PNEUMATIC FRUIT HARVESTING AND ASSOCIATED FRUIT CHARACTERISTICS

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PNEUMATIC FRUIT HARVESTING AND
ASSOCIATED FRUIT CHARACTERISTICS

by

HAROLD EUGENE QUACKENBUSH

ABSTRACT

Submitted to the Colleges of Agriculture and Engineering
of Michigan State University of Agriculture and
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the requirements for the degree of

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IN
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The main objective of this study was to investigate a possible method of harvesting tree fruits. The present method of mechanically harvesting fruit consists of shaking the main branches of a tree with a mechanical shaker to remove the fruit. The fruit after being shaken loose falls to a catching device beneath the tree. Because considerable damage results to some species of fruit when this method is used, another method of harvesting is desired. The possibility of using air movement to lower the falling fruit slowly to a catching device without bruising was investigated. Fruit removal from the tree was accomplished by hand-shaking the tree limbs.

Preliminary tests were conducted on various species and varieties of fruit to determine some of the physical characteristics. These data were used to determine terminal velocities of the test fruit which provided design values for the air velocity necessary to suspend or float the fruit.

A test duct was constructed and connected to a fan system in the laboratory. A device was constructed above the duct opening to measure impact forces of falling fruit. The impact measuring device consisted of SR-4 strain gages in a Wheatstone bridge arrangement mounted on a cantilever beam. An amplifier and oscillograph recorder were connected to the strain gages to record the results.

Fruit was connected to the cantilever beam by a nylon line. Tests were conducted by attaching various species of fruit to the line, pulling the line and fruit upward to different heights and allowing it to drop. At the bottom of the fall, a knot in the line came into contact with the beam and produced a deflection which was measured as an impact force. Several species of fruit were tested by dropping them in air streams ranging in velocity from zero to the terminal velocity of the test fruit. The impact force data provided a method of determining a height of drop in still air that would give an impact force equivalent to that obtained from dropping the fruit in a moving air stream.

The laboratory data were used in designing a field test machine. This machine represented only a portion of a full scale machine, but the principle involved was the same as for a full scale machine. The results from this machine were not completely satisfactory; however, some basic principles were established.

This study revealed that heavier fruit, dropped in a confined air stream, required greater air velocities for suspension than lighter weight fruit of the same species. Greater air velocities were necessary because the velocity required to suspend fruits was disclosed to be dependent upon the ratio of fruit weight to projected area. Tests indicated that this ratio increases with increasing weight.

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Laboratory data indicated that air velocities necessary to effectively handle fruits by pneumatic methods were very nearly equal to the terminal velocities of the fruits. Theoretical calculations gave the terminal velocity for a McIntosh apple weighing 0.432 pound as 8,180 feet per minute. Laboratory tests for this apple revealed that an air velocity of 6,500 feet per minute reduced the impact force for a five foot drop to an equivalent value received for a drop of 4.2-inches in still air.

The results from the field test machine indicated that fans capable of providing sufficient air velocities are essential and may need to be of special design if further work proves that fruit can be harvested by pneumatic methods.

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LITERATURE REVIEW

Fruit growers and research workers have partially solved the fruit harvesting problem by providing successful methods of mechanically harvesting some species of fruit, but for others the only efficient method is still hand-picking.

Some fruits are not readily adaptable to mechanical harvesting, due to their susceptibility to bruising. Catching and handling is difficult since most fruits cannot be dropped from great distances onto sharp edges or hard surfaces.

Experiments performed by Gaston and Levin (1951) indicated that drops of three inches or more caused skin breaks when tender-skinned apples struck sharp edges or wires. When McIntosh apples three inches in diameter were dropped onto a hard surface from a height of one inch, the resulting bruises averaged one-half of an inch in diameter. The larger the apple the more susceptible it was to mechanical injury. They also found that apples may be bruised by pressures as well as drops. When a gradually increasing force was applied to a portion of the surface area of an apple, no apparent damage occurred until a point was reached at which a number of cells collapsed and a visible bruise resulted. The magnitude of force causing the cells to collapse was designated as the critical force. Tests made on 80 apples showed that none of the apples in the trials were bruised by forces of less than

It is apparent that mechanization of fruit harvesting has become necessary for growers to maintain a profitable operation. The importance of mechanization can be seen not only in reducing harvest costs and solving the labor problem but also in providing increased production. Mechanizing the fruit harvest has been left mainly to the growers, small manufacturing companies, United States Department of Agriculture, and universities although a few major machinery companies have shown some interest.

Methods that have been tried in mechanizing the fruit harvest include mobile platforms, mobile ladders, hydraulic booms, and picking tubes. These techniques have not been entirely successful because of the complexity of problems involved. Fruits, unlike other mechanically harvested products, bruise easily and are highly perishable; therefore, they must be handled quickly and carefully. Tree structure is a problem as it varies with age, variety, and method of pruning employed making some fruit hard to reach. A machine that will effectively harvest tree fruit must not cause injury to the tree because it will seriously impair the following year's production.

The objectives of this research study were to:

(1) Collect data pertaining to fruit in order to establish basic physical characteristics.

(2) Investigate the use of air as a possible method of harvesting fruit by shaking it loose from the tree

and allowing it to fall without bruising. This investigation included:

(A) Laboratory tests to determine

1) the capabilities of a high velocity air stream in reducing the descent velocity of fruit.

2) flotation (terminal) velocities of various species of fruit.

3) impact forces received by fruit after falling in a high velocity air stream.

(B) Calculation of horsepower requirements, fan size, and number of fans required.

(C) The design and construction of a field machine which would demonstrate pneumatic possibilities which might be adopted in principle to a commercial machine.

(D) Testing and evaluation of the field machine under actual conditions in an orchard.

