Starch synthesis occurs from the beginning in the pear fruitlet, but it does not accumulate until late in the period of cell division (Bain, 1961). This is because the cell division process consumes available carbohydrate to such an extent that reserves are not available for starch synthesis. Thus the onset of starch accumulation in the pear fruit is a potential indicator of a precise stage in the early development of the fruit. Moreover, the point at which accumulation occurs may bear a relationship to the time from full bloom to maturity. However, Badran (1963) found little relationship between the date of the respiratory climacteric and that of starch accumulation (average time 29 days after bloom) in the McIntosh apple. This author

indicated a close association between the occurrence of starch accumulation and that of the June drop.

Methods for Evaluation of Pear Fruit Maturity

Physical Indices

For pears to command a premium price on the market, they must be above average in size. This size minimum will vary with production area, variety and market outlet. However, fruit in Michigan and elsewhere may be physiologically over-mature by the time this size requirement is met. Thus, size bears very little relationship to maturity except in areas where growing-season length and fruit size vary little from year to year. This occurs in the West Coast pear producing areas, where environmental conditions are relatively constant.

Color of the fruit is widely employed as an index of maturity. Color charts have been designed to lend some degree of objectivity to its measurement. The recent development of reflectance instruments may improve further on this test. However, early work in California (Allen, 1929, 1932) showed that cool growing areas produced fruit that were greener than those of the same physiological maturity from hot areas. Fruit color at harvest maturity also varies between seasons in the same growing area.

Flesh firmness is probably the most widely used of all maturity indices for pear fruit, as well as apples. The Magness-Taylor pressure tester is the measuring instrument commonly used (Magness and Taylor, 1926). Recently a modification of this instrument was developed by workers at the University of California.[1] This latter instrument purportedly reduces variation within and between operators to a greater extent than the original version. These two instruments were both designed to provide a quantitative and objective measurement of flesh firmness. Bourne (1965) showed that the point of "give" of the tissue approximates the "bioyield point," where the cells of the cortex separate under a shearing force (Murneek, 1923). Since the pectinaceous constituents of the cell-walls change as the fruit matures, the shearing force necessary for their separation decreases. Another component of firmness other than the bioyield point has been recognized in recent years (Drake, 1962). This is a measure of deformability of the fruit and approximates Young's modulus of elasticity (Bourne, 1969). This component may be measured by subjecting the fruit to sonic vibrations over a range of frequencies and determining its resonant

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[1]The U.C. firmness tester. Manufactured by Western Industrial Supply, Inc., 236 Clara Street, San Francisco, California 94107.

frequencies. This is described for apples by Abbott, et al. (1968) and has the advantage of being truly objective and non-destructive.

In spite of the above-described increase in sophistication in firmness measurements, the parameter itself has its limitations in truly reflecting maturity. The work of Allen (1929, 1932) has shown that, as with color, flesh firmness varies between fruit of the same maturity grown under different late-season temperature conditions. Factors such as rootstock type (Allen, 1929), soil moisture (Haller and Harding, 1938), and evaporating power of the air (Ryall and Aldrich, 1938) are also cited as factors contributing to variations in firmness of pears of optimum maturity. Ryall, et al. (1941) state that the firmness index is of use provided that means of adequate samples are compared with desirable ranges for the locality. These ranges must be determined by local experimentation. However, because of the environmental factors described above, it is a common experience to encounter no change in firmness during critical stages of maturation. Therefore, firmness is unreliable when used as the single criterion of maturity.

Another commonly used measure of harvest maturity is defined rather elusively as "finish." It can be used only by those with wide experience in the field and involves the development of certain superficial

characteristics of a mature pear fruit. These are the development of a wax or "bloom" on the fruit and a general rounding out to a pear-shape typical for the variety. Also, the lenticels of an immature pear are white in color; whereas those of the mature fruit are brown due to the suberization of the surrounding cells. Furthermore, the ground color of the skin tends to "break" more slowly in the area immediately surrounding the lenticels when maturity is reached. This makes the lenticels stand out as dark green spots (Batjer, et al., 1947). These observations are those of the experienced worker and are too subjective for general commercial use.

Chemical Indices

The disappearance of starch from the cortex of the developing pear fruit signals the beginning of maturity (Bain, 1961). Hinton (1932) studied the starch content of apples in relation to maturity in England. A standard tissue-staining test for starch in the cortical tissue using an iodine-potassium iodide solution was developed by Tiller (1934). Haller and Smith (1950) summarized results with the starch test on apples. They concluded that there was large variability, both between fruit and between seasons, in the amount of starch present at maturity. Recently, workers in England have found the starch test to be a reliable guide to pear maturity (North, 1970).

The soluble solids content of expressed juice has been used as a maturity index for pears in California for many years. According to the Agricultural Code of California issued by the California Bureau of Fruit and Vegetable Standardization (1951), pears have to meet one of the following requirements before they are considered mature:

(a) a firmness reading of not more than 23 lbs., using a plunger tip 5/16" in diameter;

(b) a soluble solids content of not less than 13%; and

(c) a yellowish green color, as indicated by the color chart prepared by the California State Department of Agriculture.

While the fruit remains on the tree, sugar content (the predominant component of soluble solids) increases at the rate of 5-10% every 10 days during the harvest period (Magness, 1920).

The percent soluble solids in McIntosh apples varies with crop load and the amount of sunshine during the growing season (Blanpied, 1960a). Under New York conditions, soluble solids content varied too much on any given sampling date to be valuable as a maturity index (Blanpied, 1960a). Claypool (1961) pointed out that temperatures above normal will cause a relatively rapid rise in soluble solids. However, he also stated that flesh firmness responded by declining more slowly with

high temperatures. Conversely, temperatures below normal resulted in rapid firmness loss but little or no soluble solids increase. Thus, situations arise where fruit meet one or the other requirement, firmness or soluble solids, but the fruit subsequently prove not to be physiologically mature. As a result, a combination index was established for California comprising both firmness and soluble solids (Batjer, et al., 1967). Its effect was to require, for example, fruit of low soluble solids content to be somewhat softer than those with high soluble solids.

A less frequently used index of fruit maturity is found in the changes in pectic substances in the fruit. Early workers (Gerhardt and Ezell, 1938; Haller, 1929) showed a relationship between pectins and softening in apples. Work in the State of Washington (Gerhardt, 1947) showed the changes in soluble pectin to be a more sensitive measure of D'Anjou pear maturity than flesh firmness. This work gives no indication of minimum levels of soluble pectin. A related index is that of juice viscosity. The appearance of soluble pectins in the juice is likely to affect its viscosity. Simpson (1953) thought that juice viscosity changes were a suitable index of Bartlett pear maturity. Maturity was reached when viscosity started to increase rapidly. However, later work from the same team (Truscott and Wickson, 1955) showed little change in juice viscosity during the pre-harvest period.

Little work has been done to relate titratable acidity of pear juice to maturity. Allen (1932) recorded changes in titratable acidity during the pre-harvest period of Bartlett pears in California. The data show a steady decline as the fruit approach maturity with considerable differences between locations. Putterill (1928) noted that fluctuations in acidity were closely and positively correlated with atmospheric temperatures. A fall in total acids immediately preceded maturity in Bartlett pears observed by Ulrich and Thaler (1957).

Physiological Indices

Gane (1934) established over thirty years ago that many fruits produce ethylene when they ripen. Hansen (1943) demonstrated, through the use of a bioassay, that it was also evolved by immature fruits. However, precise quantitication of ethylene evolution by fruits came with the development of highly sensitive gas chromatography which permits the detection of ethylene at levels of one part per billion (Pratt and Goeschl, 1969). Kidd and West (1933) found that not only did ethylene emanate from ripening fruits but also exogenous ethylene caused mature fruits to ripen. It is not proposed to discuss these two well-established facts nor to review the large amount of literature pertaining to them. Access to most of the work on ethylene can be gained through the review article by Pratt

and Goeschl (1969). Only the use of ethylene evolution (or its concentration in the internal atmosphere of the fruit) as an index of maturity is explored.

In 1962, evidence began to accumulate that ethylene was indeed the ripening hormone (Burg and Burg, 1962). Evidence was presented which showed that there may be a threshold level of ethylene above which ripening or a respiratory climacteric would occur (Burg and Burg, 1962; Biale, et al., 1954).

No work has been reported that relates ethylene evolution or internal fruit concentration to maturity of pears. That ethylene is evolved by immature Bartlett pear fruits has been long established (Hansen, 1943). This author also postulated that the concentration of ethylene would, on reaching a certain level, bring about the climacteric rise in respiration. In work with the cantaloupe, Lyons, et al. (1962) showed that an increase in ethylene concentration in the internal atmosphere of the fruit coincides with or immediately precedes the respiratory climacteric.

Recently, investigators in Ontario (Smith, et al., 1969; Smith, 1969) established that a minimum significant level of ethylene production of 0.075 ml./kg./hr. was reached prior to the occurrence of the respiratory preclimacteric minimum (PCM) in 5 out of 12 samples of McIntosh and Delicious apples. In two other cases the

PCM coincided with the first detection of ethylene (Smith, et al., 1969). The average number of days from the earliest detectable ethylene evolution to the first acceptable harvest was 7.2 days for McIntosh and 7.0 days for Delicious. Standard deviations for these means were 3.0 days and 3.8 days, respectively. They suggest that these observations may be the basis for employing ethylene production rate as a maturity index.

The evolution of volatiles other than ethylene and carbon dioxide has been studied in recent years (Jennings, 1961; Jennings and Creveling, 1963; Jennings and Sevenants, 1964; Jennings, et al., 1964; and Phan-Chon-Ton, 1965). Jennings and co-workers isolated the principal aroma component of Bartlett pear and identified it as trans: 2-cis: 4-decadienoic acid (Jennings, et al., 1964). Phan-Chon-Ton (1965) lists tentatively isopropyl acetate, butyraldehyde, amyl acetate, and secondary butanol as the major aromatic principles. A worker in Germany (Zachariae, 1967a, 1967b, 1970) and one in Italy (Serini, 1956) have attempted to correlate concentrations of certain volatiles from pear fruit to fruit maturity. Serini found maturity could be gauged by the levels of two aromatic compounds, 2,3 butylene gylcol and acetyl methyl carbinol. Zachariae (1967a, 1967b) suggested that the optimum harvest date for Clapp's Favorite and Alexandre Lucas pears (and three varieties of apple) was the date at which the total

aromatic constituents reached a minimum. He observed a steady decline to this minimum, followed by a rapid increase during ripening.

Pears, like other climacteric fruits when immature, will respond to externally applied ethylene with a temporary rise in their respiration rate (Hansen, 1967). Ripening, however, will not be induced until maturity is approached (Allen, 1930). Later work by Hansen and Blanpied (1968) was concerned with the gradual development of a capacity to ripen in response to applied ethylene as pear fruits approached maturity. The length of exposure of fruits to 500 ppm ethylene that was required to induce ripening decreased with fruit maturation. This work makes clear the distinction between the capacity of the fruit to respond to physiological ethylene concentrations and the capacity to generate such concentrations.

It has been widely accepted for many years that the beginning of the climacteric rise in respiration approximates the optimum harvest date for apples and pears (Kidd and West, 1926). Respiration and protein synthesis are stimulated by ethylene treatment of immature pear fruits. It was, therefore, suggested that ethylene initiated the biochemical changes that lead to the respiratory climacteric and ripening (Hansen, 1967). However, Richmond and Biale (1966) and Frenkel, et al. (1968) show evidence that the climacteric is not directly related to protein

synthesis. Their data show that when protein synthesis, and as a result the various ripening changes, are inhibited the respiration climacteric may continue unabated. Blanpied (1968) recognized, nevertheless, the great value that has been set on the preclimacteric minimum as a "physiological point of reference." Since it had been used in the past as an indicator of maturity, he examined possible sources of variation in its incidence. He established that there were no significant differences in the occurrence of the preclimacteric minimum for fruits from the same or different trees.

Later work by Blanpied (1969) provided convincing evidence that optimum harvest dates coincided with widely differing points on the climacteric curve from one season to another. Four apple varieties were studied over an eight-year period. Optimum harvest maturity, as judged by physiological disorder incidence, flavor and general appearance of fruits following storage, was reached at all stages on the climacteric rise and, in one case, several days after the climacteric peak.

METHODS AND RESULTS

In 1967, the basic Bartlett pear maturity survey was instituted. Since it has changed little in the four years of work described herein, a general description follows. Modifications and exclusions from this basic plan will be noted in the text in the season in which they occurred. Additional experiments were also conducted in subsequent years and will be described under the relevant year.

Eleven orchards, representing the major pear-producing areas in Michigan were selected. The location of each orchard and its approximate latitude, is given in Table 1, with the name of the grower. The dates of full bloom and petal drop were obtained from each grower where possible. In addition, similar pear bloom data were solicited from a large number of other growers in the principal pear-producing areas. For the purposes of this survey full bloom was defined as that date when 80% of the blossoms were open; petal drop as that date when 80% of the petals had fallen.

Soon after bloom, two trees were selected in each orchard as the sources of fruit for the maturity survey. These trees were considered to be typical of the orchard

Table 1. Locations of orchards used in the Michigan Bartlett pear maturity survey in 1967 with the name of the grower.

Orchard	Location	Grower	Latitude
1	Scottdale, Berrien Co.	Dongvillo	42° 03'
2	Benton Harbor, Berrien Co.	Smith	42° 08'
3	Hartford, Van Buren Co.	Heuser	42° 12'
4	Paw Paw, Van Buren Co.	Woodman	42° 14'
5	Fennville, Allegan Co.	Whightman	42° 28'
6	Fennville, Allegan Co.	MSU	42° 32'
7	South Lyon, Oakland Co.	Erwin	42° 23'
8	Grand Rapids, Kent Co.	MSU	42° 57'
9	Hart, Oceana Co.	Garnett	43° 42'
10	Ludington, Mason Co.	Vorac	43° 54'
11	Traverse City, Grand Traverse Co.	Minnema	44° 46'

as a whole and were carrying a crop-load sufficient to provide fruit for the survey. The trees were marked with string and tagged to prevent accidental picking by the grower at harvest time.

Four harvest dates were chosen for each orchard. In choosing these dates, the aim was to obtain harvests both preceding and following the date of commercial harvest. On each harvest-date, a sample of 50 fruits was picked at random from the pair of trees in each orchard. Picking was performed at each location by the local extension agent. The fruit were placed in 125-count bushel trays and packed in boxes with polyurethane foam sheets above and below each of the two trays. The boxes were enclosed by a cardboard sleeve and the resulting package taped shut and dispatched by Greyhound bus to Lansing. All harvests were taken on Mondays and the samples were picked up the same evening at the Lansing bus depot.

The fruit from each orchard and harvest were subjected to various treatments as follows:

5 fruits were selected at random and stored at 0°C overnight. These were subsequently evaluated for firmness, color and soluble solids of the juice.

8 fruits were randomly selected, weighed and used for respiration measurement using the APRIL system (Dilley, et al., 1969).[1]

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[1]Automatic Photosynthesis and Respiration Integrating Laboratory.

8 fruits were randomly selected, weighed and pre-treated with 1000 ppm of ethylene gas for 12 hours prior to the above respiration measurement. (The fruits used in the respiration measurements above also yielded data on mean fruit weight.)

29 the remaining fruit were subjected to long-term cold storage at 0°C. They were later evaluated for storage behavior.

Firmness of the initial 5-fruit sample was measured with a Magness-Taylor pressure tester, using a 5/16" diameter tip. The mean of 10 pressure measurements, two each per fruit, was computed. The color of each of these fruit was assessed using a standard color chart issued by the California State Department of Agriculture.

The soluble solids content of a composite sample of juice expressed from the same fruit was measured using a Zeiss Opton hand-refractometer.

The method of ethylene treatment was to enclose the fruit in an 11 liter polyethylene pail with a tight fitting metal lid equipped with inlet and outlet ports. Since carbon dioxide is a competitive inhibitor of ethylene action, a Kraft paper bag containing approximately 200 gms. of slaked lime was included with the fruit to prevent an excessive accumulation of carbon dioxide resulting from respiration of the fruit. The inlet and outlet ports on the lid of the container were connected by flexible rubber

tubing, thus sealing the fruit in an air tight container. Ethylene was introduced by hypodermic syringe through the tubing to produce a concentration of 1000 ppm inside the container. The sealed container was kept at 20°C for 12 hours after which the rubber tubing was disconnected and the lime bag removed. The container was then connected to the APRIL system for a week of respiration measurements at 20°C.

At the end of a week of respiration measurements, the ethylene-treated and non-treated fruit were removed and evaluations for firmness, color and soluble solids content.

In order to ascertain the relationships between the above described parameters and fruit maturity, it was necessary to store the remaining fruit from each harvest and to evaluate their storage behavior at a later date. The fruit from each harvest in the 11 orchards were removed after a period of storage and placed at a ripening temperature of 20°C. Measurements of fruit firmness and flesh breakdown were made initially and after a few days at ripening temperatures. Flesh or internal breakdown measurements are presented as an index using an arbitrary scoring system. This system involved examining each fruit individually and assigning a score of 0 to each fruit showing no symptoms of breakdown; 1 for slight; 2 for moderate and 3 for severe symptoms. The

average score for each sample was then computed and used as an overall evaluation of breakdown.

Maturity Studies in 1967

The initial flesh firmness of fruit from each harvest in the 11 test orchards together with their ripening behavior with and without ethylene treatment are shown in Table 2. Two factors were observed at this stage. First, an overall downward trend in fruit firmness with time is evident. Traditionally, fruit have been harvested when fruit firmness is not less than 18 lbs. if long-term storage is desired. Secondly, there is a marked tendency for fruit to respond to ethylene, in terms of softening, one to two weeks before non-treated fruits responded at 20°C. This difference is also reflected in the respiratory patterns of the fruit (Figure 1). The onset of the climacteric (termed the pre-climacteric minimum or PCM) occurs at a correspondingly earlier date in the treated fruit. This early response to ethylene indicates a distinction between the capacity to respond to exogenous ethylene and the capacity for autocatalytic synthesis of the gas. Fruit are physiologically capable of ripening before their own endogenous ethylene has reached levels stimulatory to ripening.

Table 2. Michigan Bartlett pear maturity survey--1967. Flesh firmness and ripening behavior at harvest in relation to time of harvest.

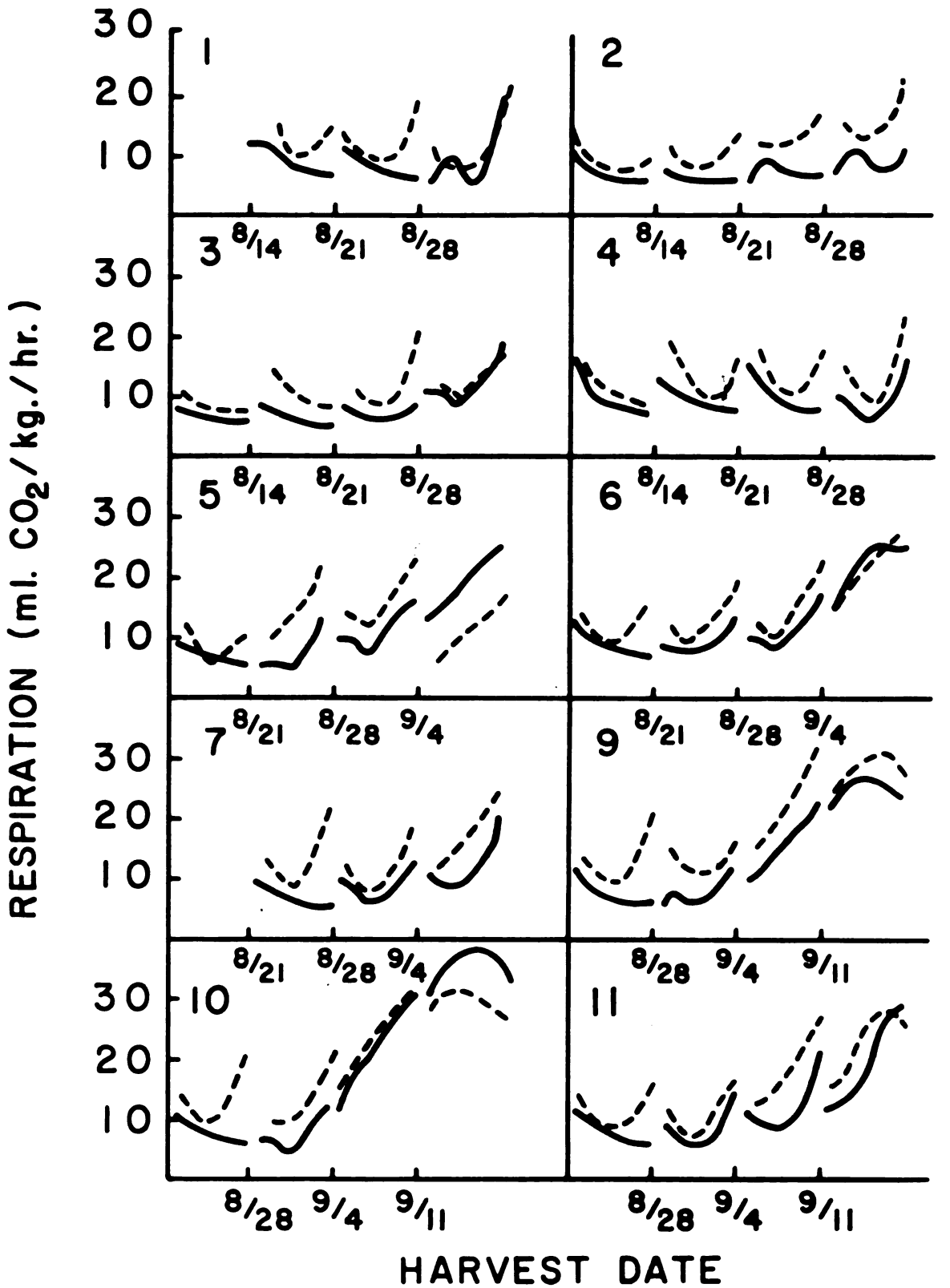
Orchard	Full bloom date FB	Harvest date HD	Days FB→HD	Flesh firmness-lbs. Initial	Plus 7 days at 20°C Air	Plus 7 days at 20°C Ethylene
1	5/10	8/7	89	-	-	-
		8/14	96	25.0	20.0	6.0
		8/21	103	21.0	17.8	3.2
		8/28	110	16.6	3.0	3.0
2	5/1	8/7	98	25.5	24.5	24.5
		8/14	105	24.5	20.5	3.0
		8/21	112	22.0	11.9	3.0
		8/28	119	15.7	3.0	3.0
3	5/5	8/7	94	22.5	23.0	21.5
		8/14	101	23.5	17.5	8.5
		8/21	108	20.0	10.5	3.2
		8/28	115	16.6	3.0	3.0
4	5/5	8/7	94	27.5	26.0	28.0
		8/14	101	25.0	22.5	8.5
		8/21	108	21.0	24.1	7.2
		8/28	115	17.5	7.5	3.1
5	5/12	8/14	94	24.0	20.0	12.1
		8/21	101	17.0	5.7	3.1
		8/28	108	16.2	3.0	3.0
		9/4	115	7.5	3.0	3.0
6	5/12	8/14	94	22.0	20.0	5.5
		8/21	101	19.0	8.6	3.8
		8/28	108	16.1	3.0	3.0
		9/4	115	12.2	3.0	3.0
7	5/16	8/14	90	-	-	-
		8/21	97	21.0	22.6	3.9
		8/28	104	15.4	11.0	3.0
		9/4	111	16.6	5.2	3.1
8	5/14	8/14	92	23.0	21.1	9.4
		8/21	99	17.1	13.9	3.2
		8/28	106	17.5	3.0	3.0
		9/4	113	10.7	3.0	3.0

Table 2. Continued.

Orchard	Full bloom date FB	Harvest date HD	Days FB→HD	Flesh firmness-lbs. Initial	Plus 7 days at 20°C Air	Plus 7 days at 20°C Ethylene
9	5/22	8/21	91	20.0	19.2	3.4
		8/28	98	19.5	9.1	3.0
		9/4	105	15.2	3.1	3.0
		9/11	112	12.0	3.0	3.0
10	5/20	8/21	93	20.5	19.1	3.2
		8/28	100	19.6	3.5	3.0
		9/4	107	12.8	3.0	3.0
		9/11	114	7.0	3.0	3.0
11	5/26	8/21	87	22.5	21.8	6.4
		8/28	94	19.6	16.9	3.0
		9/4	101	17.5	5.3	4.6
		9/11	108	16.4	3.6	3.3

Figure 1. Respiratory behavior of Bartlett pear fruits from a sequence of weekly harvests at 10 orchards in Michigan in 1967.

Graph numbers correspond to orchard numbers according to Table 1 (page 31). Solid lines are respiration curves of non-treated fruit; broken lines are respiration curves of ethylene-treated fruit.


RESPIRATION (ml. CO_2/kg./hr.)
30
20
10
1
2
3
4
5
6
7
9
10
11
8/14
8/21
8/28
9/4
9/11
HARVEST DATE

The initial color of the fruit and initial soluble solids content of the juice and the changes occurring in these parameters at 20°C with and without ethylene treatment is shown in Table 3. Color changes from green to yellow (measured on a scale of 1 to 4) closely paralleling the behavior of the fruit in loss of firmness. However, the scale is discontinuous and the means of color measurement highly subjective in comparison with the method of firmness measurement. Color measurement by visual comparison with a chart cannot, therefore, be considered a precise index of maturity. Use of more objective methods, such as those employing light transmittance devices[1] (Birth and Norris, 1965), may make color measurement more valuable. Similar arguments may be used to reject soluble solids content of the juice as a reliable maturity index. Small changes occur over the fruit maturation period that cannot be detected except when large sample sizes and accurate instruments are used.

The least equivocal test of fruit maturity is to observe their storage behavior. If fruits are harvested before they are mature, their capacity to ripen (as measured by loss of firmness) is largely undeveloped. They generally ripen slowly, if at all, during storage and

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[1]Commercial model: Internal Quality Analyzer, Model 170. Manufacturers: Neotec Instruments, Inc., 1132 Taft St., Rockville, Md. 20850.

Table 3. Michigan Bartlett pear maturity survey--1967. Fruit weight, color and juice soluble solids content and ripening behavior at harvest in relation to time of harvest.

Orchard	Harvest date	Fruit weight	Fruit color[1]			Soluble solids[2]		
				Plus 7 days at 20°C			Plus 7 days at 20°C	
			Initial	Air	Ethylene	Initial	Air	Ethylene
1	8/7	-	-	-	-	-	-	-
	8/14	114.9	1.5	-	-	10.5	11.5	11.5
	8/21	139.7	2.0	1.4	4.0	11.5	12.5	12.0
	8/28	150.7	1.5	4.0	4.0	11.5	13.0	12.5
2	8/7	100.2	1.0	1.0	1.0	10.5	-	-
	8/14	115.2	1.5	-	-	10.5	8.0	12.0
	8/21	114.5	1.5	2.2	4.0	11.0	10.5	11.5
	8/28	131.1	1.5	3.8	4.0	11.5	11.5	10.0
3	8/7	99.3	1.0	1.5	1.5	10.0	-	-
	8/14	99.0	1.5	-	-	11.0	11.0	11.0
	8/21	120.0	2.0	2.5	3.8	11.0	11.0	11.5
	8/28	115.1	2.0	4.0	4.0	11.5	11.5	11.0
4	8/7	99.1	1.0	1.0	1.0	10.5	-	-
	8/14	101.4	1.0	-	-	11.5	13.5	12.0
	8/21	126.1	1.0	1.0	2.5	12.5	12.0	13.0
	8/28	124.4	1.0	2.5	4.0	11.0	12.5	12.0

Table 3. Continued.

Orchard	Harvest date	Fruit weight	Fruit color			Soluble solids		
				Plus 7 days at 20°C			Plus 7 days at 20°C	
			Initial	Air	Ethylene	Initial	Air	Ethylene
5	8/14	111.5	2.0	-	-	10.0	11.0	11.0
	8/21	112.3	2.0	3.0	4.0	10.5	10.0	10.0
	8/28	120.5	2.0	4.0	4.0	11.0	10.5	11.5
	9/4	133.6	3.3	4.0	4.0	12.0	12.0	12.0
6	8/14	121.0	1.5	-	-	10.0	13.0	11.0
	8/21	117.1	2.0	2.2	4.0	10.5	11.0	11.5
	8/28	124.6	2.0	4.0	4.0	11.0	10.5	11.0
	9/4	165.5	3.3	4.0	4.0	12.0	12.0	12.0
7	8/14	-	-	-	-	-	-	-
	8/21	127.7	1.0	1.0	3.0	11.0	11.5	11.0
	8/28	117.5	1.0	1.5	3.0	11.0	10.5	10.5
	9/4	147.5	2.0	3.4	4.0	12.0	12.0	13.0
8	8/14	101.4	1.0	1.0	2.4	11.5	12.0	12.5
	8/21	108.0	1.5	1.8	3.0	11.0	12.0	12.5
	8/28	147.4	2.0	4.0	4.0	12.5	13.0	13.5
	9/4	147.2	3.0	4.0	4.0	13.0	-	-
9	8/21	107.6	1.0	1.2	3.0	10.0	11.0	11.0
	8/28	141.2	1.5	2.0	3.8	11.0	10.5	11.0
	9/4	137.0	1.5	3.4	4.0	12.0	11.5	11.0
	9/11	162.0	2.2	4.0	4.0	12.5	12.0	12.0

Table 3. Continued.

Orchard	Harvest date	Fruit weight	Fruit color			Soluble solids		
			Initial	Plus 7 days at 20°C		Initial	Plus 7 days at 20°C	
				Air	Ethylene		Air	Ethylene
10	8/21	124.4	1.0	1.0	3.8	10.0	10.5	11.0
	8/28	126.4	1.5	2.8	4.0	10.5	10.0	10.5
	9/4	153.8	1.5	4.0	4.0	11.5	10.0	10.0
	9/11	166.0	2.6	4.0	4.0	10.5	12.0	-
11	8/21	161.0	1.0	1.0	1.5	9.5	10.0	10.0
	8/28	178.1	1.0	1.0	2.5	9.5	9.5	10.0
	9/4	188.0	1.0	2.6	2.2	10.0	10.0	11.0
	9/11	197.9	1.5	3.5	4.0	10.5	10.0	10.0

[1]Each number is the mean of 7 fruits using a color chart from the California State Department of Agriculture. A score of 1 is allotted to dark-green fruit; 2 to light-green; 3 to pale-yellow and 4 to bright yellow fruit.

[2]Each number is a measurement of a composite juice sample from 7 fruit. The measurements were made using a Zeiss Opton hand-refractometer.

after removal show other symptoms of immaturity, such as uneven color change and flesh discoloration. Conversely, if harvested over-mature, fruits will rapidly ripen in storage and exhibit a high incidence of internal flesh breakdown during the post-storage ripening period often without normal softening. The firmness of the fruit and the incidence of breakdown, both immediately after removal from storage and after three days at 20°C, are shown in Table 4. It must be noted that successive harvests were not treated equally, since all were removed from storage on the same date. The reasons for this were wholly practical, but it was considered that little loss of information would be incurred. Thus, the earlier harvests show comparatively little breakdown although they have been stored longer. Later harvests show more breakdown because they were over-mature at harvest and the irreversible process of ripening had already been initiated.

Using Table 4, it is possible to select the harvest in each orchard series which was optimum for long-term storage. This is done by finding the latest harvest which shows little or no breakdown symptoms. These harvests are indicated in Table 5. Other measures of maturity can be compared with this "maturity index" (in truth, it is not a practical pre-harvest maturity index but is used here as a test for all other indices). Thus, from the respiration data (Figure 1) have been abstracted the dates of the

Table 4. Bartlett pear evaluation after cold storage (0°C)--removed November 9-16, 1967.[1]

Orchard	Harvest date	Days in storage	Fruit condition at removal			Fruit condition after 3 days at 20°C		
				Breakdown			Breakdown	
			Flesh firmness	External symptoms[2]	Internal symptoms[3]	Flesh firmness	External symptoms[2]	Internal symptoms[3]
1	8/7	-	-[4]	-	-	-	-	-
	8/14	87	16.8	0	0	4.6	0	0
	8/21*[5]	80	15.6	0	0	4.4	0	0
	8/28	73	14.2	0	0	4.6	0	0.8
2	8/7	-	-[4]	-	-	-	-	-
	8/14*	87	15.5	0	0	4.0	0	0.1
	8/21	80	15.0	0	0	4.2	1	0.4
	8/28	73	11.0	1	0.2	5.2	1	2.0
3	8/7	-	-[4]	-	-	-	-	-
	8/14	87	15.4	0	0	4.2	1	0.5
	8/21*	80	14.2	0	0.4	4.8	0	0.5
	8/28	73	11.2	5	0.4	5.0	1	1.7
4	8/7	-	-[4]	-	-	-	-	-
	8/14*	87	18.8	0	0	5.4	0	0.6
	8/21	80	17.4	0	0	5.4	0	1.1
	8/28	73	17.0	0	0	5.4	0	1.7

Table 4. Continued.

Orchard	Harvest date	Days in storage	Fruit condition at removal			Fruit condition after 3 days at 20°C		
			Flesh firmness	Breakdown		Flesh firmness	Breakdown	
				External symptoms[2]	Internal symptoms[3]		External symptoms[2]	Internal symptoms[3]
5	8/14	-	17.4	0	0	5.4	1	0.4
	8/21*	87	16.6	0	0	5.8	0	0.2
	8/28	80	11.2	6	0.4	7.5	4	2.3
	9/4	73	10.9	13	1.0	11.2	2	3.0
6	8/14	87	17.1	0	0	6.2	1	0.5
	8/21*	80	16.0	0	0	6.2	0	0.1
	8/28	73	14.0	0	0	6.6	0	1.3
	9/4	66	12.8	13	0	9.7	1	1.4
7	8/14	87	-4	-	-	-	-	-
	8/21*	80	17.8	0	0	4.6	0	0.5
	8/28	73	14.6	0	0	7.4	5	2.7
	9/4	66	13.2	1	0.8	7.2	0	2.5
9	8/21*	87	17.8	0	0	5.4	0	0.2
	8/28	80	16.3	0	0	5.6	0	0.6
	9/4	73	13.5	7	0.4	9.3	1	1.1
	9/11	66	13.7	21	0.6	13.1	3	2.2

Table 4. Continued.

Orchard	Harvest date	Days in storage	Fruit condition at removal			Fruit condition after 3 days at 20°C		
			Flesh firmness	Breakdown		Flesh firmness	Breakdown	
				External symptoms[2]	Internal symptoms[3]		External symptoms[2]	Internal symptoms[3]
10	8/21	87	16.9	0	0	6.2	0	0.9
	8/28*	80	16.4	0	0	6.0	0	0.2
	9/4	73	11.8	2	0.4	8.4	7	1.4
	9/11	66	10.6	29	1.5	-[4]	-	-
11	8/21*	87	16.2	0	0	5.8	0	0
	8/28	80	15.0	0	0	5.0	1	0.2
	9/4	73	13.4	0	0.4	6.0	5	1.2
	9/11	66	12.0	0	0.4	6.1	1	0.9

[1]Orchards 1-7 removed 11/9/67; orchards 9-11 removed 11/16/67.

[2]External symptoms at removal shows total number of fruit with symptoms in whole sample; external symptoms after 3 days shows only fruit that subsequently developed symptoms.

[3]Based on an index viz. 0--no symptoms, 1--slight, 2--moderate, 3--severe symptoms.

[4]Fruit not evaluated due to large incidence of breakdown.

[5]Denotes optimum harvest according to storage performance.

Table 5. The ripening behavior of ethylene-treated[1] and non-treated fruits in relation to initial flesh firmness and the optimum harvest date in 1967, as determined by storage data.

Orchard	Optimum harvest date	Flesh firmness at optimum harvest	Post-harvest ripening behavior at 20°C			
			Ethylene-treated		Non-treated	
			Firmness loss	PCM	Firmness loss	PCM
1	8/21	21.0	8/14	8/14	8/28	8/28
2	8/14	24.5	8/14	8/14	8/21	8/28
3	8/21	20.0	8/14	8/21	8/21	8/21
4	8/14	25.0	8/14	8/14	8/28	8/28
5	8/21	17.0	8/14	8/14	8/21	8/21
6	8/21	19.0	8/14	8/14	8/21	8/21
7	8/21	21.0	8/21	8/21	8/28	8/28
9	8/21	20.0	8/21	8/21	8/28	8/28
10	8/28	19.6	8/21	8/21	8/28	8/28
11	8/21	22.5	8/21	8/21	9/4	8/28

[1] 1000 ppm for 12 hours in the absence of CO_2.

harvests in which the pre-climacteric minima first occurred for both non-treated and ethylene treated fruit. Similarly, the dates of harvest at which fruit softening occurred in each case have been taken from Table 2. The dates of harvests in which these four phenomena occur are compared in Table 5 with the optimum harvest dates according to the storage data. In addition, the fruit firmness at the storage-index optimum harvest is shown as a measure of the effectiveness of the former as a maturity index.