INTRODUCTION

In production of tree fruits in the United States in 1958, Michigan ranked third in apples, fifth in peaches, fourth in pears, second in plums and first in sour cherries. The total value of Michigan production of these crops was $35,423,000 and for the United States was $421,472,000. Production costs for these fruits have increased while the average price per unit received by Michigan growers from 1953 to 1958 has decreased from six to 28 percent.[1]

A major portion of the production costs can be attributed to harvesting. Levin (1959) reported that harvesting and handling costs amounted to over 50 percent of the cost of production for some species of fruit. In addition to high harvest costs, recruitment of labor to harvest the fruit has become a major problem. Much of the available labor lacks experience. They are demanding higher wages and improved housing while in return, the growers sometimes receive a poor quality of harvested fruit due to carelessness of the workers. Adrian, Fridley, and Kaupke (1959) reported that hand harvesting of tree fruits in California required 60 to 100 man-hours per acre while in the highly mechanized harvest of small grains only three man-hours were required.

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[1]Michigan Agricultural Statistics, July 1959.

7.5 pounds. Tests with different varieties of apples two and one-half inches in diameter produced the results given in Table I.

TABLE I Critical forces for apples[a]

(For each force a three-eights inch diameter bruise resulted on a two and one-half inch apple.)

Variety	Force[b] lb.
Wealthy	7.5
McIntosh	8.5
Northern Spy	12.0
Jonathan	18.0

a. Table reproduced from "How to Reduce Apple Bruising," Gaston and Levin, 1951.

b. Data based on 160 bruise measurements made on 80 apples.

To determine whether apple picking could be successfully mechanized and what characteristics an effective mechanical picker should possess, a time and motion study was conducted by Gaston and Levin (1953). Their study revealed the following pertinent factors:

(1) The motions involved in picking apples are selective, diversified and complex.

(2) Considerable mechanical injury takes place during conventional picking operations.

(3) Approximately 40 percent of the fruit are picked from the ground and 60 percent from ladders.

(4) Seventy-three percent of the workers time is spent picking apples.

(5) Nineteen percent of the workers time is spent moving fruit to and placing it in crates, and returning to picking position.

(6) Three percent of the worker's time is spent moving his ladder.

(7) Five percent of the workers time is spent in smoking, eating apples, and in other non-productive activities.

These factors indicated that 22 percent of the workers time (excluding rest) was spent on unproductive activities; therefore, a mechanical device which could eliminate a part of this time should enable a worker to pick more fruit. They stated that many growers have tried to eliminate this time loss by using mobile platforms and ladders.

Development of these methods led to the design of the "steel squirrel." This machine permitted the operator to position himself almost anywhere in the tree to facilitate picking. Hill and Brazelton (1955) reported that five years of field tests indicated that a worker on the steel squirrel could do from one and one-half to two times as much as he could do on a ladder. They stated that costs for owning and operating the machine ranged from 21 cents to 33 cents per hour with the difference being attributed mainly to engine life and availability of repairs. The machine was widely adaptable to various climates and type of jobs.

Harvesting methods employing hand-shaking, pole, pneumatic and hydraulic shakers were tried on Michigan grown fruits and evaluated by Gaston, Levin, and Hedden (1958). Experiments included harvesting trials with red tart cherries, sweet cherries, plums, pears, and blueberries. Chemicals, to loosen the fruit so that mechanical separation would be easier, were also used. In conjunction with the shakers, a catching device was used under the tree to catch the fruit as it fell. Many types of catching devices were constructed and tested to find one which would work effectively with a shaker mechanism. Tests indicated that 80 to 90 percent of the crop could be harvested with the hydraulic shaker and a cloth covered semi-circular catching frame on cherries and plums. This method was, however, objectionable for use on pears since considerable injury occurred. Comparison of harvesting costs for red tart cherries revealed that for mechanical harvesting it cost one cent per pound as compared to the usual grower cost of two and one-half cents per pound. Bruising studies indicated that tart cherries could be harvested with no more bruising than occurs when they are hand-picked.

Development of hydraulic shakers and catching frames as a method of fruit harvesting has been continued by a number of fruit growers constructing and testing catching devices in an attempt to increase the efficiency of operation. Among these growers is Friday Tractor Company, located in southwestern Michigan, who during the 1960 season developed a catching device which conveyed the fruit up sloping sides to a conveyor that moved the fruit to a tank of water. Fork-lift equipment was adapted for handling the water tank.

Gaston and Levin (1960) reported that blueberries could be harvested mechanically by means of a hand held vibrator that moves metal fingers through an amplitude of one-fourth to one-half of an inch at the rate of 700 to 800 cycles per minute. To remove the berries, the fingers of the vibrator are held against the fruit bearing stems. A vibrator could separate blueberries from five to ten times as fast as the work could be done by hand.

Levin, Gaston, Hedden, and Whittenberger (1960) reported that a tractor-mounted hydraulically-activated boom-shaker was developed in 1958, by Gould Brothers Incorporated of San Jose, California, for harvesting nut crops. Tests conducted on red tart cherries with this shaker during the 1959 season indicated that 95 percent of the cherries could be separated from the tree. The grade of unsorted mechanically harvested cherries varied from 70 to 95 percent U. S. No. 1. Total mechanical harvesting costs varied from one-half to over two and one-half cents per pound. Under conditions existing in many orchards, mechanical harvesting enabled seven men to do the work of 33 hand-pickers and reduced harvesting costs by one-half. They also stated that several hundred bushels of "juice" apples were harvested with machines and placed in containers at a per-crate cost of approximately three cents. They concluded that improved collecting units may make it possible to reduce the amount of bruising so that apples which are to be made into baby food or apple sauce could also be harvested mechanically.

A time and motion study was made by Adrian, Fridley, and Kaupke (1959) on boom type tree shakers coordinated with a low-profile self-propelled catching frame. Prune harvesting tests with this equipment indicated that it was possible to harvest 30 boxes per man-hour with a shaker speed of 30 trees per hour. This was six times the rate of the average hand harvest. Bruising damage to the prunes amounted to about six percent. A harvest rate of 60 trees per hour with a three man crew was obtained in 1960. Bulk handling of the fruit was required for this harvest rate. This method also was tried on peaches, apricots, and olives, but to minimize fruit on fruit impact, baffles were needed to decelerate the fruit before it fell on the conveyor area. With these fruits, two additional problems were apparent. These consisted of damage to the fruit before it separated from the tree and damage to the fruit by limbs as it dropped through the tree.