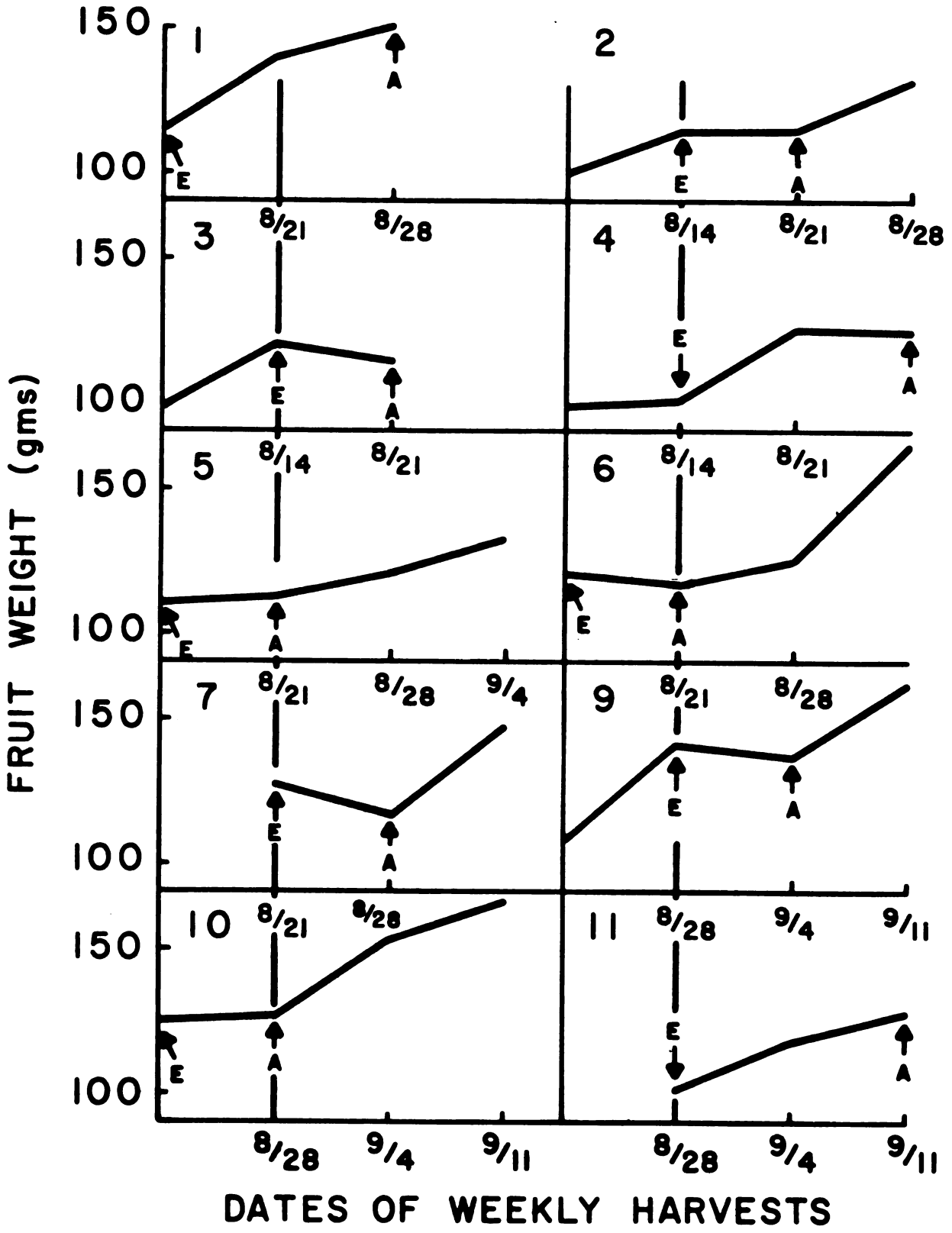
The main conclusion to be drawn from the data in Table 5 is that there is no single index precise enough to indicate optimum harvest consistently. In most cases, there is simultaneity between firmness loss and PCM occurrence, both for ethylene-treated and non-treated fruit. These changes occur in the treated fruit at the optimum harvest or the week before. In the non-treated fruit they occur at the optimum or one to two weeks later. In each orchard, there is a delay of one or two weeks between the changes in treated and non-treated fruit. The optimum harvest date for storage in each case lies within the time span thus delineated. However, in some cases the optimum coincides with the point when changes occur in the treated fruit; at other times it coincides with the time when these changes occurred in the non-treated fruit (Figure 2).

The fruit firmness at the optimum harvest for long term storage varied widely, ranging from 24.5 to 17.0 lbs.

Figure 2. Patterns of fruit growth during maturation, with the relationships among optimum harvest according to storage behavior, and the occurrence of flesh firmness loss in both ethylene-treated (E) and non-treated fruit (A). Data from weekly harvests at 10 orchards in Michigan in 1967.

Optimum harvest dates are adjusted to the vertical line to facilitate comparisons.

Graph numbers refer to orchard numbers according to Table 1 (page 31).


150
100
1
2
3
4
5
6
7
9
10
11
E
A
8/14
8/21
8/28
9/4
9/11
FRUIT WEIGHT (gms)
DATES OF WEEKLY HARVESTS

In commercial practice, fruit would not be picked at 24.5 lbs. and would be considered over-mature for lengthy storage at 17.0 lbs. The fruit firmness index thus seems to be inadequate to measure pear fruit maturity.

It is worth noting in Figure 2 that there was frequently a temporary cessation or slowing of fruit growth prior to the harvest in which fruits softened in air. After the fruits reached this physiological stage, growth was again resumed, often more rapidly than before the period of little growth.

The dates of full bloom and the best harvest for long-term storage, with the number of days between them, are summarized in Table 6. The mean period between bloom and optimum harvest in 1967 was 99.4 days, with a range of 21 days. The more northerly orchards tended to mature in fewer days.

On the basis of the 1967 data it was concluded that no precise measure of maturity had been found. Nevertheless, it appeared that the best chances for long-term storage occurred when fruit were harvested in the week immediately following the first appearance of a softening or climacteric response in the ethylene-treated fruit. Waiting an additional week allowed for a considerable increase in fruit size (Figure 2) but with increased risk of shortening the storage life.

Table 6. The dates of full bloom and optimum harvest and the number of days between them in 1967.

Orchard	Full bloom date FB	Harvest date HD	Days FB to HD
1	5/10	8/21	103
2	5/1	8/14	105
3	5/5	8/21	108
4	5/5	8/14	101
5	5/12	8/21	101
6	5/12	8/21	101
7	5/16	8/21	97
8	5/14	-	-
9	5/22	8/21	91
10	5/20	8/28	100
11	5/26	8/21	87
			$\bar{x}$ 99.4

Maturity Studies in 1968

The same orchards were used for the basic pear maturity study in 1968, with two exceptions. Orchard 5 was that of Mr. Harry Overhiser at Casco in Allegan County, and Orchard 7 was that of Mr. Peabody at Fenton in Shiawassee County.

Stored fruits were frozen to -6.6°C overnight due to failure of the thermostatic control. Therefore, data on storage behavior were not obtained in 1968.

The details of bloom, harvest, flesh firmness and changes in firmness during ripening for each orchard are presented in Table 7. Fruits were not available from Orchard 4 in 1968. Fruit maturity and development was generally similar to that of 1967, except that in at least two orchards (numbers 5 and 6) there was a lag of 3 weeks or more between fruit softening in ethylene-treated and non-treated fruit. Furthermore, the pattern of growth observed in 1967 where fruit growth slowed down in the week preceding the softening response of non-treated fruit, was not apparent in 1968 (Figure 3).

The respiration data (Figure 4) also show lags of 3 weeks or more between the occurrences of the PCM's in treated and non-treated fruits from Orchards 1, 6 and 11. In Orchards 7 and 9, the PCM's of the treated and non-treated samples coincided. However, in each case, the

Table 7. Michigan Bartlett pear maturity survey--1968. Flesh firmness and ripening behavior at harvest in relation to time of harvest.

Orchard	Full bloom date FB	Harvest date HD	Days FB→HD	Flesh firmness-lbs. Initial	Plus 7 days at 20°C Air	Plus 7 days at 20°C Ethylene
1	4/27	8/12	107	22.0	23.6	19.2
		8/19	114	22.1	21.2	11.7
		8/26	121	20.1	21.9	4.6
		9/2	128	-	-	-
2	4/27	8/12	107	26.5	23.6	26.9
		8/19	114	23.7	22.1	4.5
		8/26	121	21.3	5.8	8.3
		9/2	128	-	-	-
3	4/25	8/12	109	27.5	25.6	26.8
		8/19	116	21.2	22.8	5.7
		8/26	123	20.6	19.5	5.8
		9/2	130	19.8	10.2	2.7
5	5/4	8/12	100	25.3	28.1	25.6
		8/19	107	22.4	24.8	7.4
		8/26	114	18.8	18.5	5.6
		9/2	121	19.1	18.6	3.8
6	5/4	8/12	100	27.0	26.1	26.1
		8/19	107	22.6	24.2	9.9
		8/26	114	20.9	21.4	9.6
		9/2	121	20.1	18.9	8.5
7	5/1	8/20	111	19.2	25.4	12.7
		8/26	117	22.8	19.0	4.0
		9/3	125	21.6	11.4	3.1
		9/9	131	18.4	3.8	3.6
8	5/1	8/12	103	28.8	30.6	30.2
		8/19	110	24.6	25.0	14.8
		8/26	117	21.6	23.9	7.8
		9/2	124	21.1	15.4	4.5
		9/9	131	17.7	3.5	3.2

Table 7. Continued.

Orchard	Full bloom date FB	Harvest date HD	Days FB→HD	Flesh firmness-lbs. Initial	Plus 7 days at 20°C Air	Plus 7 days at 20°C Ethylene
9	5/10	8/12	94	24.5	25.6	24.2
		8/19	101	21.2	22.6	19.4
		8/26	108	20.0	21.0	3.1
		9/2	115	19.5	2.7	2.8
10	5/9	8/12	95	25.2	22.6	24.7
		8/19	102	22.0	22.0	5.9
		8/26	109	19.2	21.6	3.8
		9/2	116	19.9	7.7	2.9
11	5/13	8/19	98	28.2	25.4	21.8
		8/26	105	22.8	23.6	5.6
		9/2	112	22.7	21.2	7.1
		9/9	119	21.5	6.8	4.1

Figure 3. Patterns of fruit growth during maturation, with the relationships between the occurrences of flesh firmness loss in ethylene-treated and non-treated fruit. Data from weekly harvests at 10 orchards in Michigan in 1968.
Graph numbers refer to orchard numbers according to Table 1 (page 31).

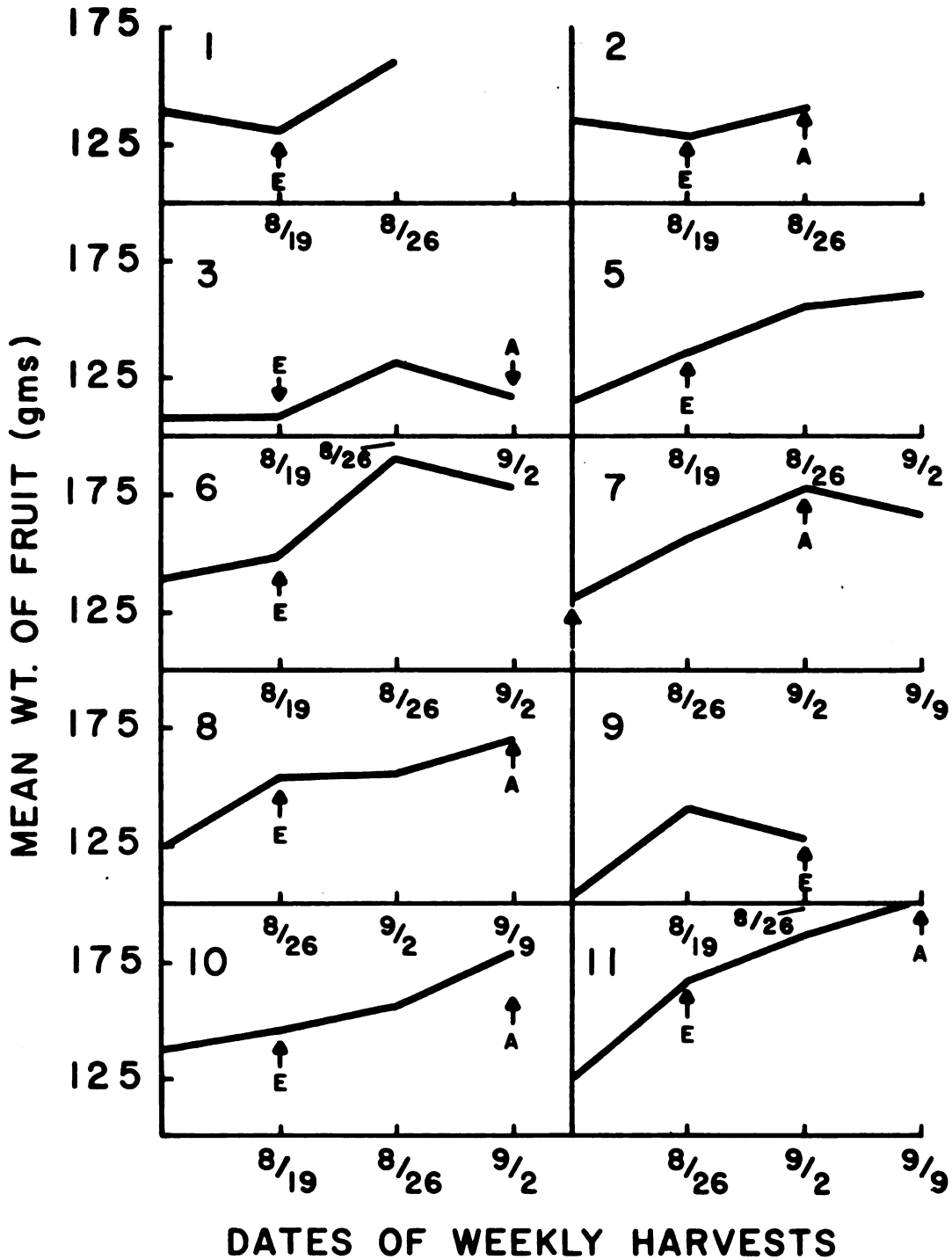
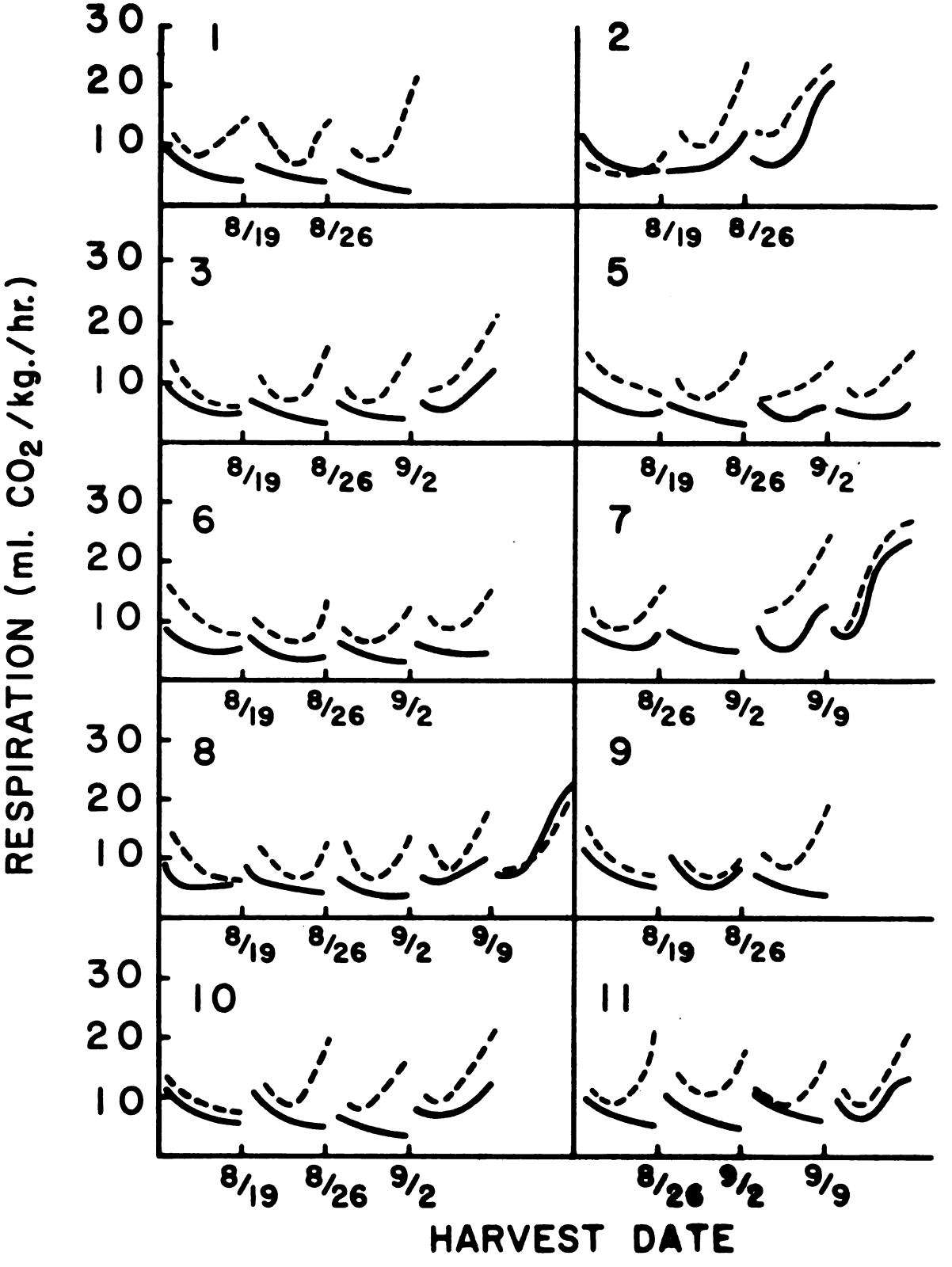

MEAN WT. OF FRUIT (gms)
175
125
1
2
3
5
6
7
8
9
10
11
E
A
8/19
8/26
9/2
9/9
DATES OF WEEKLY HARVESTS

Figure 4. Respiratory behavior of Bartlett pear fruits from a sequence of weekly harvests at 10 orchards in Michigan in 1968.

Graph numbers correspond to orchard numbers according to Table 1 (page 31). Solid lines are respiration curves of non-treated fruit; broken lines are respiration curves of ethylene-treated fruit.


RESPIRATION (ml. CO2 /kg./hr.)
30
20
10
1
2
3
5
6
7
8
9
10
11
8/19
8/26
9/2
9/9
HARVEST DATE

non-treated fruits in the subsequent harvest showed no signs of a climacteric rise.

A further difference in ripening behavior between 1967 and 1968 was that the simultaneity observed in 1967 between the PCM and fruit softening was less frequent in 1968. In 5 of the 10 orchards from which fruits were harvested in 1968, softening occurred one week later than the PCM for ethylene-treated fruits. Similar data for non-treated fruits, although incomplete, show definite delays in five orchards (Table 8).

Studies of Fruit Response to Ethylene as a Measure of Maturity

Since the softening response to ethylene treatment had become an integral part of the pear maturity-test program, a more detailed study of this response was initiated in 1968. The study was based on work by Hansen and Blanpied (1968) on Anjou and Bosc pears. Fruits from an orchard in Hart, Michigan were harvested at weekly intervals and subjected to ethylene treatments to determine the concentration and time dependency for ripening in relation to developmental stage.

The first experiment involved treatment of the fruits with a series of ethylene concentrations for a constant 12 hour period at 20°C in the absence of carbon dioxide. The method and materials used in this and the

Table 8. A comparison of times of occurrence of pre-climacteric minimum and firmness loss in ethylene-treated and non-treated fruit in 1968.

	Ethylene-treated fruit			Non-treated fruit		
Orchard	PCM	Firmness loss	Delay (weeks)	PCM	Firmness loss	Delay (weeks)
1	8/12	8/19	1	>8/26	>8/26	?
2	8/12	8/19	1	8/19	8/26	1
3	8/19	8/19	0	9/2	9/2	0
5	8/19	8/19	0	8/26	>9/2	1+
6	8/19	8/19	0	>9/2	>9/2	?
7	8/19	8/19	0	8/19	9/2	2
8	8/19	8/26	1	9/2	9/9	1
9	8/19	8/26	1	8/19	>8/26	1+
10	8/19	8/19	0	9/2	9/2	0
11	8/19	8/26	1	9/9	9/9	0

following experiment were those of the standard ethylene treatment described above for the basic maturity study. The concentrations of exogenous ethylene were 0 (control), 10, 100, 500 and 1000 ppm. At the end of the 12-hour treatment period, the fruit containers were opened and ventilated and the fruits allowed to ripen at 20°C. Flesh firmness was measured initially and at 2 or 3 day intervals taking a random sample of 5 fruits each time.