Levin (1958) reported that time and motion studies revealed that on the average a human picker separates apples from the tree and places them in a field box at the rate of one every three seconds. From this fact, it is apparent that a mechanical harvesting method for apples will need to be at least this efficient and must accomplish the job without causing mechanical injury to the fruit.

Hydraulic boom type shakers in combination with catching frames have contributed considerably to a solution of the harvesting problem for some tree fruits, but a problem still remains for others. An annual report by Adrian (1958) stated that boom type shakers have not proven satisfactory for use in the coastal areas where normally three to four harvests are required. As a solution to this problem, it was felt that a pulsating air blast might shake the trees sufficiently to remove the fruit. Tests were conducted on prunes in 1958 with a John Bean speed sprayer on which the nozzle had an oscillator attachment to produce a pulsating air stream. The unit was moved down the rows at ground speeds of one and two miles per hour. Fruit removal was nearly the same as that for handshaking. Adrian reported that 1959 trials included a blower on which the rate of air flow and frequency of cycling could be varied. A Buffalo centrifugal fan was used which had nozzle areas of one-half and one square foot. The nozzles were driven through an arc of about 90 degrees in order to subject the tree to several sharp blasts of air. Ground speed was about one-half mile per hour. The nozzle oscillated at speeds that varied from 60 to 120 cycles per minute. Air velocities ranged from 5,440 to 9,150 feet per minute with the higher velocities being more effective. The controlling factor on fruit removal was the ratio of force required to remove the fruit from the tree to the weight of the fruit (F/W). This ratio (F/W) represented the number of g's acceleration required for fruit removal. In any event, it was found that a higher percentage of fruit must be removed for this method of harvest to be practical.

The citrus industry is also experiencing labor problems in harvesting citrus fruit and, therefore, are looking toward mechanization as a solution. Coppock and Jutras (1959) reported that preliminary tests of a boom type tree shaker for harvesting grapefruit and oranges proved unsatisfactory. Considerable bark damage occurred from the limb grasping device on the shaker and only 50 to 80 percent of the fruit were removed with oranges being the most difficult to shake loose. A mobile pickers platform was constructed for use in studying the design requirements and economics of this general type of machine. It was found for picking Valencia oranges that the operational picking rate of an inexperienced operator using the pickers platform was increased four percent over that for conventional methods. A new method being developed by Coppock (1960) is a "picking spindle." This device consists of spindles three inches in diameter and 24-inches long mounted parallel on four and one-half inch centers. The spindles have tapered flights of rubber which form an auger. The flights rotate and gently pull on the fruit until it is detached from the tree.

The development of bulk bins for use in harvesting and handling fruit has helped tremendously in paving the way for mechanical fruit harvesting. McBirney (1959) reported that about 186,000 bins were used in the Pacific Northwest area in 1958. Research revealed that apples and pears could be harvested and handled in bins with no more injury than when harvested in standard boxes. Bulk bins usually hold about 25 to 27 apple boxes of fruit. The Northwest standard apple box has a volume about one percent greater than a standard bushel. Bulk bin size is commonly 47- to 48-inches square, 29- to 33-inches high outside and 24-to 28-inches high inside. They weigh from 100 to 150 pounds and their gross weight when filled with apples is approximately 1,000 pounds. There are many advantages associated with their use, some of which are, faster picking, total cost savings, labor savings, improved fruit quality, and more storage capacity. It was reported that bulk handling saved Washington State about half a million dollars in 1959.

McBirney also reported on some of the picking aids tried in the Pacific Northwest. Among these was a vacuum type picking unit developed by a New York manufacturing firm for apples, oranges, and perhaps other fruit. This device consisted of a vacuum chamber on the end of a long supply tube attached to a vacuum supply. Fruit was placed in the vacuum chamber by an operator on the ground maneuvering the vacuum chamber to the fruit. The vacuum power unit exerted a pull on the fruit, separated it from the branch and allowed it to fall to the ground through a cushioned spiral conveyor tube attached to the vacuum chamber. Tests in 1956 with the unit indicated that apples could be picked without bruising, however, the unit was slower than hand-picking and it was very tiring to operate. Another method was a picking funnel and tube. The funnel was attached to the picker with the tube extending down to a bin. The worker was positioned by a mobile platform. Tests of this type of equipment indicated an increase in picking rate of about 40 percent. McBirney reported that one of the newest ideas is hedgerow planting of dwarf or semi-dwarf trees planted in 12 foot rows and pruned to give a four foot width. Picking will be accomplished by pulling a picking machine through the space between the rows. The picking machine will consist of pickers on elevated platforms picking about two feet into each tree row.

An article appearing in the Farm Journal (1960) stated that dwarf trees are becoming popular throughout the country from Maine to Washington. Besides cutting costs, these trees start producing two or three years after planting, produce higher quality fruit than standard trees because of better spraying and pruning, produce up to 2,700 or 3,600 bushels of fruit per acre and eliminate dangerous and expensive ladder work. They are planted as a row crop six feet apart in the row with 12 feet between rows, giving 605 trees per acre. A grower in Grant County, Washington reported that his 1959 costs with dwarf apple trees averaged $300 an acre. Aside from 14.2-cents per 40 pound lug for picking,his highest cost was $30 per acre for hand weeding. Similar costs in standard trees may run $500 to $700 per acre. Thus, dwarf trees reduced the cost per acre by approximately one-half.

PHYSICAL CHARACTERISTICS OF VARIOUS SPECIES OF FRUIT

Large variations among fruit species were evident, therefore, it was necessary to establish basic values for some of the physical characteristics. These characteristics were necessary to facilitate theoretical calculations and provide information applicable to pneumatic fruit harvesting as described in this manuscript.

The following information was obtained for each species and variety:

(1) Average diameter.

(2) Average weight.

(3) Ratio of weight to projected area.

(4) Average area.

(5) Force required to remove the fruit from the tree.

(6) Relation between force to remove the fruit from the tree and the weight.

(7) Firmness of the flesh for some species of fruits.

Apparatus

Scales

A Mettler Precision Balance, model K7T, was used to weigh the fruit. This balance had a range of zero to 800 grams with scale divisions calibrated in tenths of a gram.