The results of the ethylene concentration experiment are shown in Table 9. Fruits from the first harvest softened markedly in 8 days at 20°C when treated with 500 and 1000 ppm ethylene. Fruits subjected to 100 ppm ethylene began to soften at 8 days, while those receiving 0 or 10 ppm did not. Fruits from the second harvest showed a more rapid response to 100 ppm. At the third harvest marked softening was observed for the control fruits and those treated with the three highest ethylene concentrations but the 10 ppm ethylene treatment appeared to delay ripening. At final harvest fruits ripened similarly regardless of treatment.

The second experiment was designed to investigate ripening rate in relation to exposure time to ethylene at 500 ppm. The exposure times were 0 (control), 6, 12, 24 and 48 hours. Fruit were harvested and treated as in the concentration study. The fruit containers were opened and ventilated after the prescribed exposure time had elapsed

Table 9. Influence of ethylene concentration on ripening as measured by flesh firmness in relation to time of harvest of Bartlett pears from Hart, Michigan in 1968.

Days following treatment	Ethylene concentration (ppm)[1]				
	0	10	100	500	1000
		August 13			
0	24.5[2]				
2	26.6	27.4	25.2	24.4	25.2
4	27.4	25.5	23.9	25.8	22.8
6	22.5	24.3	22.6	18.6	17.0
8	23.3	22.6	18.7	8.0	7.2
		August 19			
0	22.2				
2	22.1	22.1	21.5	22.3	22.5
4	23.0	23.9	21.6	15.0	13.0
7	22.2	20.6	7.4	6.2	6.3
		August 27			
0	20.8				
2	20.6	22.7	20.4	21.3	21.8
4	20.2	22.0	23.8	21.1	22.7
7	7.8	20.2	7.7	8.4	5.7
		September 3			
0	19.5				
2	16.8	16.5	16.9	16.3	15.4
5	2.7	2.4	2.1	2.3	2.3

[1]Ethylene applied for 12 hours in absence of CO_2.

[2]U.C. Firmness Tester with 5/16" dia. tip.

and random samples were taken at intervals for flesh firmness measurements as described for the first experiment.

The results were consistent with those of the concentration study (Table 10). The first harvest comprised fruit which softened rapidly after exposure to 500 ppm ethylene for 24 and 48 hours. A 12-hour exposure led to partial softening (to a firmness of 14.3 lbs.) at the end of 8 days. Ripening behavior was similar in the fruit from the second harvest. Fruits in the control and 6-hour exposure of the third harvests had softened slightly after 7 days. Fruits from the fourth harvest softened markedly after 5 days even without supplemental ethylene.

The results in 1968 confirmed the 1967 data that no precise relationship existed between flesh firmness at harvest and other maturity indices. The temporal relationship between the ripening response to ethylene and the endogenous ripening response was irregular. It was considered worthwhile, however, to examine more precisely the development of the response to ethylene in maturing pear fruits. This response reflects directly the capacity of the fruit to ripen and is therefore related to maturity. The data demonstrate an increasing capacity (or decreasing resistance) for ripening through a sequence of harvests. At relatively premature stages, only long exposures or high concentrations of ethylene initiated a ripening response. As fruits mature, shorter exposures to, or lower

Table 10. Influence of duration of 500 ppm ethylene treatment on ripening as measured by flesh firmness in relation to time of harvest of Bartlett pears from Hart, Michigan in 1968.

Days following treatment	Duration of ethylene treatment (hours)[1]				
	0	6	12	24	48
			August 13		
0	24.5[2]				
2	23.9	23.4	24.6	25.0	24.6
4	26.0	25.4	25.4	22.6	20.4
6	24.3	25.5	24.7	11.5	8.7
8	25.6	25.6	14.3	3.6	3.2
			August 19		
0	22.2				
2	23.4	23.5	24.2	22.6	21.3
4	20.0	18.6	20.2	18.8	22.2
7	22.0	20.6	10.3	6.0	3.4
			August 27		
0	20.8				
2	21.1	19.2	20.1	21.2	18.6
4	21.4	20.1	20.1	17.1	21.0
7	17.5	16.9	7.5	5.2	6.9
			September 3		
0	19.5				
2	18.9	19.6	17.8	17.7	19.5
5	6.7	3.7	2.8	2.8	3.2

[1]Ethylene was applied in the absence of CO_2.

[2]U.C. Firmness Tester with 5/16" dia. tip.

concentrations of exogenous ethylene suffice until finally, endogenous ethylene is sufficient to initiate ripening. As ripening is initiated, autocatalytic synthesis of ethylene occurs producing sufficient gas to mask the effect of an exogenous supply.

Further work in examining the ripening response to ethylene is warranted. Ideally, the period of such a study should encompass the whole period of development of such a response. This period begins with complete insensitivity of the fruit to ethylene in terms of a ripening response and ends with a complete lack of additional response to exogenous ethylene when endogenous ethylene levels become sufficient. Data from several sites over several years may serve to show a general pattern of development. Moreover, the variability about this general pattern may be explained by environmental and physiological factors such as temperature, moisture and age and vigor of the tree.

Maturity Studies in 1969

There was no change in the list of orchards used for maturity studies in 1969.

Initial flesh firmness and ripening changes are shown in Table 11. Fruits from each orchard and each harvest were stored and evaluated for storage performance. Optimum harvest dates for long storage life were selected

Table 11. Michigan Bartlett pear maturity survey--1969. Flesh firmness and ripening behavior at harvest in relation to time of harvest.

Orchard	Full bloom date FB	Harvest date HD	Days FB→HD	Flesh firmness-lbs. Initial	Plus 7 days at 20°C Air	Plus 7 days at 20°C Ethylene
1	5/4	8/11	99	24.8	25.1	24.1
		8/18	106	22.2	22.4	20.2
		8/25	113	20.5	19.6	8.8
		9/2	121	-	-	-
2	5/4	8/11	99	25.3	26.4	25.0
		8/18	106	24.3	21.7	18.2
		8/25	113	20.4	18.6	4.7
		9/2	121	-	-	-
3	5/4	8/19	107	20.3	18.8	16.7
		8/25	113	18.2	15.5	4.9
		9/2	121	15.8	3.9	4.8
		9/9	128	-	-	-
4	5/6	8/19	105	22.7	21.4	19.4
		8/25	111	19.9	19.9	4.4
		9/2	119	19.0	15.6	3.6
		9/9	126	-	-	-
5	5/7	8/18	103	22.5	22.4	21.5
		8/25	110	20.9	20.2	5.1
		9/2	118	19.5	19.2	6.2
		9/9	125	18.9	4.6	3.8
6	5/7	8/18	103	24.8	25.2	23.8
		8/25	110	22.8	23.7	22.2
		9/2	118	20.6	22.3	21.9
		9/9	125	19.8	19.0	3.4
7	5/9	8/11	94	25.6	27.2	28.0
		8/18	101	24.2	24.3	22.5
		8/25	108	21.2	21.5	15.0
		9/2	116	19.1	19.2	7.6
		9/9	123	18.3	17.2	6.0

Table 11. Continued.

Orchard	Full bloom date FB	Harvest date HD	Days FB→HD	Flesh firmness-lbs. Initial	Plus 7 days at 20°C Air	Plus 7 days at 20°C Ethylene
8	5/5	8/11	98	26.1	24.0	19.5
		8/18	105	23.1	22.8	4.3[1]
		8/25	112	19.8	19.5	14.8
		9/1	119	20.2	17.5	4.0
		9/9	127	18.4	17.7	3.7
9	5/13	8/11	90	28.3	28.2	31.6
		8/18	97	24.5	23.0	22.9
		8/26	105	22.5	23.4	4.2
		9/2	112	20.0	19.9	3.0
10	5/14	8/11	89	33.4	29.2	32.8
		8/18	96	26.4	25.8	26.2
		8/26	104	21.6	22.8	4.1
		9/2	111	20.5	22.0	3.0
11	5/26	8/25	91	21.4	23.6	21.3
		9/1	98	20.1	19.7	14.1
		9/9	106	19.9	18.6	5.2
		9/15	112	20.2	15.3	3.3

[1]Possibly due to accidental exposure to ethylene in transit.

on the basis of these evaluations. These harvest optima are listed in Table 12 with full bloom dates, the elapsed days between these two events and the harvest at which fruit responded to ethylene treatment.

In four orchards out of eleven, softening in response to ethylene treatment occurred one week before the optimum harvest date; the ethylene response and optimum harvest coincided in six orchards; and in one orchard, the ethylene response appeared to follow the optimum harvest date by one week.

The mean length of the period between full bloom and optimum harvest for long term storage in 1969 was 115.0 days, compared with 99.4 days in 1967 (Table 12).

The maturity study in 1969 confirmed that the physiological stage of maturity marked by the ethylene response is consistently close to optimum harvest maturity (Table 12).

Phenological Studies in 1969

Methods

In 1969, three years data on Bartlett pear maturity had been accumulated. An attempt was made to examine the relationship between the environment and the length of the maturation period. Since previous work indicated that temperature was the predominant environmental component influencing maturation time, this was examined first.

Table 12. Dates of full bloom, optimum harvest and the response of pear fruits to ethylene treatment in 1969.

Orchard	Full bloom date FB	Optimum harvest date HD	Days FB to HD	Date of ethylene response
1	5/4	8/25	113	8/25
2	5/4	8/25	113	8/25
3	5/4	8/25	113	8/25
4	5/6	9/2	119	8/25
5	5/7	9/9	125	8/25
6	5/7	9/2	118	9/9
7	5/9	9/9	123	9/2
8	5/5	9/1	119	9/1
9	5/13	9/2	112	8/26
10	5/14	8/26	104	8/25
11	5/26	9/9	106	9/9
			$\bar{x}$ 115.0	

In the period of 1967-1969, a total of 31 orchard-year observations were recorded. The time period between bloom and maturity was calculated, as accurately as possible for each of the observations. The date of maturity was defined as the date of that weekly harvest whose fruit softened to a firmness of less than 13 lbs. during 7 days at 20°C, without pre-treatment with ethylene.

Although the optimum harvest date based on storage data is accepted as a better measure of maturity, the absence of such data in 1968 limited season-to-season variability. This variability was considered important in a preliminary phenological study and development of a prediction formula. The harvest at which the ethylene response first occurs appears to coincide frequently with that subsequently exhibiting maximum storage life. However, the time of first ethylene response is not clear in the frequent cases where this response occurred at the first harvest. For these reasons, the harvest date for which softening of non-treated pears first occurred was considered as the maturity reference date.

From the 33 orchard-year observations, 15 were selected because they met the following two criteria:

(a) they contained an accurate estimate of full bloom;

(b) the harvest data showed unequivocally the weekly harvest at which fruits softened in air at 20°C during a 7 day period.

An estimate of full bloom was considered accurate when it was reported personally by the grower and when it was consistent with reports from surrounding orchards. The maturity date was considered accurate when fruit softened sufficiently according to the established criterion when they clearly had not the previous week. There were five observations in each of the three years of study (Table 13).

For each of the orchards remaining in the study, the location of the nearest meteorological station was established. Maximum and minimum temperatures were recorded for each day throughout the period between full bloom and maturity. The mean temperature was calculated as the arithmetic mean of the maximum and minimum temperatures.

Heat units per day throughout maturation were calculated. For the initial studies, an arbitrary base temperature of 40°F was used. The heat units for a single day were the number of degrees by which the daily mean exceeded the base temperature. Days with mean temperatures below 40°F were allotted no heat units rather than a negative number. Weekly accumulations of heat units for three weeks through nine weeks after full bloom were recorded. Simple regressions of each weekly total on the dependent variable, days from full bloom to maturity, were calculated yielding an estimate of the length of the

Table 13. Bloom and harvest data used in preliminary phenological studies.

Datum[1]	Orchard	Year	Full bloom date FB	Date of harvest maturity HM	Days FB to HM
1	2	1967	5/1	8/21	112
2	5	1967	5/12	8/21	101
3	7	1967	5/16	8/28	104
4	9	1967	5/22	8/28	98
5	11	1967	5/26	9/4	101
6	2	1968	4/27	8/26	121
7	3	1968	4/25	9/2	130
8	5	1968	5/4	9/9	128
9	7	1968	5/1	9/3	125
10	9	1968	5/10	9/2	115
11	2	1969	5/4	9/2	121
12	3	1969	5/4	9/2	121
13	4	1969	5/6	9/8	125
14	8	1969	5/5	9/16	134
15	11	1969	5/26	9/23	120

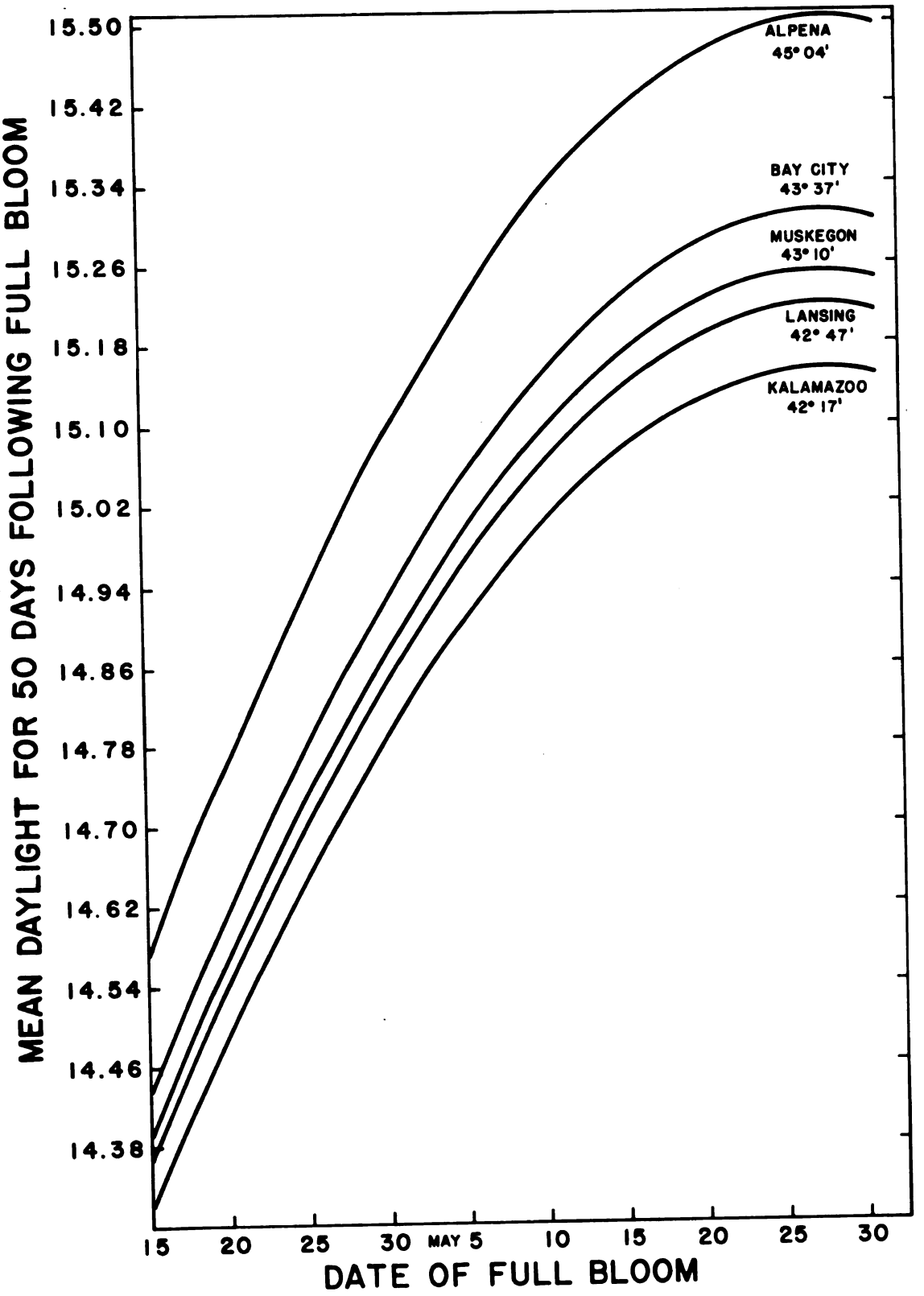
[1]Subsequent tables bear this numbering system only.

[2]Date at which fruits softened to 13 lbs. or less during 7 days at 20°C.

post-bloom period having the greatest influence, via its temperature pattern, on maturation time. Subsequent regression analysis, using daily accumulations of heat units, estimated the length of this period to the nearest day. An estimate was also made of the relationship between the length of the maturation period and heat-unit accumulations throughout this entire period.

It was recognized by Nuttonson (1948) that the heat-unit system described above was limited in its measurement of actual conditions for plant development. He argued that days with the same mean temperature but with widely differing day lengths should not be ascribed the same amount of heat units. Day length varies with latitude and (except at the Equator) calendar date. Moreover, day length change in Michigan is most rapid during late April and early May, the period during which Bartlett pear bloom occurs. It can be seen from Figure 5 that pears blooming on May 5 in Kalamazoo (latitude 42° 17'N) will receive a daily average of 14.9 hours of daylight in the following 50 days. In contrast, if pears bloom at Alpena on May 25 (latitude 45° 04'N), a 50 day post-bloom period will consist of 15.5 hours of daylight per day. Less extreme differences occur when pears bloom on different dates at the same latitude or on the same date at different latitudes.

Figure 5. Mean daily hours for a 50-day period following full bloom for full bloom dates between 15 April and 31 May. Data for five locations in Michigan.


15.50
15.42
15.34
15.26
15.18
15.10
15.02
14.94
14.86
14.78
14.70
14.62
14.54
14.46
14.38
MEAN DAYLIGHT FOR 50 DAYS FOLLOWING FULL BLOOM
ALPENA
45° 04'
BAY CITY
43° 37'
MUSKEGON
43° 10'
LANSING
42° 47'
KALAMAZOO
42° 17'
15
20
25
30
MAY 5
10
15
20
25
30
DATE OF FULL BLOOM

These differences in daylight hours demonstrate an inherent source of error in the remainder-index heat unit system. Thus it was hypothesized that, by weighting the heat-unit accumulations with the mean day length of the post-bloom period studies, more accuracy may be achieved in the resulting regression equation. The regression using the original 15 orchard-year observations was repeated using heat-unit accumulations weighted with the corresponding mean day length.

Following the initial analyses, an attempt was made to establish the most suitable base temperature. Two methods were employed. The first, described by Arnold (1969), involved a regression of percent development per day on the mean temperature of the post-bloom period under study. Percent development per day was calculated thus:

$$\frac{100}{\text{Number of days between full bloom and maturity}}$$

The regression equation produced is solved for zero percent development per day. This is considered to be the minimum temperature for development, or the base temperature.

The second method of base temperature estimation involves a series of regressions of maturation time on heat unit accumulations of the post-bloom period under study. Using the same raw data but different base

temperatures to calculate heat units, the most suitable base temperature will correspond to the best fitting regression equation.

Results

The period immediately following bloom during which fruit maturation is influenced strongly by temperature conditions in the orchard appears to be approximately seven weeks in length (Table 14). Heat unit accumulations (base 40°F) during successively longer periods following bloom show increasing regression coefficients on the time between bloom and maturity. At seven weeks, the coefficient reaches its maximum and thereafter declines. In Table 15, similar regression coefficients are compared but in this case they correspond to heat unit accumulations for periods increasing by one-day increments between six weeks (42 days) and eight weeks (56 days). Clearly the length of the influential post-bloom period is 50 days. The regression equation of heat units (base 40°F) on days between bloom and maturity is $\hat{Y} = 202.25 - 0.0800X$, where X is the number of heat units accumulated in the first 50 days following bloom.

The use of heat units alone thus accounts for about 94% of the variation exhibited in the period between bloom and maturity (since the regression coefficient at 50 days in Table 15 is -0.938). If the 50-day heat unit

Table 14. Simple regression coefficients (R) of heat units (base 40°F) accumulated over various periods (in weeks) after bloom and the time from full bloom to harvest maturity.

Datum	Days FB to HM	Heat units (40° base) accumulated						
		3 wks	4 wks	5 wks	6 wks	7 wks	8 wks	9 wks
1	112	260	415	583	841	1094	1289	1501
2	101	367	569	809	990	1173	1340	1545
3	104	437	672	899	1085	1264	1477	1651
4	98	504	727	907	1093	1274	1468	1688
5	101	519	678	947	983	1164	1341	1551
6	121	347	442	581	807	1035	1210	1412
7	130	281	343	464	628	856	1011	1203
8	128	288	396	585	778	925	1105	1279
9	125	297	394	534	796	948	1133	1316
10	115	337	523	736	881	1041	1220	1405
11	121	389	581	718	887	1058	1276	1510
12	121	322	491	610	756	906	1114	1322
13	125	297	477	580	761	920	1147	1351
14	134	313	487	594	747	879	1090	1273
15	120	356	462	627	775	971	1197	1403
R		-0.77	-.80	-0.88	-0.89	-0.93	-0.89	-0.89

Table 15. Simple regression coefficients (R) of heat units (base 40°F) accumulated over various periods (in days) after bloom and the time from full bloom to harvest maturity, and the corresponding best-fitting regression equation.

Period after bloom (days)	R	
42	-0.88983	
43	-0.89974	
44	-0.90694	
45	-0.91225	
46	-0.92142	
47	-0.92883	
48	-0.92761	
49	-0.93073	
50	-0.93804	$\hat{Y} = 202.25 - 0.0800X^{1}$
51	-0.93750	
52	-0.92876	
53	-0.91766	
54	-0.90793	
55	-0.89887	
56	-0.89444	
Full	+0.89310	

[1]X = no. heat units (40° base) accumulated in the first 50 days following bloom.

accumulations are weighted with the corresponding mean day length for this period, a one percent improvement is gained in predicting the maturity date (Table 16), and the standard error of prediction is reduced by almost 0.5 day.

The arbitrary choice of a 40°F base temperature allowed the above basic relationships to be established. In order to develop the most accurate prediction formula it was necessary to ascertain the true base temperature. Arnold's (1959) method of regression of percent development per day on the overall mean temperature for the 50-day post-bloom period yielded a base temperature of 33.7°F (Table 17). This was unexpectedly low and may be due to an assumption that the relationship between growth and temperature is truly linear. The second, more empirical approach of comparing regressions of heat unit accumulations on days from bloom using different base temperatures showed 42°F to be the most suitable base (Table 18). When heat units (base 42°F) are combined with mean day length, there is no appreciable change over heat units (base 40°F) alone (Table 19). Thus, all heat-unit calculations that follow are made using a base of 40°F.

Maturity Studies in 1970

Orchards were as in 1969 with the exception that Orchard 10 was that of Mr. Lister of Ludington in Mason County, Michigan.

Table 16. A comparison of regression coefficients (R), regression equations ($\hat{Y}$) and standard errors of the estimates (S) between use of heat units (40°F base) alone and heat units weighted by the mean day length in the 50-day post-bloom period for regression on days from full bloom to maturity.

Datum	Days FB to HM	$\bar{X}$ daylength in 50 days after bloom	Heat units (base 40°F) accumulated in 50 days after bloom
1	112	14.810	1126
2	101	15.093	1209
3	104	15.148	1282
4	98	15.294	1309
5	101	15.503	1183
6	121	14.703	1056
7	130	14.646	883
8	128	14.939	953
9	125	14.867	975
10	115	15.149	1069
11	121	14.880	1082
12	126	14.924	1021
13	121	14.880	934
14	133	14.962	898
15	119	15.503	1007
	Using heat units x $\bar{X}$ daylength		Using heat units alone
R	-0.9504		-0.9380
$\hat{Y}$	$197.121 - 0.0050X^1$		$202.25 - 0.0800X^2$
S	3.68		4.09

[1]X = 50-day heat unit accumulation x 50-day mean temperature.

[2]X = 50-day heat unit accumulation.

Table 17. Method for calculating correct base temperature by a regression of percent development per day on the overall mean temperature for the first 50 days after bloom.

Datum	Days FB to HM	Percent development per day	$\bar{X}$ temperature of 50-day period
1	112	0.892	61.660
2	101	0.990	63.250
3	104	0.961	65.190
4	98	1.020	65.360
5	101	0.990	62.970
6	121	0.826	60.460
7	130	0.769	56.860
8	128	0.781	58.220
9	125	0.800	59.370
10	115	0.869	60.680
11	121	0.826	61.270
12	126	0.793	59.490
13	121	0.826	58.250
14	133	0.751	57.750
15	119	0.840	59.440

$\hat{Y} = -1.074 + 0.0319X$

where $\hat{Y}$ = percent development/day and X = $\bar{X}$ temperature for 50-day period.

Solving equation when $\hat{Y} = 0$: X = 33.7°

Table 18. Simple regression coefficients (R) of heat unit accumulations at 50 days after full bloom, using different base temperatures, and the time from full bloom to harvest maturity, and the best-fitting regression equation.

Base temperature (°F)	R	
34	-0.93738	
36	-0.93738	
38	-0.93746	
40	-0.93804	
42	-0.93832	$\hat{Y} = 194.75 - 0.0804X$
44	-0.93809	
46	-0.93724	
48	-0.93553	
50	-0.93171	

Table 19. A comparison of the effectiveness of heat unit base temperatures in prediction equations when combined with mean day length data (dependent variable $\hat{Y}$ = days from full bloom to harvest.

Independent variable X	R	Prediction equation
50-day heat unit total (base 40°F) x 50-day mean day length	-.9504	$\hat{Y} = 197.08 - 0.00499749X$
50-day heat unit total (base 42°F) x 50-day mean day length	-.9500	$\hat{Y} = 190.46 - 0.00505264X$

The flesh firmness and ripening changes are listed in Table 20. In three cases, the harvest when softening in air occurred followed the harvest that exhibited a softening response to ethylene by one week (Orchards 1, 4 and 7). In three other cases (Orchards 5, 6 and 8) there was a two-week delay. The three northernmost orchards produced fruit of almost identical behavior with a three-week lag between the two responses.

Refrigeration failure caused the fruits to ripen in 1970. Thus, results from the cold-storage evaluation of fruit were not obtained.

Three years of testing softening responses of fruit, both ethylene-treated and non-treated, and the optimum harvest for long term storage, lead to the conclusion that the use of such physiological responses have limited value in assessing maturity precisely. This conclusion led to the examination of two further parameters of pear fruit maturity, namely the disappearance of starch and the accumulation of endogenous ethylene in the internal atmosphere.

Starch Hydrolysis in the Maturing Fruit

As the pear fruit approaches maturity, starch hydrolysis is initiated. The use of a simple iodine-starch reaction can monitor this disappearance. The fruit is cut transversely across the carpellary region and the

Table 20. Michigan Bartlett pear maturity survey--1970. Flesh firmness and ripening behavior at harvest in relation to time of harvest.

Orchard	Full bloom date FB	Harvest date HD	Days FB→HD	Flesh firmness-lbs.		
					Plus 7 days at 20°C	
				Initial	Air	Ethylene
1	5/8	8/10	94	21.7	23.9	16.1
		8/17	101	21.4	19.3	3.5
		8/24	108	19.3	5.2	2.8
		8/31	115	13.4	3.7	3.5
2	5/8	8/10	94	24.4	26.0	14.0
		8/17	101	21.9	23.2	3.5
		8/24	108	-	-	-
		8/31	115	-	-	-
3	5/10	8/10	92	20.9	23.4	12.3
		8/17	99	20.9	19.0	4.1
		8/24	106	19.3	13.8	2.5
		8/31	113	15.9	13.0	3.8
4	5/2	8/10	100	22.4	25.4	21.1
		8/17	107	21.5	20.8	5.4
		8/24	114	21.2	9.4	3.1
		8/31	121	16.3	5.1	4.3
5	5/9	8/10	93	21.4	23.1	11.9
		8/17	100	22.1	22.1	5.7
		8/24	107	18.8	7.2	2.6
		8/31	114	16.4	4.1	4.3
6	5/11	8/10	91	21.8	25.0	11.6
		8/17	98	22.4	19.9	5.6
		8/24	105	20.4	11.7	3.5
		8/31	112	15.8	7.7	3.6
7	5/10	8/10	92	25.3	25.1	27.1
		8/17	99	23.4	23.1	12.5
		8/24	106	22.4	7.9	3.3
		8/31	113	16.7	9.5	5.6
8	5/10	8/10	92	23.5	27.0	10.6
		8/17	99	24.0	23.0	3.8
		8/24	106	22.0	10.4	3.3
		8/31	113	19.0	6.9	3.6

Table 20. Continued.

Orchard	Full bloom date FB	Harvest date HD	Days FB→HD	Flesh firmness-lbs. Initial	Plus 7 days at 20°C Air	Plus 7 days at 20°C Ethylene
9	5/17	8/17	92	27.6	25.5	10.0
		8/24	99	21.4	17.8	5.6
		8/31	106	19.6	19.2	7.1
		9/7	113	17.4	3.2	3.2
10	5/13	8/17	96	20.8	20.8	5.2
		8/24	103	19.6	18.0	5.5
		8/31	110	17.8	17.1	4.9
		9/7	117	16.6	4.4	3.4
11	5/23	8/17	86	21.8	22.1	6.6
		8/24	93	20.1	19.3	3.0
		8/31	100	18.0	18.0	3.5
		9/7	107	18.3	3.2	2.9

cut surface wetted thoroughly with a solution of 1% iodine in 4% potassium iodide. An intense blue-black color reaction results with an immature fruit. Patches of unstained tissue in the carpellary region appear and enlarge as the fruit matures until, in a ripe fruit, no reaction is apparent. An index was devised whereby fruit were assessed for starch content and scores assigned between 0 (for complete absence of color reaction) and 10 (for an intense color reaction over the whole fruit cross-section). In Table 21, the index of starch disappearance is outlined for each orchard. The test trees in Orchard 2 were inadvertently harvested and, since weekly changes in starch and ethylene levels were not observed, this orchard is excluded from consideration.

It is apparent that starch has already started to disappear by the time fruits soften in response to 1000 ppm ethylene (standard treatment). At this stage, the starch index ranged from 6.5 to more than 9.9. Fruits that ultimately softened in one week at 20°C without ethylene treatment, showed starch index values ranging between 3.2 and 9.8. Such wide ranges notwithstanding, the value of the starch index may be as an early detector of maturity. When starch begins to disappear, flesh firmness is high and ethylene levels in the fruit internal atmosphere are low, making it difficult to assess how close the fruits are to maturity. If starch disappearance

Table 21. A comparison of two maturity indices, starch disappearance and ethylene levels in the fruit internal atmosphere, for 10 orchards in 1970.

Orchard	Harvest date	Days from full bloom	Starch index[1]	Internal ethylene[2] ppm	
				Mean	Median
1	8/17 E[3]	101	6.5	0.036	0.037
	8/24	108	6.3	0.157	0.110
	8/31	115	2.6	1.400	1.165
3	8/17	99	8.8	0.034	0.033
	8/24	106	7.9	0.101	0.080
	8/31	113	6.3	0.109	0.101
4	8/17 E	107	9.6	0.073	0.056
	8/24	114	8.8	0.113	0.068
	8/31	121	6.1	0.169	0.188
5	8/17	100	8.2	0.030	0.025
	8/24	107	5.3	0.569	0.229
	8/31	114	5.5	1.112	1.238
6	8/17	98	9.9	0.022	0.023
	8/24	105	9.8	0.089	0.055
	8/31	112	3.1	0.281	0.208
7	8/17 E	99	8.6	0.041	0.026
	8/24	106	7.5	0.043	0.035
	8/31	113	4.2	0.291	0.094
8	8/17	99	9.4	0.022	0.022
	8/24	106	7.5	0.107	0.102
	8/31	113	5.7	0.145	0.153
9	8/17 E	92	9.4	0.036	0.030
	8/24	99	7.2	0.062	0.063
	8/31	106	6.8	0.046	0.036
	9/7	113	6.1	0.543	0.240
10	8/17 E	96	9.3	0.025	0.025
	8/24	103	7.0	0.063	0.062
	8/31	110	6.0	0.080	0.072
	9/7	117	3.9	1.921	1.439

Table 21. Continued.

Orchard	Harvest date	Days from full bloom	Starch index[1]	Internal ethylene[2] ppm	
				Mean	Median
11	8/17 E	86	8.6	0.020	0.017
	8/24	93	7.2	0.023	0.024
	8/31	100	5.4	0.103	0.086
	9/7	107	3.2	0.800	0.843

[1]Based on a scale from 10 (completely blue) to 0 (no blue color). Mean

[2]Mean and median of 7 fruit measurements.

[3]E denotes the harvest date where softening followed the standard ethylene treatment; where it is not indicated, and response occurred in the previous week.

provides an early sign of approaching maturity, then more precise indices, such as internal ethylene levels, may be used to follow it closely.

Ethylene Concentrations in the Maturing Fruit

The internal atmospheres of a representative sample of fruit were also analyzed. A hypodermic syringe needle (Luer-lock type), with a cleaning wire inserted, was pushed into the carpellary region of the fruit. Penetration of the needle point to the seed cavity facilitated the eventual drawing of an internal atmosphere sample. The purpose of the cleaning wire was to prevent plugging of the needle by cortical tissue during insertion. After the needle was in position, the fruit was immersed in water, the cleaning wire removed and the syringe barrel fitted to the needle. A sample of the internal atmosphere (2-5 ml) of a fruit was drawn, the syringe barrel disconnected, and any juice or water expelled by pressing the plunger until gas bubbles began to escape. The syringe was then plugged with a tightly-fitting serum cap and the syringe removed from the water. One milliliter samples were then removed from this syringe through the serum cap using smaller syringes. These samples were then injected into a Varian Aerograph 1200 gas chromatograph. The 1/8" x 4-foot column was packed with activated alumina, the

column temperature was 60°C with a N_2 carrier-gas flow of 40 ml/min. The instrument was capable of measuring 0.01 ppm in a 1 ml sample which gave a peak height of 1 cm against a background noise level of 5 mm. Table 21 contains the results of these analyses for each harvest beginning on August 12, 1970.

The internal atmosphere ethylene concentration in fruits from 10 orchards harvested on August 17th ranged from 0.017 to 0.056 ppm with a median value of 0.025 ppm. In 9 of the 10 cases the value was 0.037 ppm or less. On this date fruits from all 10 orchards lacked capacity to soften in air at 20°C during 7 days (Table 20) but exhibited a softening response to a 12-hour treatment with 1000 ppm of ethylene. On August 24th fruits from the 10 orchards ranged from 0.024 to 0.229 ppm ethylene with a median value of 0.065 ppm which is approximately double that of the previous week. In 7 out of the 10 orchards the value was 0.080 ppm or less. Fruits from all but the three northernmost orchards softened during a 7 day period in air. The three northern orchards had fruit ethylene levels ranging from 0.024 to 0.064 ppm. As the week before, fruits from all orchards softened in response to applied ethylene. On August 31st, the median ethylene level in fruits from the 10 orchards was 0.121 ppm, again about double the week before, and ranged from 0.072 to 1.24 ppm. Fruits from the three northern orchards had the

lowest internal ethylene levels and ranged from 0.072 to 0.086 ppm and these fruits did not soften during the 7 day ripening period following harvest but responded to applied ethylene as before. The northern orchards were sampled again on September 7 and fruits contained median ethylene levels ranging from 0.24 to 1.44 ppm and they softened in air during the 7 day ripening period. Clearly, capacity of fruits to ripen on their own following harvest is related to their internal ethylene level. Fruits ostensibly attain the capacity to respond to exogenous ethylene several weeks before they accumulate sufficient ethylene of their own to initiate ripening.

The individual fruit internal ethylene concentrations that make up the mean values in Table 21 were plotted against flesh firmness of the same fruits (Figure 6). A regression equation was calculated and, as expected, the regression coefficient was very highly significant. The wide variation is a measure of the unreliability of the flesh firmness test as a maturity index. In the 1970 season, fruits appeared generally to be well embarked into ethylene autocatalysis at a concentration of 50 ppb and a corresponding flesh firmness of 19.4 lbs. At 100 ppb, the firmness had declined to 18.4 lbs.

In Figure 7, a corresponding scatter diagram of internal ethylene concentrations versus the number of days from full bloom is shown. The regression coefficient was

Figure 6. The rise in fruit internal atmosphere ethylene concentrations in relation to the change in flesh firmness. Data from 10 orchards in Michigan in 1970.