Caliper and engineers scale

An outside caliper was used to determine the fruit diameters and an engineers scale used as a standard of comparison for obtaining the diameter measurements from the calipers.

Pressure tester

A Magness-Taylor pressure gauge was used to determine firmness of some of the fruit. This device consisted of a plunger, with a changeable tip for use with different fruit. The tip of the plunger was pressed into the flesh of the fruit where the skin had been removed. The resistance of the fruit to penetration of the plunger tip was registered on the handle of the tester in pounds. The plunger tip contained a line which indicated the depth that the tip should penetrate the fruit.

Spring scale

Spring scales with ranges of zero to 64 ounces and zero to 25 pounds were used to pull on the fruit and measure the force required to separate the fruit from the supporting limb. A small wire hook was constructed, for each type of fruit, as a means of attaching the fruit to the scales.

Procedure

Different species and varieties of fruit were selected from those available on the Michigan State University Horticultural Farm. The fruit was removed from the tree by the spring scale for each species and variety chosen. This consisted of attaching a specially designed wire hook to the scale and then slipping the wire hook around the fruit. The hook was arranged in a stable position to permit application of a pulling force through the scale in a direction parallel with the fruit stem. Force was steadily applied to the scale manually until the fruit separated from its supporting limb. The magnitude of force occurring at separation was observed and recorded for a total of 50 fruits for each species and variety. Each fruit was given an identifying number by placing the number on masking tape and than securing the tape to the fruit.

Each of these fruits was weighed. Diameter measurements were taken with the caliper by measuring the maximum and minimum diameters. The maximum and minimum diameters occurred at different orientations on the fruits for the various species, but in most cases, for varieties of the same species, these measurements occurred at the same orientation.

Firmness tests were made on peaches and apples with a Magness-Taylor pressure gauge. These measurements were obtained by removing a thin slice about the size of a nickel from the surface of the fruit. By holding the fruit in the palm of the hand, the plunger tip was placed on the cut surface and force applied to the gauge handle with the other hand to cause the tip to penetrate the flesh of the fruit. For peaches, a five-sixteenths inch diameter tip was used and a seven-sixteenth inch diameter tip used for apples. Two measurements were made on each fruit. On peaches, these measurements were obtained from the cheek and suture. The suture is defined as the seam extending from the stem end to the blossom end and connecting the cheeks of the peach. The cheeks are located on either side of the suture. On apples, the firmness readings were obtained from the blushed and unblushed areas. The blushed area is the area where more color change has occurred and the unblushed is the area which lacks color compared with the blushed. The unblushed area is usually yellow in color and is called the "ground" color or underlying color.

The fruit selection for each species and variety, hereafter called samples, was made at random from the tree and an attempt was made to choose fruits of various size, shape, and maturity on the same tree.

Results

The results are presented in Table II as average values for the samples of 50 fruits each. The average fruit diameters appearing in Table II were obtained by averaging the maximum and minimum diameter measurements of each fruit and then averaging these values for the entire sample to obtain single average values. The values of projected area and the ratio of weight to projected area were computed using the average values for diameters and weights of the various fruits.

Graphs were constructed to determine the relation between weight and projected area for each sample of fruit. Two of these graphs are presented in Figures 1 and 2. The remaining graphs are presented in Figures 3 through 10 and are included in Appendix I. The graphs shown in Figures 1 and 2 were selected from the graphs for the entire group of samples as

TABLE II **Average values from 50 fruit for each species and variety**

Species and Variety	Date of Harvest (1960)	Weight lb.	Diameter in.	Proj. Area in.^{2}	Ratio of Wt./Proj. Area lb./in.^{2}	Force to Remove lb.	Force to Puncture Flesh lb.	
							Blushed	Unblushed
APPLES								
McIntosh	9/28	0.371	2.73	5.85	0.063	4.5	15.0	13.6
Cortland	9/28	0.392	2.75	5.92	0.066	5.2	15.4	14.6
Jonathan	10/19	0.288	2.55	5.10	0.056	4.4	15.4	14.7
Northern Spy	10/19	0.403	2.79	6.11	0.066	9.6	14.7	14.1
APRICOTS								
Montgamet	8/2	0.064	1.44	1.63	0.039	0.89		
BLUEBERRIES								
Jersey	8/18	0.001	0.35	0.10	0.012	0.25		
							Cheek	**Suture**
CHERRIES								
Montmorency	7/28	0.010	0.83	0.55	0.019	0.22		
PEACHES								
Red Haven	8/16	0.396	2.76	5.98	0.066	6.0	10.1	8.1
Elberta	9/20	0.404	2.78	6.07	0.066	3.4	7.5	4.8
PLUMS								
Stanley Prune	9/7	0.078	1.59	1.98	0.039	1.8		

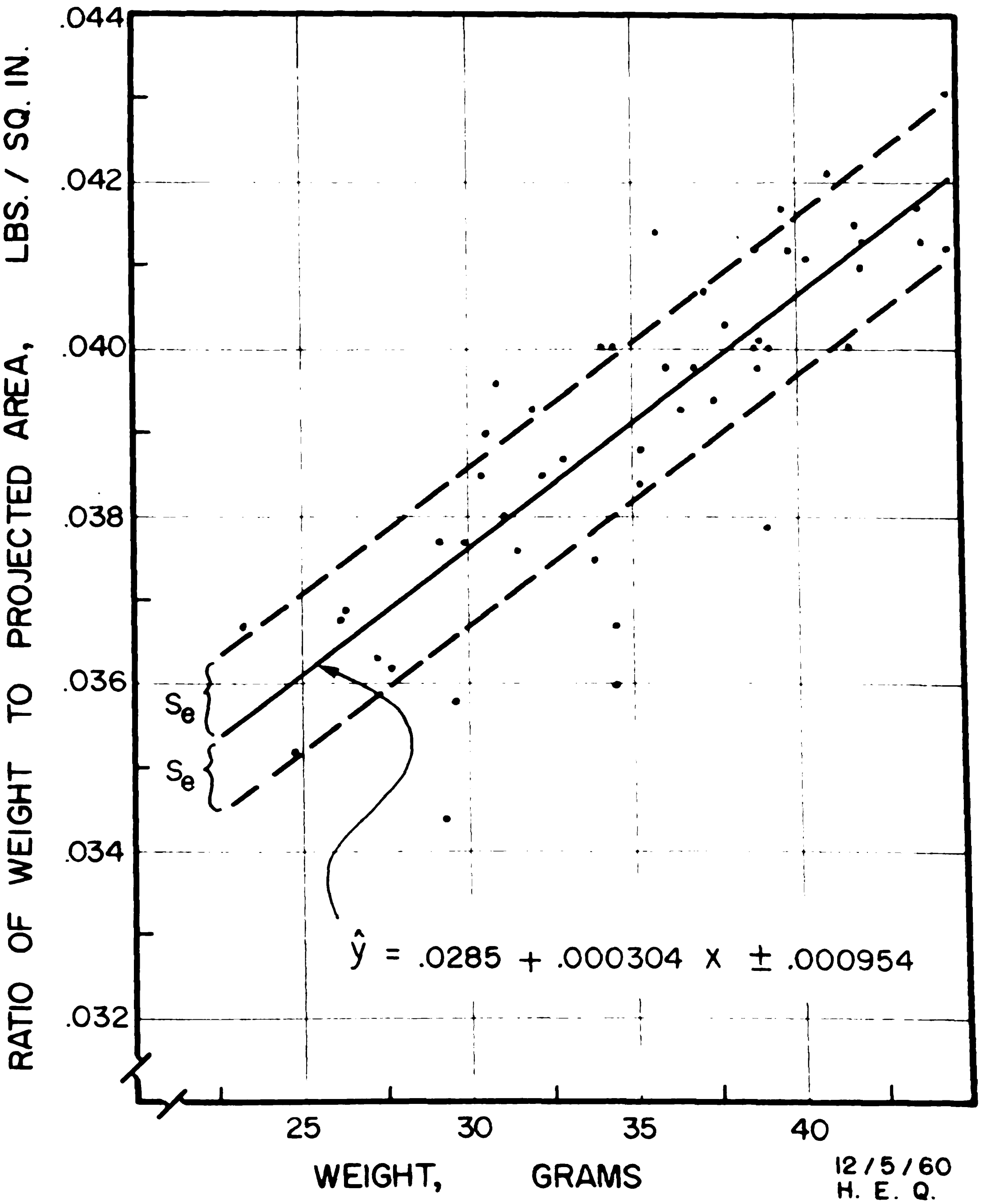

Figure 1. Relation between weight and projected area for Stanley Prune plums.

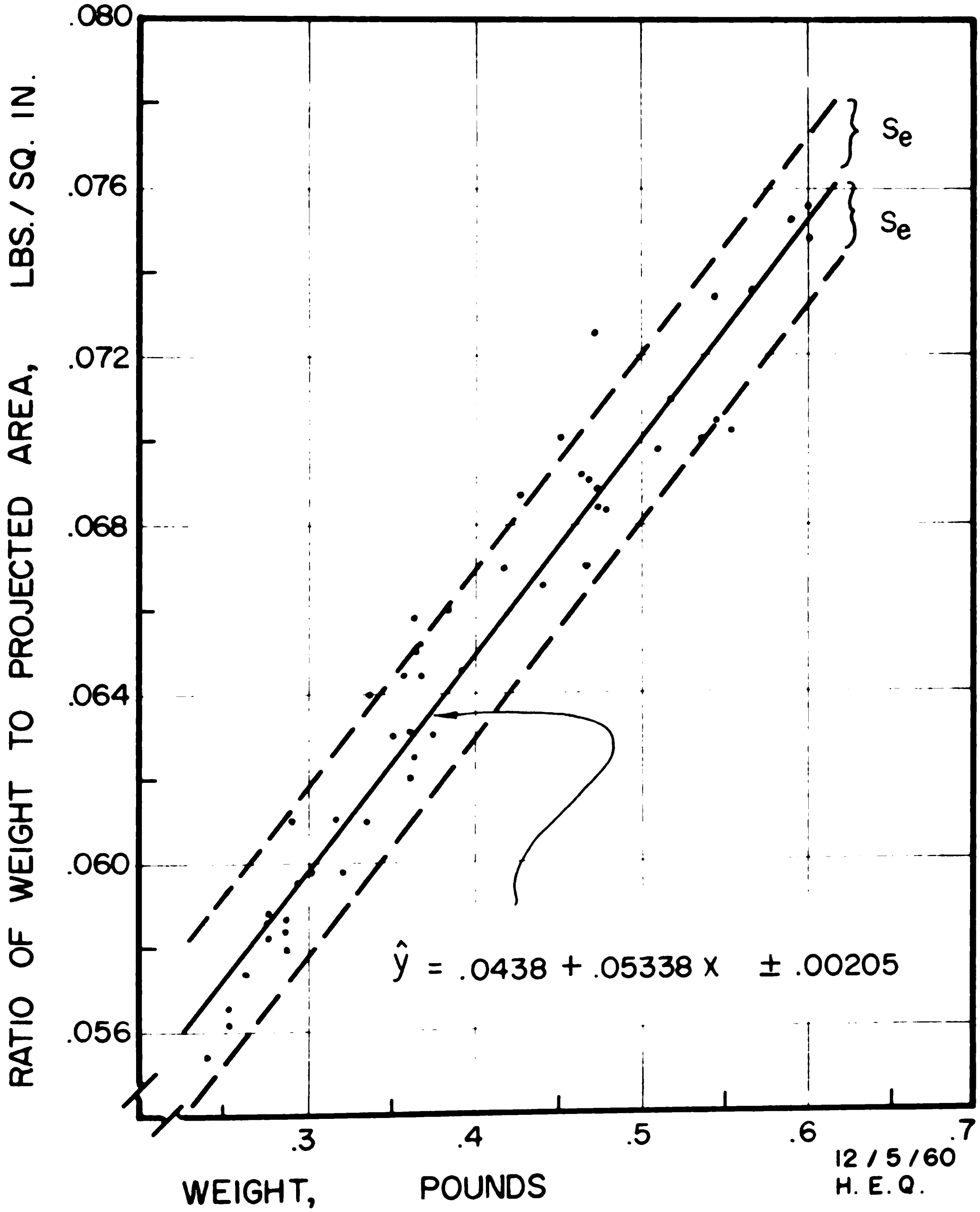

Figure 2. Relation between weight and projected area for Red Haven peaches.

representing those with the greatest and least scatter of points from a line. The data on these two graphs were subjected to correlation and regression analyses and the method of least squares used to obtain the regression lines through the scatter of points. Also, the standard error of estimate was computed and is shown on each graph by the dashed line on either side of the regression line. For clarity, only the results of these computations are shown in Table III. The details are presented in Appendix II.