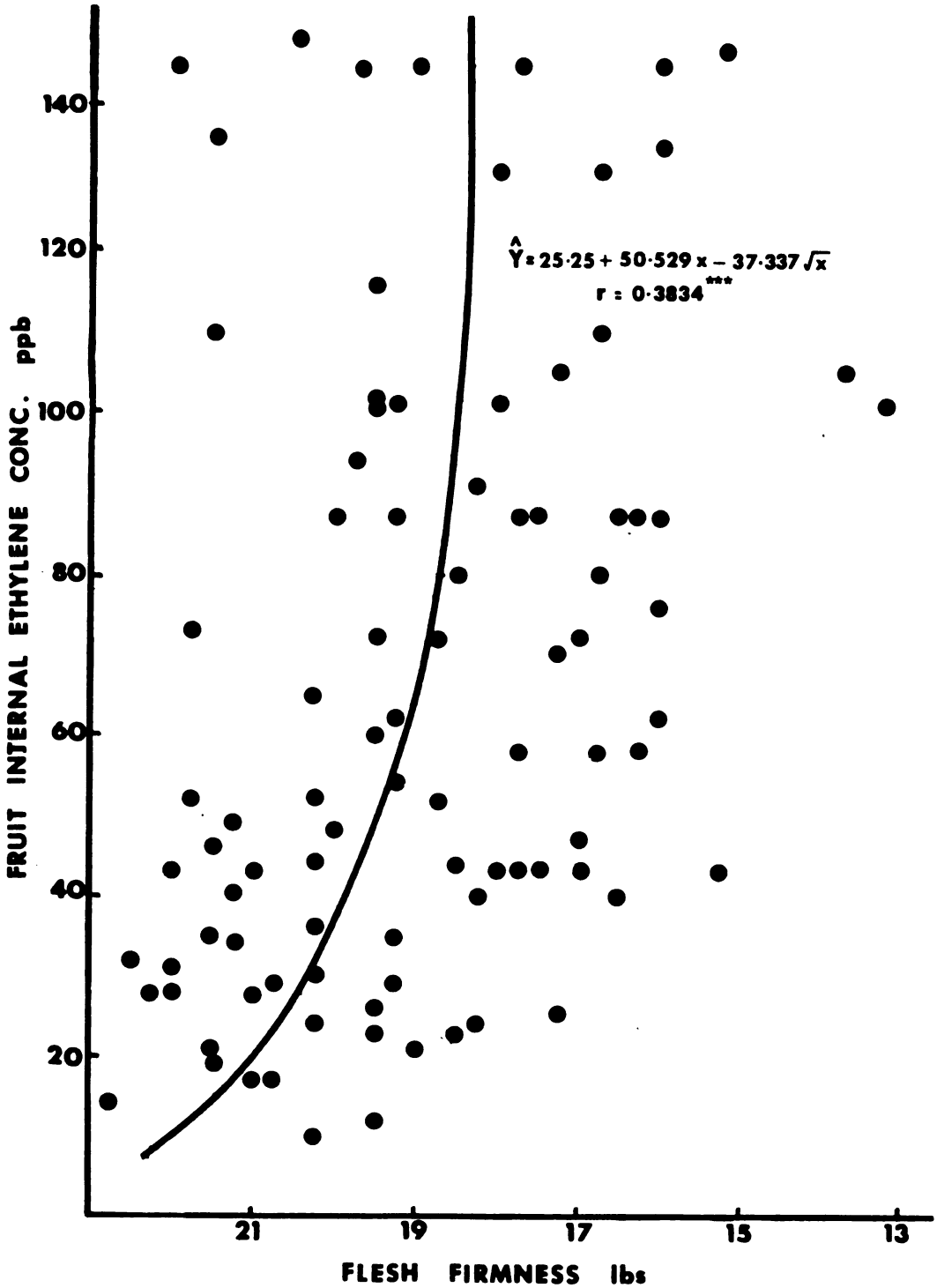
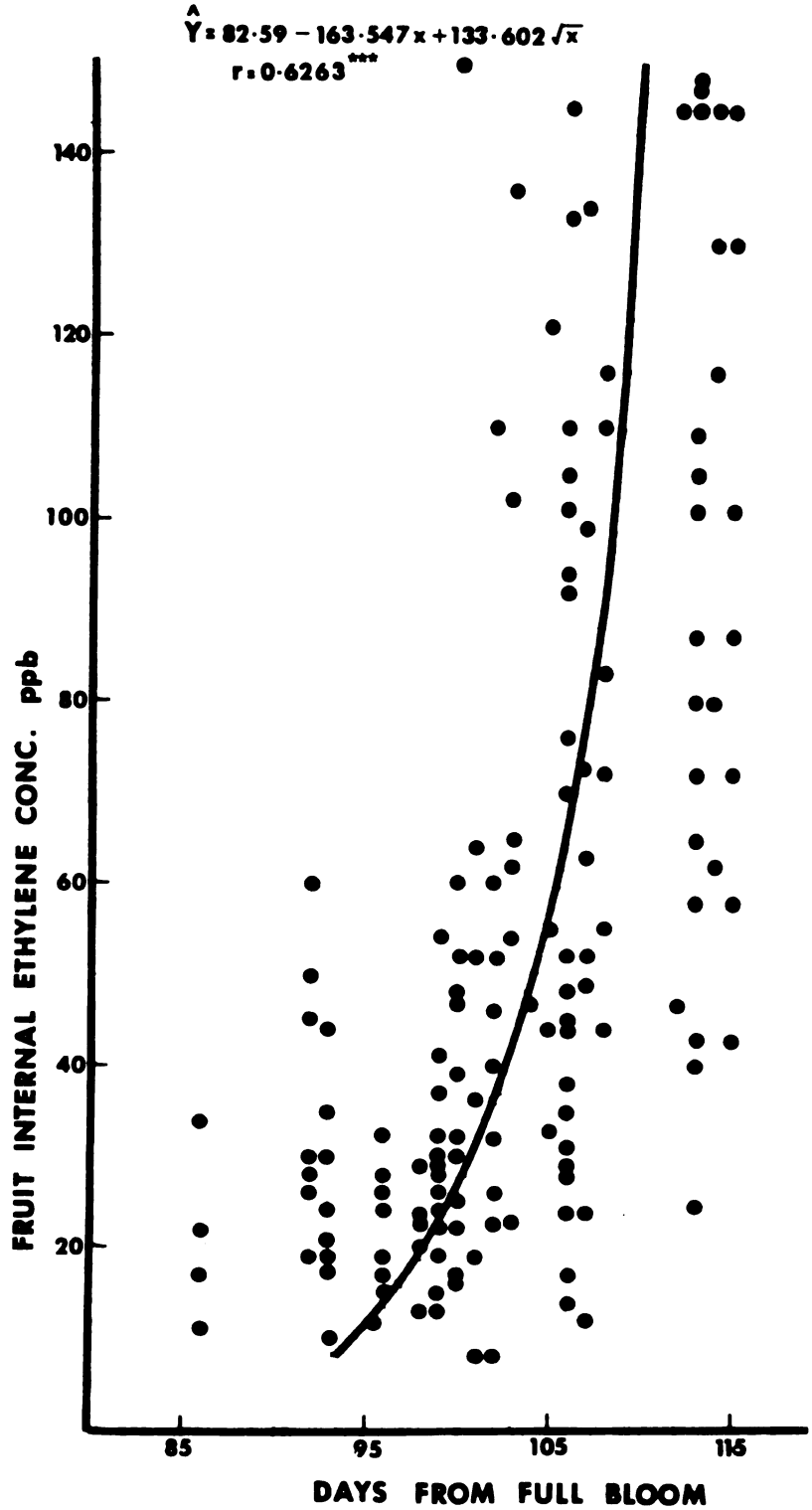

$\hat{Y} = 25{\cdot}25 + 50{\cdot}529\,x - 37{\cdot}337\sqrt{x}$
$r = 0{\cdot}3834^{***}$
FRUIT INTERNAL ETHYLENE CONC. ppb
140
120
100
80
60
40
20
21
19
17
15
13
FLESH FIRMNESS lbs

Figure 7. The rise in fruit internal atmosphere ethylene concentrations in relation to the number of days from full bloom. Data from 10 orchards in Michigan in 1970.


$\hat{Y} = 82.59 - 163.547x + 133.602\sqrt{x}$
$r = 0.6263^{***}$
FRUIT INTERNAL ETHYLENE CONC. ppb
140
120
100
80
60
40
20
85
95
105
115
DAYS FROM FULL BLOOM

again very highly significant. The variability in this case was primarily due to differing post-bloom temperatures. An internal concentration of 50 ppb ethylene was reached, on the average, at 104.0 days and 100 ppb at 108.5 days.

The Relationship between Internal Fruit Ethylene and Ripening Response

The harvests of August 24, 1967 were sampled for internal ethylene concentration both initially and at the end of seven days at ripening temperatures. Furthermore, subsequent harvests of the northern orchards (numbers 9, 10 and 11) were measured similarly. These initial and final ethylene concentrations are listed for each harvest, together with the loss of firmness of the same or similar fruits in the seven day ripening period, in Table 22. The same data are graphically expressed in Figure 8, except that initial and final firmness readings are shown instead of the actual change in firmness.

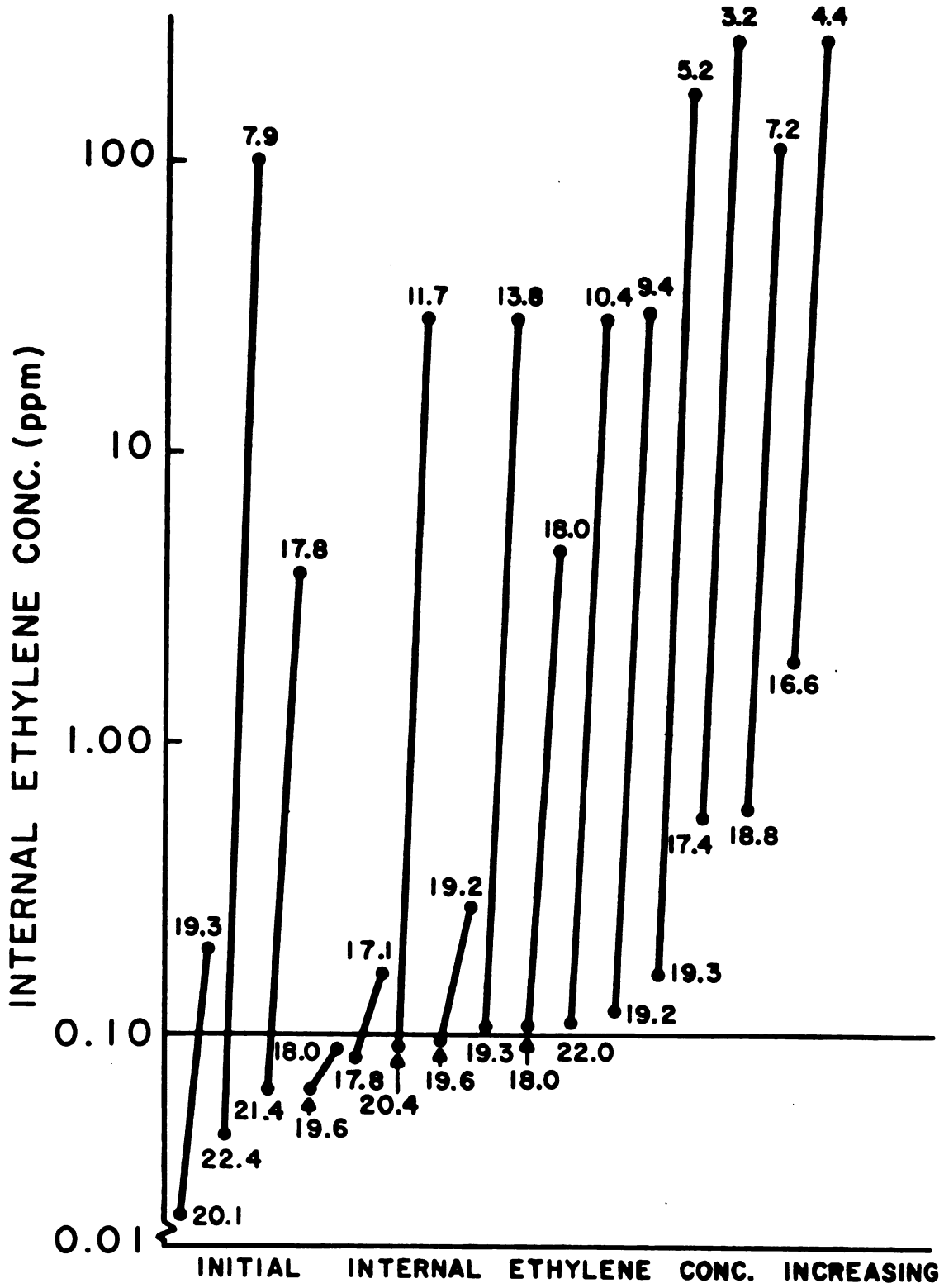
It is apparent from the data in Table 22 and Figure 8 that as the internal ethylene level approaches 0.1 ppm the fruits generally soften during the 7 day ripening period at 20°C with a corresponding marked increase in the internal ethylene concentration. When these data are ranked from high to low firmness change, irrespective of orchard or harvest date (Table 22), it becomes

Table 22. Initial fruit internal ethylene concentrations, concentrations present after 7 days at 20°C and the change in fruit firmness after 7 days at 20°C.

Orchard	Harvest date	Ethylene concentrations ppm				Δ Firmness
		Initial		Final		
		Mean	Median	Mean	Median	
11	9/7	0.800	0.843	204	161	15.1
7	8/24	0.043	0.035	104	48.7	14.5
9	9/7	0.543	0.240	268	257	14.2
1	8/24	0.157	0.110	177	104	14.1
11	9/2	0.041	0.038	81.2	69.9	12.7
10	9/7	1.92	1.44	272	227	12.2
4	8/24	0.113	0.068	32.4	21.0	11.8
5	8/24	0.569	0.229	114	63.3	11.6
8	8/24	0.107	0.102	30.4	11.4	11.6
6	8/24	0.089	0.055	28.4	1.84	8.7
3	8/24	0.101	0.080	28.9	15.8	5.5
9	8/24	0.062	0.063	3.97	2.54	3.6
10	8/24	0.063	0.062	0.090	0.070	1.6
11	8/24	0.023	0.024	0.200	0.081	0.8
10	8/31	0.080	0.072	0.165	0.193	0.7
9	8/31	0.096	0.086	0.280	0.229	0.4
11	8/31	0.103	0.086	4.53	2.24	0.0

Figure 8. Changes in fruit internal ethylene concentration and fruit firmness over a 7-day period at 20°C for 16 harvests from 10 orchards in Michigan in 1970.

Initial and final flesh firmness values are shown at the bottom and top of each line respectively.


INTERNAL ETHYLENE CONC. (ppm)
100
10
1.00
0.10
0.01
INITIAL INTERNAL ETHYLENE CONC. INCREASING
7.9
17.8
11.7
13.8
10.4
9.4
5.2
3.2
7.2
4.4
16.6
18.8
17.4
18.0
19.2
19.3
17.1
19.3
19.2
18.0
22.0
17.8
19.6
18.0
20.4
19.6
21.4
22.4
20.1

immediately apparent that marked softening only occurs in those instances where fruits have achieved capacity for autocatalytic ethylene production. A firmness change of 5 lbs. or more accompanies a one hundred to three hundred-fold increase in the internal ethylene concentration during the 7 day ripening period. This tremendous increase in ethylene may occur from initial values of as low as a 0.035 ppm median level to as high as a 1.44 ppm median level. It may be concluded from these data that autocatalysis of ethylene production precedes and may in fact cause initiation of softening. This is supported by the data of the 8/31 harvest for Orchard 11. In this case the ethylene level increased more than 40-fold yet no softening took place during the 7 day period at 20°C following harvest. If ethylene was derived at least in part by reactions proceeding simultaneously with softening this increase would not have been observed. Further support for this argument comes from observations with many other fruits in which an increase in internal ethylene precedes by at least 3 hours an increase in respiration rate.

Ostensibly, Bartlett pear fruits' capacity for autocatalytic ethylene synthesis is not simply dependent on a precise threshold level of ethylene but may be tempered significantly by other physiological factors.

The data in Table 22 and Figure 8 can be used to examine the relationships between initial and final

firmness, the change in firmness and the initial and final internal ethylene concentrations of the fruit. These relationships are expressed by the regression coefficients and equation in Table 23. It can be seen that initial firmness bears no relationship to the final firmness or change in firmness. It is, however, highly correlated with initial ethylene concentration and somewhat less so with final ethylene concentration. The change in firmness cannot be predicted from the initial values of firmness or internal ethylene concentration. On the other hand, it is highly correlated with final ethylene concentration. The equation expressing the relationship between firmness change and initial and final ethylene concentrations can be found at the bottom of Table 23.

Ethylene Treatment Studies

The investigation using exogenous ethylene to evaluate fruit maturity was repeated in 1970. The method employed was the same as in 1968. The results for 1970 are presented in Tables 24 and 25.

The ethylene-concentration study showed that fruit, harvested on August 12, began to lose firmness eight days after a 12-hour treatment with 500 and 1000 ppm ethylene (Table 24). The following harvest, one week later, showed substantial softening after six days in response to ethylene concentrations as low as 100 ppm. The control showed

Table 23. The relationships (as regression coefficients and their standard errors) between various indices of maturity; and the equation expressing the relationship between internal fruit ethylene concentration and firmness loss during ripening.

Dependent Variable	Independent variable(s)	Regression coefficient	Standard error (lbs.)
Initial firmness	Final firmness	0.3205 NS	
	Initial ethylene concentration	0.6233**	
	Final ethylene concentration	0.5139*	
Change in firmness (ΔP)	Initial firmness	0.0562 NS	
	Initial ethylene concentration (IE)	0.4301 NS	
	Final ethylene concentration (FE)	0.7642***	3.92
	IE and FE	0.8049***	3.75
	IE and ℓ_n (FE)	0.9093***	2.63

The relationship between internal fruit ethylene concentrations and ripening behavior:

$$\Delta P = 3.2126 - 0.507\ IE + 1.914\ \ell_n\ [FE]$$

Table 24. Influence of ethylene concentration on ripening as measured by flesh firmness in relation to time of harvest of Bartlett pears from East Lansing, Michigan in 1970.

Days following treatment	Ethylene concentration (ppm)[1]				
	0	10	100	500	1000
			August 12		
0	25.4				
2	25.7	25.3	26.3	25.1	26.0
4	26.3	25.8	25.5	25.8	26.2
6	26.0	25.4	24.0	21.7	20.9
8	25.8	26.0	24.0	16.7	15.8
			August 19		
0	23.0				
2	23.2	22.4	23.1	21.7	20.9
4	18.7	22.6	15.4	12.3	11.7
6	14.2	21.1	9.3	5.9	5.1
			August 26		
0	19.7				
2	19.1	20.5	19.3	20.0	19.8
4	13.7	15.1	12.1	11.0	10.1
6	5.6	5.9	5.3	3.7	3.2
			September 2		
0	17.8				
2	12.1	12.7	13.0	12.3	11.7
4	2.7	2.4	2.4	2.6	2.3

[1]Ethylene treatment for 12 hours in the absence of CO_2.

Table 25. Influence of duration of ethylene treatment on ripening, as measured by flesh firmness, in relation to time of harvest of Bartlett pears from East Lansing, Michigan in 1970.

Days following treatment	Duration of ethylene treatment (hours)[1]				
	0	6	12	24	48
		August 12			
0	25.4				
2	25.7	25.3	25.1	25.0	24.9
4	26.3	25.7	25.8	21.2	22.0
6	26.0	26.0	21.7	11.9	10.7
8	25.8	25.6	16.7	6.3	4.5
		August 19			
0	23.0				
2	23.2	22.8	21.7	21.3	21.6
4	18.7	18.2	12.3	10.3	8.7
6	14.2	9.9	5.9	3.5	3.1
		August 26			
0	19.7				
2	19.1	19.3	20.0	19.7	19.2
4	13.7	11.2	11.0	9.1	5.2
6	5.6	4.1	3.7	2.3	2.8
		September 2			
0	17.8				
2	12.1	16.7	12.3	13.2	12.0
4	2.7	3.0	2.6	2.4	2.6

[1] 500 ppm ethylene applied in absence of CO_2.

partial softening while the 10 ppm-treated fruit were still almost as firm as they were six days before. It appears that low concentrations of exogenous ethylene have an inhibitory effect on ripening. The subsequent harvests showed a declining tendency to respond to ethylene as fruit acquire their own capacity to evolve the gas.

The ethylene-exposure study (Table 25) shows, in the first harvest, a large response to 48-hour and 24-hour exposures to 500 ppm ethylene. Partial softening occurred in the fruit exposed for 12 hours. The second harvest yielded fruit that softened partially in the control group and increasingly with longer exposures. Treated fruits in subsequent harvests behaved in a similar manner to the control fruits.

Prediction of Maturity in 1970

Phenological Methods

The prediction formula developed after the 1969 season was used for the first time in 1970 to predict fruit maturity. Heat unit accumulations (base 40°F) for the 50 days following bloom, mean day length for the same period, the predicted number of days between full bloom and maturity, and the predicted date of maturity are listed for each orchard in Table 26. The actual dates of the harvests at which fruit softened to 13 lbs. pressure or less in 7 days at 20° are also given.

Table 26. Predicted dates of fruit maturity[1] for each orchard, with actual date for comparison.