TABLE III Results of regression analyses

	Correlation Coefficient (r)	Standard Error of Estimate (S_e)	Equation of Regression Line $\hat{y}$ = Ratio of Fruit wt. per proj. area x = Weight of Fruit
Fig. 1	0.844**	± 0.000954	$\hat{y} = 0.0285 + 0.000304\ (x) \pm 0.000954$
Fig. 2	0.995**	± 0.00205	$\hat{y} = 0.0438 + 0.05338\ (x) \pm 0.00205$

(**) Highly significant. $\hat{y}$ = An estimate of y.

A statistical analysis was not applied to those graphs appearing in Appendix I since the graphs of Figures 1 and 2 were chosen as representative of the extremities of all the samples. The data on the graphs in Appendix I are expected to give a correlation coefficient of $0.844 \leq r \leq 0.995$. Regression lines drawn on these graphs were not calculated, but were estimated by averaging a group of points at each end of the plot and then constructing the line through the average of these points.

Discussion

Theoretical calculations which are presented in the following section (THEORETICAL ANALYSIS) disclosed that air velocities necessary to suspend fruit in an air stream are dependent upon the ratio of fruit weight to projected area. It was revealed by the data collected that this ratio varied among fruits of the same species. Therefore, the relationship of this ratio with fruit weight was established.

The graphs presented in Figures 1 through 10 give the joint distribution of fruit weight and the ratio of fruit weight to projected area. Correlation analyses were conducted with the data from two of these graphs (Figures 1 and 2) to determine the degree of association between these variables. Also, regression analyses on the same two samples were conducted for the "regression of the ratio of fruit weight to projected area on weight." In statistics, the word "regression" means average relationship, thus the analyses presented gives the relation between the mean value of the weight to projected area ratio for a given value of weight. The regression lines for the graphs of Figures 1 and 2 permit estimating the ratio of weight to projected area when the weight is known. These regressions should not, however, be used to estimate the weight with a known weight-projected area ratio. The scatter of points on the graphs for all samples (Figures 1 through 10) indicated that the relationship between these variables was linear. To establish whether or not a linear relationship could be assumed for calculation purposes a theoretical equation was established. The derivation of this equation consisted of representing the fruit weight as

$$W = \gamma V \qquad (1')$$

where:

γ = specific weight of the fruit, pounds per cubic foot

V = volume of the fruit, cubic feet

Assuming the fruit as spheres permitted representing the volume as

$$V = \frac{4}{3} \pi r^3 \qquad (2')$$

Substituting equation (2′) into equation (1′) gives

$$W = \frac{4}{3} \pi \gamma r^3$$

and solving for (r) gives

$$r = \sqrt[3]{\frac{3W}{4\pi\gamma}} \qquad (3')$$

The ratio of fruit weight to projected area can be written as

$$\frac{W}{A} = \frac{4 \pi \gamma r^3}{3 \pi r^2} = \frac{4}{3} \gamma r \qquad (4')$$

and substituting, equation (3′) into equation (4′) gives

$$\frac{W}{A} = \gamma \frac{4}{3} \sqrt[3]{\frac{3W}{4\pi\gamma}} = C \sqrt[3]{W} \qquad (5')$$

where:

$$C = \frac{4}{3} \sqrt[3]{\frac{3}{4\pi\gamma}}$$

Equation (5′) gives the relation between fruit weight and the ratio of fruit weight to projected area and reveals that instead of a linear relationship, a cubic relationship exists.

Values of the ratio ($\frac{W}{A}$) were computed with equation ($5'$) using the fruit weights encountered in this study. Graphs made with these data revealed that for the range in fruit weights for a species very little change in slope occurred and for all practical purposes a linear relationship could be assumed. The computations involved in the regression analyses were therefore based on a linear relationship.

The coefficients of correlation (r) for the data contained in the graphs of Figures 1 and 2 are presented in Table III with double asterisks attached to the values indicating that each value was highly significant. The correlation coefficient for a sample of this size (N = 50) with N-2 degrees of freedom need only be equal to or greater than 0.279 to be significant at the five percent level and equal to or greater than 0.361 to be significant at the one percent level.[2] These values of correlation coefficients to be significant, mean that when there are 48 degrees of freedom, only five percent of the time would a correlation coefficient as large or larger than 0.279 occur "by chance" if the true or population correlation coefficient was zero. And only one percent of the time would a correlation coefficient as large or larger than 0.361 occur "by chance" if the true or population correlation coefficient was zero.[3] Hence it can be concluded that the probability of being wrong, in using the regression line to estimate the weight-area ratio, is less than one percent. Therefore, the correlation coefficients obtained from the analyses can be

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[2]Values of correlation coefficients obtained from Table 11, Walker and Lev.

[3]Garrett, 1956.

labeled highly significant indicating that there was a high degree of association between the two variables on each graph.

The equations of the regression lines can be used to compute an estimated weight-area ratio if the weight is known. These equations, however, provide an estimated value that falls between the value obtained, plus or minus the standard error of estimate.

This same type of analysis could be applied to those graphs appearing in Appendix I. The author feels, however, that the results obtained with the graphs given in Figures 1 and 2 would include within these limits any results obtainable from the remaining samples. These analyses revealed that the ratio of fruit weight to projected area does not remain constant among fruit of a species but increases with increasing fruit weight. Since a high degree of association exists between this ratio and fruit weight, the weight-area ratio can be estimated from the regression lines if the weight of the fruit is known.

Graphs were made for the force required to remove the fruit from the tree versus the weight of the fruit for all the samples. The points were highly scattered and did not readily suggest any relationship. Correlation analyses were made for the data of two samples (peaches and apples) which were chosen to represent the samples with the least and most scatter of points. These analyses and the graphs (Figures 11 and 12) are presented in Appendix II. As an approximation for a line through the scatter of points, a linear relationship was assumed. The analyses gave negative correlation coefficients for each sample with one correlation coefficient at the borderline of being significant at the five and one percent levels. The other correlation coefficient was nearly zero, indicating that very little relationship existed.

To eliminate any error involved in the method of obtaining these forces, the pulling force data were grouped and graphs constructed for groups versus fruit weights. These graphs did not present any significant change from the previous graphs. It was, therefore, concluded that the results of the correlation analyses for these data were valid and there was no linear relationship between the force to remove the fruit from the tree and the weight of the fruit.

It was also concluded that fruit maturity was probably the most predominant factor in causing the variation in pulling forces since fruit of various maturities were selected.

The force required to puncture the fruit's flesh, obtained by a pressure tester, was presented in Table II for apples and peaches. Fruit growers usually employ this tester as an aid in determining the maturity of fruit to allow them to select the proper time for picking. This tester was used in a study conducted on bruising of McIntosh apples in a packing house by Burt (1959) to determine the firmness at which apples could be handled mechanically. The evidence found indicated a firmness index around ten or eleven pounds below which apples could not be safely handled mechanically on a packing line. They found that firmness of the fruit was probably the most important single factor in determining the amount and severity of bruising incurring to an apple in the packing operation.

The firmness data given in Table II was obtained only to establish typical values of the relative firmness between different varieties and species of fruit. No attempt was made to use this data to determine the degree of handling permissible in harvesting.

Smock and Neubert (1950) stated that there are numerous limitations of the pressure tester. These limitations should be considered before trying to evaluate any pressure test data. Some of the factors are:

(1) The firmness of a given variety varies from season to season.

(2) The firmness of a given variety varies from one location to another.

(3) The pressure tester usually gives a higher reading on the blushed side of the fruit than on the unblushed side.

(4) Mature well-colored apples on the outside of the tree may have a higher pressure test than less mature apples on the inside of the tree.

(5) Soil fertilization with nitrogen fertilizer application may affect the firmness.

(6) Temperature of the fruit and its moisture content

have an effect on the pressure test reading.

(7) Fruit size has an influence on firmness. Large fruits are usually but not always softer than small fruits.

The primary usefulness of the test is to tell the difference in firmness between two or more lots of the same variety on a given date or to tell the general degree of ripeness.

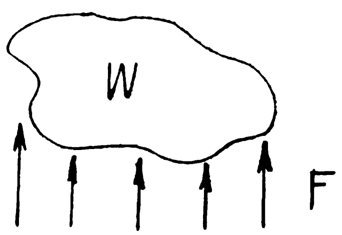
THEORETICAL ANALYSIS

To aid in designing laboratory and field apparatus for conducting tests on various species of fruit, an analysis of a particle in an air stream was made. The principal items of investigation were: air velocities needed for flotation of fruit, fan size and output, and horsepower requirements.

A particle in free fall will reach a steady-state velocity that depends upon the physical characteristics of the particle, the fluid in which it is falling, and the accelerational force. The steady-state velocity (terminal velocity) is also the air or liquid velocity required to suspend or float a particle.

The net force acting on a particle in a given direction (in this case vertical) is the sum of the frictional force and the external force. The following analytical procedure is adapted from a treatment of this particle characteristic by Lapple and Shepherd (1940).

For a particle falling in a vertical air stream,



the forces involved are

$$m \frac{dV_p}{dt} = W - F \qquad (1)$$

where:

W = particle weight, pounds

F = frictional drag force, pounds

but considering the buoyant force of the air gives

$$W = \gamma_p \, v_p - \gamma \, v_p$$

and by definition, the drag force is

$$F = \frac{C \, V^2 \gamma \, A}{2g}$$

therefore equation (1) becomes

$$m \frac{dV_p}{dt} = v_p(\gamma_p - \gamma) - \frac{C \, V^2 \gamma \, A}{2g}$$

or

$$\frac{dV_p}{dt} = g\left(\frac{\gamma_p - \gamma}{\gamma_p}\right) - \frac{C \, V^2 \gamma \, A}{2 \, W} \qquad (2)$$

where:

V = relative velocity ($V_a + V_p$), feet per second

V_p = velocity of the particle, feet per second

V_a = velocity of the air, feet per second

t = time, seconds

W = particle weight, pounds

γ = fluid specific weight, pounds per cubic foot

γ_p = specific weight of particle, pounds per cubic foot

C = particle aerodynamic drag coefficient, dimensionless

$\mathcal{V}_p$ = volume of particle, cubic feet

A = projected area of particle, square feet

g = acceleration due to gravity, 32.2 feet per second per second

m = mass of the particle

This equation must be solved by a method of approximations since it cannot be solved explicitly. Solving this equation by the method of approximations will not be dealt with here as this analysis pertains to finding a steady state velocity. For steady state conditions dV_p/dt is zero and equation (2) can be solved for terminal velocity giving

$$V = \sqrt{\frac{2\,g\,W}{\gamma\,C\,A}\left(\frac{\gamma_p - \gamma}{\gamma_p}\right)} \qquad (3)$$

For most agricultural products, the term $\left(\frac{\gamma_p - \gamma}{\gamma_p}\right)$ is very nearly unity; therefore, it will be neglected in calculations involving equation (3).

Equation (3) can be used to determine the terminal velocity of a particle falling in still air or it can be used to determine the air velocity necessary to suspend or float a particle. The latter is the principle concern of this analysis. Henderson and Perry (1955) presented a method of solving equation (3) but for this analysis the following procedure was used.

Drag Coefficient (C) is a function of velocity, thus a direct solution of equation (3) is impossible unless values of drag coefficient can be determined. To make use of existing data for drag coefficients, the assumption was made that all particles encountered in this work were spheres. This assumption was justified for most of the samples used. Dalla Valle (1948) indicated that existing data for drag coefficient on spheres had been determined by Wadell (1934). His results were presented by Dalla Valle in a graph of drag coefficient versus Reynolds number (Re). Reynolds number is dimensionless and is equal to $\frac{V_a d \gamma}{\mu}$, where d is the average diameter of the sphere and μ is the viscosity of the air.