Orchard	Full bloom date FB	$\bar{X}$ daylength[2]	Heat units[2] accumulated	Days FB to HM	Dates of maturity	
					Predicted	Actual
1	5/8	14.963	1322	98	8/14	8/24
2	5/8	14.963	1322	98	8/14	8/24
3	5/10	14.999	1247	105	8/23	8/31
4	5/2	14.834	1206	109	8/19	8/24
5	5/9	15.042	1176	110	8/27	8/24
6	5/11	15.077	1200	108	8/27	8/24
7	5/10	15.060	1228	106	8/24	8/24
8	5/10	15.060	1193	108	8/26	8/24
9	5/17	15.252	1217	105	8/30	9/7
10	5/13	15.199	1179	109	8/30	9/7
11	5/23	15.492	1190	106	9/5	9/7

[1]Defined as the date at which fruit acquires the capacity to ripen (to a firmness of 13 lbs. or less in seven days) at 20°C.

[2]For the 50-day period following full bloom.

The predicted dates of maturity lie within 5 days of the actual date in 6 of the orchards. Three of the orchards where prediction was less accurate occurred in the southwest of the state, with errors ranging between 8 and 10 days. Two orchards in the north showed prediction errors of 8 days.

The errors incurred in prediction of harvest dates in 1970 led to a re-examination of the effect of temperature on maturity. The work of Baker and Brooks (1944) and Brown (1953) suggests that there is an optimum temperature above which fruit maturity is retarded. Low temperatures in the month preceding harvest unexpectedly hastened pear ripening in Oregon (Mellenthin, 1966).

In order to examine directly the effect of seasonal temperatures on fruit maturity, a maturity phenomenon that occurred in the orchard was considered most appropriate. Such a response is more likely to reflect ambient conditions than are laboratory tests of maturity. In four years' accumulated data on initial flesh firmness at harvest, a sudden drop in firmness was frequently noted between successive harvests. This "firmness drop" invariably exceeded 2 lbs. but, more importantly, the fruits were relatively mature before the drop, in terms of firmness and ripening behavior, and considerably past optimum maturity a week later. The orchards which showed this distinct firmness drop are listed, with details of time

and degree of drop, in Table 27. Details of full bloom and heat units (base 40°F) accumulated in the 50 days following full bloom are also given.

A regression of the number of days between full bloom and the firmness drop on the above heat-unit accumulations yielded a low (although highly significant) simple regression coefficient of -0.5381. The relationship was expressed by the following equation:

$$\hat{Y} = 160.53 - 0.0482X$$

where X = total heat units (base 40°F) for the 50 day post-bloom period.

The deviations of the data in Table 27 from the line of best fit represented by this equation are a measure of the difference between actual and predicted dates of firmness drop. Those deviations are shown in Table 28, together with details of temperature maxima above 80°F and minima below 50°F for 4 weeks and 2 weeks, respectively, before the firmness drop. It is clear that in those orchards where the firmness drop occurred unexpectedly late, very high temperatures were recorded in the four weeks before harvest, while few or no chilling temperatures occurred in the two weeks before harvest. Conversely, in cases where the firmness drop occurred early, low temperatures occurred invariably during the preceding two weeks.

Table 27. Details of full bloom, heat unit accumulations and the flesh firmness drop in maturing fruit.

Orchard	Year	Full bloom date FB	Heat units	Firmness drop date	Days FB→FD	Flesh firmness at harvest	
						Preceding FD	Following FD[1]
2	1967	5/1	1126	8/21	112	22.0	15.7
3	1967	5/5	1122	8/21	108	20.0	16.6
4	1967	5/5	1130	8/21	108	21.0	17.5
5	1967	5/12	1209	8/14	94	24.0	17.0
6	1967	5/12	1209	8/21	101	19.0	16.1
7	1967	5/16	1282	8/21	97	21.0	15.4
8	1967	5/14	1203	8/14	92	23.0	17.1
9	1967	5/22	1309	8/28	98	19.5	15.2
10	1967	5/20	1150	8/28	100	19.6	12.8
11	1967	5/26	1183	8/28	94	19.6	17.5
8	1968	5/1	916	9/2	124	21.1	17.7
3	1969	5/4	1021	8/19	107	20.3	18.2
1	1970	5/8	1322	8/24	108	19.3	13.4
3	1970	5/10	1247	8/24	106	19.3	15.9
6	1970	5/11	1200	8/24	105	20.4	15.8
7	1970	5/10	1228	8/24	106	22.4	16.7
8	1970	5/10	1193	8/24	106	22.0	19.0
9	1970	5/17	1217	8/31	106	19.6	17.4
11	1970	5/23	1190	8/24	93	20.1	18.0
					mean firmness	20.7 ±1.8	16.5 ±1.6

[1]One week later.

Table 28. The relationship between errors incurred when predicting the firmness drop in Bartlett pears and late-season temperature extremes. Selected orchards 1967 to 1970.

Orchard	Year	Deviation from predicted date[1] (days)	Temperature extremes preceding pressure drop			
			Maxima >80°F		Minima <50°F	
			No. days	Total°	No. days	Total°
8	1967	-11	11	34	4	22
11	1967	-10	5	15	1	5
11	1970	-10	17	80	2	4
5	1967	-8	8	25	4	26
10	1967	-5	6	12	6	26
3	1969	-4	4	20	2	16
7	1967	-2	12	36	0	0
6	1967	-1	11	41	1	7
6	1970	0	14	66	1	2
9	1967	+1	6	11	2	19
3	1967	+2	14	73	0	0
4	1967	+2	16	75	0	0
8	1970	+3	17	98	1	1
9	1970	+4	13	47	0	0
3	1970	+5	18	102	2	4
7	1970	+5	18	77	0	0
2	1967	+6	22	150	0	0
8	1968	+8	12	79	4	21
1	1970	+11	18	120	0	0

[1]The number of days by which the actual date of pressure drop differs from that predicted by the regression equation (+ = later; - = earlier).

[2]During a 4-week period preceding the firmness drop.

[3]During a 2-week period preceding the firmness drop.

Since pre-harvest temperature extremes modify the time from full bloom to fruit maturity as it is predicted by the regression equations shown in Table 16, such modifications were put on a mathematical basis, as shown in Table 29. The variables used in each prediction equation are shown with the corresponding regression coefficient and standard-error of prediction (in days). Those equations developed earlier (using heat units alone and heat units weighted by the mean photoperiod) are shown also for comparison.

There is a clear advantage in using an upper limit of 80° for the daily maximum temperature (thus creating a maximum daily heat unit increment of 40). The regression coefficient and the standard error improve from -0.9380 to -0.9483 and from 4.09 days to 3.75 days, respectively. A similar improvement had already been noted when heat units (base 40°F) were weighted with the mean photoperiod. The use of both modifications in a multiple regression equation appears to afford little or no improvement. Similarly, the use of data on either excessively hot days or excessively cool nights improves the regression coefficient. The use of both in combination with heat units (base 40°F and upper limit 80°F) yields the highest regression coefficient at -0.9546.

The corresponding coefficients and standard errors when the 1970 data are added to that of 1967-1969 are

Table 29. A comparison of various regression analyses in developing a precise prediction formula using the 15 orchard-years in the original formula.

Variable(s)	R[1]	SE[2]
1. Heat units (base 40°F) for 50-day post-bloom period	-0.9380	4.09
2. 1 x 50-day post-bloom mean photoperiod	-0.9504	3.67
3. 1 with 40 heat units/day maximum	-0.9483	3.75
4. 3 x 50-day post-bloom mean photoperiod	-0.9506	3.67
5. 4 and total degrees above 80°F in 4-week period before harvest	-0.9509	3.81
6. 4 and total degrees below 50°F in 2-week period before harvest	-0.9541	3.68
7. 4, total degrees >80°F and total degrees <50°F	-0.9546	3.83

[1]R = the regression coefficient.

[2]SE = the standard error of prediction in days.

given in the following table (Table 30). A similar pattern is evident, although the regression coefficients are slightly lower. The difference between the standard errors of the best fitting equations, Tables 29 and 30 is 0.21 days.

Morphological and Physiological Methods

A study of early indicators of maturity was implemented during the 1970 season. The purpose was to ascertain the existence of a precisely located developmental event in the early stages of fruit growth. If such an event, similar to Stoll's (1968) T-stage for apples, were to bear a definite temporal relationship to ultimate fruit maturity, then it would be a useful long-term predictor of maturity. Two parameters were chosen for study in five orchards throughout the state, one of them morphological and the other physiological.

The morphological parameter studied was the early growth pattern of the fruit. Mitchell (1950) found that growth of the fruit slowed significantly for a short period after bloom. In each of five orchards, 20 fruits were randomly selected and tagged. The polar diameter of the fruit was measured at intervals of two to three days, beginning 24 days after full bloom. Measurements were made using calipers with a Vernier scale, accurate to 0.1 mm. The resulting growth curves are shown in Figure 9.

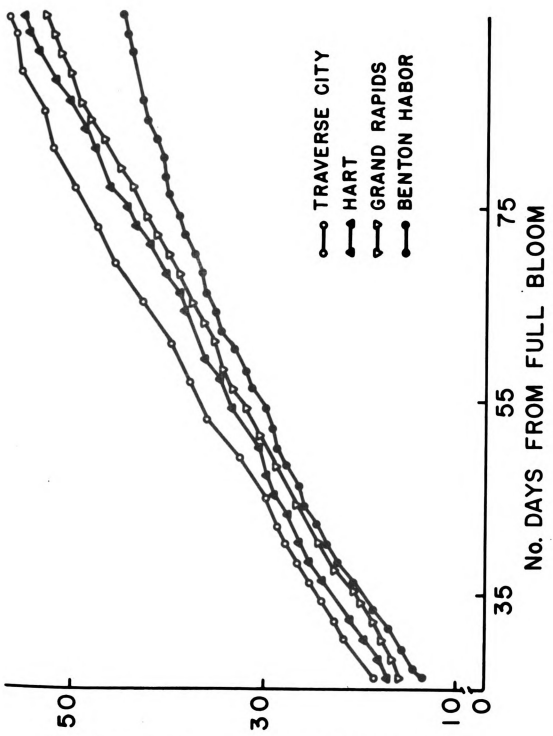
Table 30. A comparison of various regression analyses in developing a precise prediction formula using the 15 original orchard-years plus 8 selected 1970 orchard-years.

Variable(s)	R[1]	SE[2]
1. Heat units (base 40°F) for 50-day post-bloom period	-0.9070	4.40
2. 1 x 50-day post-bloom mean photoperiod	-0.9191	4.12
3. 1 with 40 heat units/day maximum	-0.9201	4.09
4. 3 x 50-day post-bloom mean photoperiod	-0.9248	3.98
5. 4 and total degrees above 80°F in 4-week period before harvest	-0.9250	4.06
6. 4 and total degrees below 50°F in 2-week period before harvest	-0.9293	3.96
7. 4, total degrees >80°F and total degrees <50°F	-0.9298	4.04

[1]R = the regression coefficient.

[2]SE = the standard error of prediction in days.

Figure 9. The growth of Bartlett pear fruits in four locations in Michigan in 1970.


FRUIT TRANSVERSE DIAMETER mm
50
30
10
0
35
55
75
No. DAYS FROM FULL BLOOM
TRAVERSE CITY
HART
GRAND RAPIDS
BENTON HABOR

That for the orchard in East Lansing is shown separately in Figure 10 with embryo growth for comparison. Embryo growth was measured by extracting the seeds from 10 fruits at 3-day intervals randomly selecting 20 and excising and measuring each embryo.

No marked slowing of growth was found in any of the orchards studied. Minor fluctuations occurred at random points on the curve but these appear to be results of environmental vagaries rather than the developmental physiology of the fruit.

The physiological change that was studied in the developing fruit was that of starch accumulation. A random selection of 10 fruit were cut open and examined for the presence of starch. The method was the same as that described for the starch appearance study in 1970. The starch accumulation date was taken to be that date when 90% of the fruit showed starch accumulation at 9 a.m. The dates are shown for each of the five orchards in Table 31 with the corresponding dates of full bloom and harvest maturity.

No constant relationship exists in the data between the time of starch accumulation and full bloom; nor between starch accumulation and maturity. However, these relationships, in the case of three orchards, show great similarity. Approximately 45 days separated full bloom and starch accumulation and a mean of 63 days elapsed

Figure 10. The growth of Bartlett pear fruits and embryos at East Lansing in 1970.

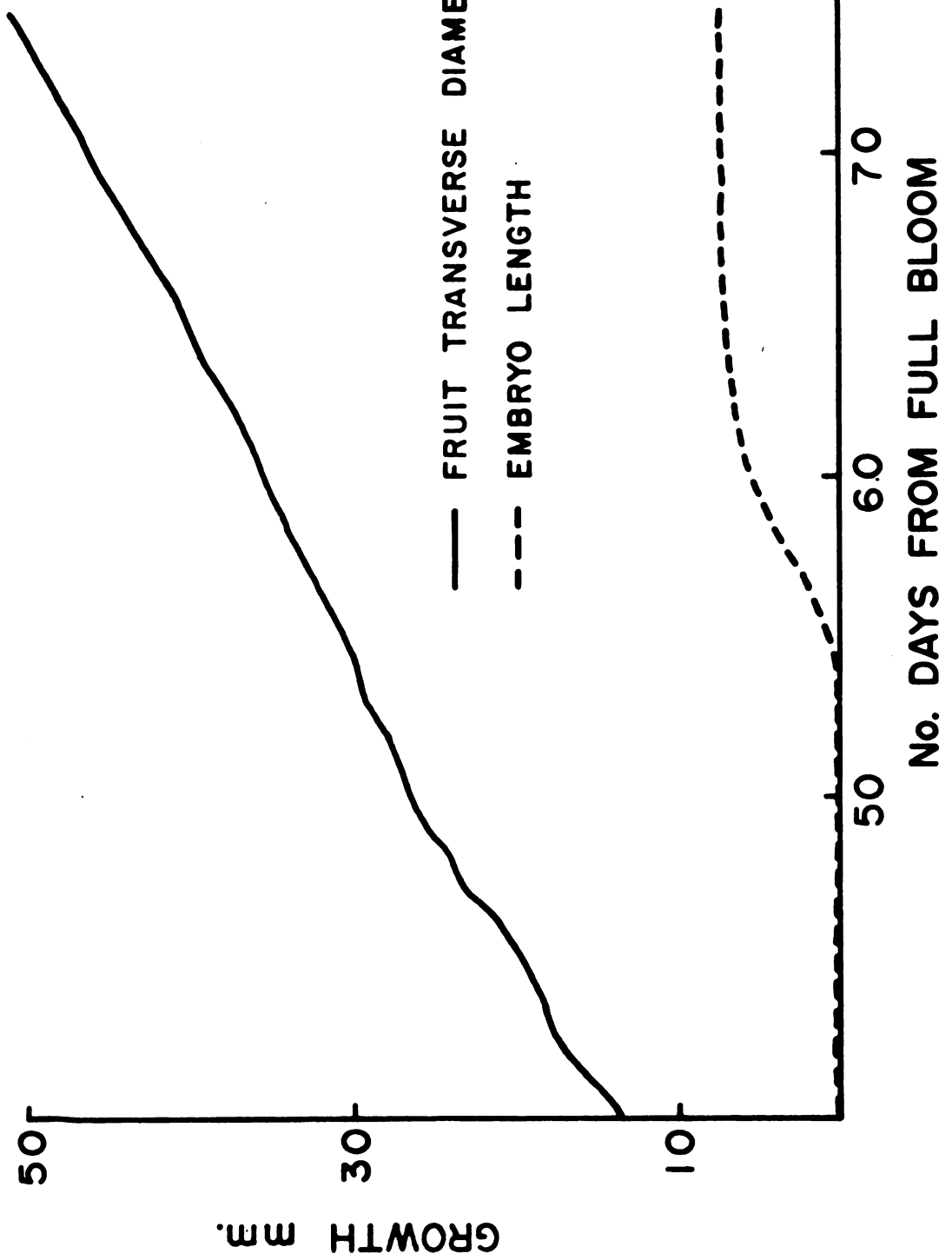

GROWTH mm.
50
30
10
50
60
70
No. DAYS FROM FULL BLOOM
FRUIT TRANSVERSE DIAMETER
EMBRYO LENGTH

Table 31. The relationship between the date of full bloom, the date of starch appearance and the date of fruit maturity.

Location	Date of full bloom		Date of starch accumulation		Fruit maturity
Scottdale	5/8	25[1]	6/2	83[2]	8/24
Grand Rapids	5/10	45	6/24	61	8/24
East Lansing	5/10	44	6/23	62	8/24
Hart	5/17	45	7/1	68	9/7
Traverse City	5/23	<42	before 7/4[3]	>65	9/7

[1]The number of days elapsed between full bloom and starch appearance.

[2]The number of days elapsed between starch appearance and fruit maturity.

[3]Starch estimation was started too late to obtain the precise date.

between starch accumulation and fruit maturity. The relative position of starch accumulation differed in the other two orchards, one in the extreme south and the other in the extreme north.

Summary of Maturity Studies, 1967 to 1970

The four years' maturity data are summarized in Tables 32 to 34.

The date of the harvest when 1000 ppm ethylene for 12 hours first caused fruits to soften over 7 days at 20°C is shown for each orchard and each year in Table 32. The number of days from full bloom to that date is also shown, together with the range for each orchard in four years and the yearly means and standard deviations for all orchards.

The wide variation in maturity date and time from full bloom to maturity is to be noted. The seasons of 1967 and 1970 were relatively early; those of 1968 and 1969 were relatively late. Heat unit accumulations for the first 50 days following bloom were high in the "early" years and low in the "late" years (Tables 13, 14 and 26).

It is clear that the use of a fixed calendar date or a constant number of days from bloom to determine harvest maturity is inadequate. The calendar date for first ethylene response ranges over at least 9 days and up to 30 days in a single orchard. The number of days between bloom and ethylene response varies similarly, between 10

Table 32. The number of days from full bloom to the date at which harvested fruits first softened[1] in response to ethylene.[2] Data for 11 orchards and 4 years, 1967 to 1970.

	Year									
	1967		1968		1969		1970		Range	
Orchard	Date	Days from FD	Date	Days from FB[5]	Date	Days from FB	Date	Days from FB	Date	Days from FB
1	8/14	96[3]	8/19	114	8/25	113	8/17	101	8/14-8/25	96-114
2	8/14	105	8/19	114	8/25	113	8/17	101	8/14-8/25	101-114
3	8/14	101	8/19	116	8/25	113	8/10	92	8/10-8/25	92-116
4	8/14	101	-	-	8/25	111	8/17	107	8/14-8/25	101-111
5	8/14	94	8/19	107	8/25	110	8/10	93	8/10-8/25	93-110
6	8/14	94[3]	8/19	107	9/9	125	8/10	91	8/10-8/9	91-125
7	8/14	90[4]	8/20	111	9/2	116	8/17	99	8/14-9/2	90-116
8	8/14	92	8/26	117	9/1	119	8/10	92	8/10-9/1	92-119
9	8/21	91[3]	8/26	108	8/26	105	8/17	92	8/17-8/26	91-108
10	8/21	93[3]	8/19	102	8/26	104	8/17	96[3]	8/17-8/26	93-104
11	8/21	87[3]	8/26	105	9/9	106	8/17	86[3]	8/17-9/9	86-106
Mean	8/16 ±3.1	94.9 ±5.3	8/21 ±3.6	110.1 ±5.0	8/29 ±6.0	112.3 ±6.3	8/14 ±3.9	95.5 ±5.9		

[1]To a pressure of 13 lbs. or less in 7 days at 20°C.

[2]1000 ppm for 12 hrs. in the absence of CO_2.

[3]This date is assumed. It may have been earlier.

[4]This date is assumed. Estimated from adjacent orchards.

[5]FB denotes full bloom.

Table 33. The number of days from full bloom to the date at which harvested fruits first softened[1] during 7 days at 20°C. Data for 11 orchards and 4 years, 1967 to 1970.

	Year									
	1967		1968		1969		1970		Range	
Orchard	Date	Days from FB[3]	Date	Days from FB	Date	Days from FB	Date	Days from FB	Date	Days from FB
1	8/28	110	9/2	128[2]	9/2	121[2]	8/24	108	8/24-9/2	108-128
2	8/21	112	8/26	121	9/2	121[2]	8/24	108[2]	8/21-9/2	108-121
3	8/21	108	9/2	130	9/2	121	8/31	113	8/21-9/2	108-130
4	8/28	115	-	-	9/9	126[2]	8/24	114	8/24-9/9	114-126
5	8/21	101	9/9	128[2]	9/9	125	8/24	107	8/21-9/9	101-128
6	8/21	101	9/9	128[2]	9/16	132	8/24	105	8/21-9/16	101-132
7	8/28	104	9/3	125	9/16	130	8/24	106	8/24-9/16	104-130
8	8/28	106	9/9	131	9/9	134	8/24	106	8/24-9/9	106-134
9	8/28	98	9/2	115	9/9	119	9/7	113	8/28-9/9	98-119
10	8/28	100	9/2	116	9/9	118	9/7	117	8/28-9/9	100-118
11	9/4	101	9/9	119	9/22	119	9/7	107	9/4-9/22	101-119
Mean	8/26 ±4.7	105.1 ±5.5	9/4 ±4.8	124.1 ±5.8	9/10 ±6.4	124.2 ±5.8	8/28 ±6.5	109.4 ±4.4		

[1]To a pressure of 13 lbs. or less in 7 days at 20°C.

[2]This date is assumed. It may have been later.

[3]FB denotes full bloom.

Table 34. The number of days from full bloom to the date at which the initial fruit firmness was 19 lbs. or less. Data for 11 orchards and 4 years, 1967 to 1970.

	Year									
	1967		1968		1969		1970		Range	
Orchard	Date	Days from FB[2]	Date	Days from FB	Date	Days from FB	Date	Days from FB	Date	Days from FB
1	8/28	110	9/2	128[1]	9/2	121[1]	8/31	115	8/28-9/2	110-128
2	8/28	119	9/2	128[1]	9/2	121[1]	8/24	108[1]	8/24-9/2	108-128
3	8/28	115	9/9	137[1]	8/25	113	8/31	113	8/25-9/9	113-137
4	8/28	115	-	-	9/2	119[1]	8/31	121	8/28-9/2	115-121
5	8/21	101	8/26	114	9/9	125	8/24	107	8/21-9/9	101-125
6	8/21	101	9/9	128[1]	9/16	132[1]	8/31	112	8/21-9/16	101-132
7	8/28	104	9/9	131	9/9	123	8/31	113	8/28-9/9	104-131
8	8/21	99	9/9	131	9/9	127	8/31	113	8/21-9/9	99-131
9	9/4	105	9/9	122[1]	9/9	119[1]	9/7	113	9/4-9/9	105-122
10	9/4	107	9/9	123[1]	9/9	118[1]	8/31	110	8/31-9/9	107-123
11	9/4	101	9/16	126[1]	9/22	119[1]	8/31	100	8/31-9/22	101-126
Mean	8/28 ±5.9	107.0 ±8.9	9/7 ±7.5	126.8 ±6.4	9/8 ±7.5	121.7 ±5.4	8/30 ±4.0	111.4 ±5.2		

[1]This date is assumed. It may have been later.

[2]FB denotes full bloom.

and 34 days. Within years, standard deviations for the four years are between 3.1 and 6.0 days for calendar date and between 5.0 and 6.3 days for the number of days from bloom to ethylene response.

Similar variation obtained when the dates of first softening of non-treated fruits were compared (Table 33). The period elapsed between the first response to ethylene and the first softening of non-treated fruits varied between 10 and 14 days, with a mean of 12.5 days. These two stages in maturity enclose a period during which fruits have a capacity to ripen in response to exogenous ethylene and gradually generate internal ethylene concentrations that will induce endogenous ripening.

The dates at which fruits first reached a flesh firmness of 19 lbs. or less are shown for each orchard and year in Table 34. Variation is again high but this point is reached generally within 2 days of non-treated fruits softening in air.

In Table 35 are summarized the annual means and standard deviations of the three maturity indices discussed above. Also shown are the prediction equations for the first response to ethylene and the first softening of non-treated fruits, using heat units (base 40°F, maximum 80°F) weighted by mean day length. These equations are based on four years' data, 1967 to 1970.

Table 35. Annual means and standard deviations for the number of days from full bloom to the dates of first ethylene response, first softening of non-treated fruits and initial flesh firmness of 19 lbs. or less.

Maturity index	1967 Date	1967 Days from FB[1]	1968 Date	1968 Days from FB	1969 Date	1969 Days from FB	1970 Date	1970 Days from FB
Softening of ethylene-treated fruits	8/16 ±3.1	94.9 ±5.3	8/21 ±3.6	110.1 ±5.0	8/29 ±6.0	112.3 ±6.3	8/14 ±3.9	95.5 ±5.9
Softening of non-treated fruits	8/26 ±4.7	105.1 ±5.5	9/4 ±4.8	124.1 ±5.8	9/10 ±6.4	124.2 ±5.8	8/28 ±6.5	109.4 ±4.4
Initial fruit firmness 19 lbs. or less	8/28 ±5.9	107.0 ±8.9	9/7 ±7.5	126.8 ±6.4	9/8 ±7.5	121.7 ±5.4	8/30 ±4.0	111.4 ±5.2

Prediction equations based on four years data.

1. For the first softening of ethylene-treated fruits ($\hat{Y}_1$)

$$\hat{Y}_1 = 179.08 - 0.00420x \quad (r = -0.8213;\ s.e. = 5.31)$$

2. For the first softening of non-treated fruits ($\hat{Y}_2$)

$$\hat{Y}_2 = 188.64 - 0.00456x \quad (r = -0.9248;\ s.e. = 3.98)$$

X = 50-day post-bloom heat unit accumulation (40°F base and 80°F maximum) x mean daylength for 50-day post-bloom period.

[1]FB denotes full bloom.

DISCUSSION

Considerable variation was noted in the time taken for Bartlett pears to mature in Michigan (Tables 32 to 35 and A1). Maturity varies widely both between orchards in a single season and between seasons.

There was a strong negative relationship between post-bloom temperatures and maturity. Moderately high temperatures during this period shortened the time taken to maturity, although a maximum was observed above which development was retarded. This maximum was approximately 80°F. The period during which temperature exerted the strongest influence on fruit maturity was the 50-day period immediately following bloom. This period closely approximates the period of most active cell-division in the cortex of the fruit, as measured by Bain (1961).

Zimmerman (1965) and Mellenthin (1966) found this post-bloom period to be 8 weeks and 9 weeks, respectively, using a base temperature of 45°F, for Bartlett and Anjou pears in Oregon. In California, Dewey[1] found a 20-day post-bloom period better than 30 or 40 days, using base temperatures of 42°, 45° or 48°F in 1967.

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[1]D. H. Dewey, unpublished data, 1967.

The base temperature found to be most suitable when calculating heat units was about 40°F. The relationship between heat units (base 40°F) accumulated over the 50 day post-bloom period (x) and the time from full bloom to maturity ($\hat{Y}$) is expressed thus:

$$\hat{Y} = 202.25 - 0.0800x$$

$$(r = 0.9380; \text{ s.e.} = 4.09)$$

Heat units do not express the degree of exposure to warm temperatures; they are merely a function of the maximum and minimum daily temperatures. Weighting heat unit accumulations with the mean day length for the period improved the equation somewhat:

$$\hat{Y} = 197.12 - 0.005x$$

$$(r = .9504; \text{ s.e.} = 3.68)$$

Using the latter equation, the standard error in predicting maturity is 3.68 days.

The accuracy of a prediction equation is a function of the accuracy of the data from which it was derived. Furthermore, if inaccurate data are employed when harvest predictions are to be made, large errors in prediction may accrue. If a full bloom date is judged wrongly by one day, this may represent an error of 30 or more heat units. This, in turn, can mean a 3-day error in prediction of harvest date.

It is clear that a strong relationship exists between post-bloom temperatures and maturity. Extreme temperatures later in the growing season have a modifying effect on this relationship. Thus extremely high temperatures had a retarding effect on maturity. Low temperatures (below 50°F) caused fruit to ripen unexpectedly early. Fruit ripening is dependent on ethylene. Ethylene biosynthesis, like all biological systems, requires optimum conditions for uninterrupted development. High temperatures appear to retard the development of this system, resulting in a delay in the onset of ethylene-mediated ripening. Low temperatures late in the maturation period can reverse such high-temperature retardation. Low-temperature stress, or chilling, causes ethylene to be produced in fruit tissue (Elmer Hansen--personal communication, 1971). If the fruit are approaching maturity, autocatalytic synthesis of ethylene and ripening will ensue. This explains Mellenthin's (1966) observation that low heat-unit accumulations in the immediate pre-harvest period were associated with premature ripening. The effects of late season temperature extremes are shown in Tables 28 to 30.

The growth pattern of the fruit did not show the definite lag period between the 60th and 80th days that was observed by Mitchell (1950). This lag period appears to be equivalent to Stage II of growth in the stone fruits

(Prunus spp). Mitchell (1950) showed that embryo growth was very rapid during the lag in growth of the whole pear fruit. This is also the case with stone fruits. However, a Stage II in pear fruit growth has not been reported elsewhere. It is likely that it may appear only in response to a limiting factor, such as sunlight or moisture. In such cases, growth of the embryo may occur at the expense of fruit growth.

The appearance of starch in the cortex of the developing fruit occurred at 44 or 45 days after full bloom in 3 of the 5 orchards in which measurements were made. In the southernmost orchard, starch accumulation started considerably earlier. In the most northern orchard starch accumulation had occurred at an unknown number of days less than 42. There appeared to be no consistent relationship between starch accumulation dates and harvest maturity. This is in agreement with Badran's (1963) work with apples. In both apples and pears, however, starch accumulation starts toward the end of the cell-division stage in the cortex. It therefore reflects a probable decline in energy requirement by the fruit tissue.

As pear fruits mature they become increasingly sensitive to ethylene. With immature fruits, the response may be only a temporary rise in the respiration rate. Further development leads to a full ripening response.

The degree of response depends on the maturity of the fruit and the intensity or duration of exposure to ethylene. Thus the concentration of, or degree of exposure to, ethylene required to induce a ripening response declines as the fruit matures. This was shown in experiments in 1968 (Tables 9 and 10) and 1970 (Tables 26 and 27). This decline reflects the development of an endogenous system capable of synthesizing ethylene in amounts sufficient to induce ripening. The monitoring of the ethylene response, therefore, provides a means of following fruit maturation from its early stages.

In each year of the study of ethylene response, a relatively low exogenous concentration of 10 ppm delayed ripening (in terms of loss of firmness) in comparison with the control. This suggests that, at a certain stage of maturity, 10 ppm ethylene is inhibitory to ripening. This suggests that the endogenous ethylene system is subject to a type of feed-back control. Concentrations of ethylene insufficient for ripening may temporarily halt or slow ripening. This hypothesis agrees with observations by Blanpied[1] of mature, but unripe, apples stored with ripening pears. The apples were noticeably retarded in ripening in comparison to others stored alone. Work is in

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[1]G. D. Blanpied, personal communication.

progress in this laboratory[1] on the kinetics of feed-back inhibition of ethylene biosynthesis using the etiolated pea epicotyl bioassays.

A standard treatment of 1000 ppm ethylene for 12 hours was employed in the maturity program with a view to developing it as a maturity index. There was no constant relationship between the time of response to this treatment and the time of softening of non-treated fruit. Moreover, neither of these "maturity stages" bore a strong relationship to the optimum harvest as judged by storage performance. However, storage potential appears to reach its maximum in the period delineated by these two stages. The length of this maturity period varied between 10 and 14 days during the 4 years of study with a mean length of 12.5 days (Tables 32 and 33). Fruits reached a firmness of 19 lbs. on the average at or about the end of this period (Table 34). Fruit growth continued after this period, often at a more rapid rate than during the period. This increased growth may have been the result of the rise in ethylene biosynthesis. This occurred at the end of the maturity period, since the latter is marked by endogenous firmness-loss in harvested fruits.

Since the rise in endogenous ethylene production must immediately precede fruit ripening, measurements were

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[1]D. R. Dilley and E. Sfakiotakis, personal communication.

made of internal ethylene concentrations in mature and ripening fruits. Fruit firmness was measured using the same fruits. As expected, initial flesh firmness bore a highly significant relationship to initial internal ethylene concentration and a significant relationship to final internal ethylene concentration, after 7 days at 20°C (Table 23 and Figure 6). No indication was found that initial ethylene concentration or initial flesh firmness had high value per se in predicting or estimating fruit maturity. The data in Figure 6 show that fruits with an internal ethylene concentration of 100 ppb are very likely to lose firmness rapidly. Fruits with ethylene between 50 and 100 ppb may or may not ripen. The factors (other than ethylene) that determine the fruits' propensity to ripen are not well understood. It is clear, however, that fruits acquire a capacity to respond to exogenous ethylene well before they will ripen on their own (Tables 20 and 21). The level of ethylene in immature fruits is below 20 ppb and closely approximates the concentration in the air (Figures 7 and 8). It increases slowly during the maturation period (Tables 21, 22 and Figure 7) until autocatalysis is initiated. Median ethylene levels in fruits from 10 orchards were found approximately to double at weekly intervals from an initial value of 25 ppb on August 17, 1970, to a value of 121 ppb on August 31. It is clear from the data that this is a prerequisite for

pear fruit ripening. For ripening to occur, ethylene must increase approximately 100-fold in a 7 day period.

The concentration at which autocatalysis occurs appears to vary between fruit samples. Fruits with similar internal ethylene concentrations may respond very differently (Figure 8). The pear fruit is a complex organ with variable physical and chemical properties. Thus, it is unwise to think in terms of such constants as threshold values. It appears, however, that 100 ppb is a saturating concentration of ethylene, a conclusion that conforms with those of Burg and Burg (1962) and Biale, et al. (1954).

A plot of initial internal ethylene concentrations versus initial firmness readings from the same fruit yields a significant relationship, but the variability around the line of best fit is high (Figure 6). It is noteworthy that at a flesh firmness reading of 19.4 lbs., internal ethylene concentration reached a level of 50 ppb and thereafter rose very rapidly.

Internal ethylene concentrations were also plotted against days from full bloom (Figure 7). A more significant relationship obtained, with a mean time of 104 days being taken to reach a half-saturation concentration of 50 ppb. This compares with a mean time of 95.5 days to a softening response to 1000 ppm exogenous ethylene and 109.4 days to softening of non-treated fruits.

The disappearance of starch from maturing fruits appeared to commence shortly before the maturity period which begins when the fruits respond to the standard ethylene treatment (Table 21). Thus, it may be possible to develop the technique into a valuable maturity index in conjunction with measurements of flesh firmness and internal ethylene concentrations.

The errors in long range prediction of maturity are partly explained by late-season extremes of temperature. The ripening of non-treated fruits is affected by the presence or absence of chilling temperatures in the orchard immediately prior to harvest. This would tend to modify the length of the period designated above as the maturity period. Considerable benefit can be gained by a long-range approximation of harvest maturity but it is no substitute for measurement of maturity using reliable indices.

The findings of this thesis present the grower and producer with a well-defined period during which pears may be harvested. Pears will be relatively large at the end of this period or later. Size increases of 20-30% are common in the week following this period (Figure 2). To gain this size (and yield per acre), a low storage potential must be tolerated. Storage periods must be short (about 3-4 weeks) and processing plans made to accommodate early removal from storage. Conversely, if the buyer cannot

process the crop so soon or wishes for other reasons to have a long period of supply from storage, then he must accept a smaller size. Furthermore, the grower should be paid a premium for such fruits to compensate for the loss of potential size.

CONCLUSIONS

Maturity dates for Bartlett pear vary widely from year to year. This precludes the use of such methods for determination of optimum harvest date as a fixed calendar date or a constant number of days from full bloom.

The variation in maturity date could be accounted for largely by heat unit accumulations in a period following full bloom. This period was 50 days in length for Michigan Bartlett pears, which coincided with the period of maximum cell-division frequency in the fruit cortical tissues (Bain, 1961). The base temperature used for heat unit calculation was 40°F and a maximum daily increment of 40 heat units (corresponding to 80°F) was used. Heat unit accumulations were adjusted by weighting with the mean day length for the 50-day period.

The correlation between heat unit accumulations calculated by this method and the number of days between full bloom and maturity was sufficiently high that the simple regression equation can be used as a prediction formula. Predictions of maturity can be made up to 8 weeks in advance with a standard error of less than 4 days.

Late-season temperatures modified the predicted maturity date. Temperature maxima above 80°F tended to retard maturity, while chilling temperatures below 50°F caused mature fruits to ripen prematurely. It is, therefore, imperative that growers observe such temperature extremes and be prepared to make the necessary adjustments.

As pear fruits mature, they become increasingly sensitive to ethylene in terms of ripening response. When fruits softened to a flesh firmness of 13 lbs. or less in 7 days at 20°C after a 12 hr. treatment with 1000 ppm ethylene, they were considered mature. Subsequently, their capacity to produce ethylene increased until they softened to a flesh firmness of 13 lbs. or less in 7 days at 20°C, without exogenous ethylene treatment. Such fruits were mature but often considerably past the optimum harvest for long term storage. However, they had gained considerably in size since first reaching maturity.

A concept of a maturity period is proposed. This period begins when fruits first respond to 1000 ppm ethylene as outlined above and ends when non-treated fruits behave similarly. The period varied in length during 4 years of study and careful monitoring of internal fruit ethylene concentrations will assist in tracing its progress. Supplementary information may be gained from measurements of fruit firmness and the disappearance of starch from the flesh.

The decision as to time of harvest rests jointly with the grower and the processor. Gains in size become mutually incompatible with gains in storage life as the maturity period progresses. It is recommended that fruits with long storage life command a premium price to compensate for loss in potential size. If shorter storage periods and earlier processing can be accommodated, pear fruits in Michigan can more frequently reach desirable size.

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APPENDIX

Table A1. Dates when Bartlett pears were first received[1] at three processing plants in Michigan over the period 1951-1966.[2]

Year	Benton Harbor	South Haven	Fennville
1951	8/22	8/25	8/25
1952	8/19	8/25	8/21
1953	8/17	8/19	8/19
1954	8/19	8/21	8/25
1955	8/15	8/17	8/22
1956	8/22	8/25	8/25
1957	8/21	8/27	8/26
1958	8/16	8/23	8/25
1959	8/12	8/14	8/12
1960	8/22	8/25	8/25
1961	8/24	8/28	8/28
1962	8/13	8/13	8/15
1963	8/19	8/19	8/19
1964	8/17	8/17	8/19
1965	8/17	8/19	8/23
1966	8/25	8/25	8/29
Mean and S.D.	8/19 ± 3.6	8/21 ± 4.6	8/22 ± 4.7
Range	8/12 - 8/25	8/13 - 8/28	8/12 - 8/28

[1]The date of first reception of fruits is assumed to be approximately the date when local fruits were considered mature.

[2]Personal communication from Mr. James Wilson, Raw Products Manager, Michigan Fruit Canners, Benton Harbor.