For a particle having vertical motion in a gravitational field, Dalla Valle presented the following three equations which cover the span of the curve mentioned above.

a) Streamline motion $10^{-4} < Re < 2$, $C = 24/Re$

b) Intermediate motion $2 < Re < 500$, $C = 0.4 + 40/Re$

c) Turbulent motion $500 < Re < 10^5$, $C = 0.44$

Vennard (1958) presented a plot of the same variables over a wider range of Reynolds numbers and stated that the drag coefficient for a sphere is roughly constant from $Re \sim 1{,}000$ to $Re \sim 2.5 \times 10^5$. At $Re \sim 2.5 \times 10^5$, the drag coefficient suddenly drops more than 50 percent and then increases gradually with further increase in Reynolds number.

To establish which value of drag coefficient applied to fruits, an air velocity was assumed and a Reynolds number computed. A corresponding value of drag coefficient was obtained from the graph of Reynolds number versus drag coefficient presented by Vennard. These values were used in equation (3) to solve for the weight (W) which the assumed air velocity could support. This weight was compared with the weight of fruits given in Table II to determine whether the air velocity should be increased or decreased. A few trials indicated that a velocity of 3,000 to 7,000 feet per minute was needed to support the fruit of the weights given. Reynolds number ranged from 10^4 to 1.5×10^5 for these velocities, thus the motion was in the turbulent range and the drag coefficient could be taken as constant and equal to 0.44.

To facilitate computations of terminal velocity, standard air conditions of 70 degrees Fahrenheit at one atmosphere of pressure and 50 percent relative humidity were assumed. The specific weight of air at these conditions is given as 0.075 pounds per cubic foot and the viscosity is equal to 1.232×10^{-5} pounds per foot-second.[4] Using (γ) equal to 0.075 pounds per cubic foot and (C) equal to 0.44 reduces equation (3) to

$$V = 31{,}800 \sqrt{\frac{W}{A}} \qquad (4)$$

where:

V = terminal velocity, feet per minute

W/A = ratio of fruit weight to projected area, pounds per square inch.

This equation indicates that the terminal velocity of fruit is dependent only on the ratio of fruit weight to projected area under the assumed conditions.

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[4]Madison, R. D. (1949).

Table IV presents the results obtained by using equation (4) to calculate terminal velocities of the various fruits. The weight-area ratios for these calculations were obtained from Table II, Figures 1 and 2 and from the graphs contained in Appendix I.

Values of Reynolds number given in Table IV are within the range, given by Dalla Valle and Vennard, for which drag coefficient is roughly constant and equal to 0.44. Thus, the terminal velocities computed with (C) equal to 0.44 and given in Table IV were acceptable. These velocities apply only to air conditions of one atmosphere at 70 degrees Fahrenheit and must be computed for conditions other than these.

Theoretically, flotation or suspension of average specimens of these fruits should occur at the terminal velocities given in Table IV. The data from Figures 1 and 2 and that of Figures 3 through 10 in Appendix I indicate that lighter weight fruit will move upward and heavier fruit will move downward in an air stream with the velocities given in Table IV for the fruit weights given.

Under actual conditions, it would be desirable to use an air velocity which would allow all fruit to descend slowly in an air stream and gently be caught on a catching mechanism.

Horsepower Consideration

An important consideration is the horsepower required to move air at these velocities. The following formula gives the

TABLE IV Terminal velocities

Fruit	Weight lb.	Ratio of $\frac{\text{Weight}}{\text{Proj. Area}}$ lb./in.^{2}	Reynolds Number Re	Terminal Velocity ft./min.
APPLES				
McIntosh	0.371	0.0626	1.83×10^5	7950
Cortland	0.392	0.0654	1.89×10^5	8130
Jonathan	0.288	0.0561	1.63×10^5	7580
Northern Spy	0.403	0.0649	1.91×10^5	8100
APRICOTS				
Montgamet	0.064	0.0386	7.60×10^4	6250
BLUEBERRIES				
Jersey	0.001	0.0118	1.02×10^4	3450
CHERRIES				
Montmorency	0.010	0.0194	3.12×10^4	4440
PEACHES				
Red Haven	0.396	0.0646 ± 0.00205	1.89×10^5	8080 ± 130
Elberta	0.404	0.0658	1.92×10^5	8160
PLUMS				
Stanley Prune	0.078	0.0392 ± 0.000954	8.45×10^4	6290 ± 80

air horsepower required.

$$\text{Air horsepower} = \frac{Q \gamma H}{33{,}000}$$

where:

Q = cubic feet of air delivered per minute

γ = specific weight of fluid, pounds per cubic foot

H = total head, feet

Total head is composed of static and velocity pressure. It is assumed for this application of fans that static pressure would be negligible; therefore, free delivery was assumed and only velocity pressure considered in the head (H) term. The velocity head is given by $V_a^2/2g$. To compute the volume flow rate (Q), it was necessary to assume a diameter for the branch area of a tree. This diameter was assumed to be 15-feet. Using air conditions of 70 degrees Fahrenheit at one atmosphere and an air velocity of 7,000 feet per minute gives the following results:

$$Q = V_a A = \frac{7{,}000 \text{ ft.}}{\text{min.}} \times \frac{3.14 (225) \text{ ft.}^2}{4}$$

$$= 1{,}238{,}000 \text{ cfm}$$

$$H = \frac{V_a^2}{2g} = \frac{(7{,}000)^2 \text{ ft.}^2}{\text{min.}^2} \times \frac{\text{min.}^2}{3{,}600 \text{ sec.}^2} \times \frac{\text{sec.}^2}{64.4 \text{ ft.}}$$

$$= \frac{4.9 \times 10^7}{3{,}600 (64.4)} = 212 \text{ feet of head}$$

Specific weight of air (γ) = 0.075 lb./ft.^{3}

$$\text{Air horsepower} = \frac{1{,}238{,}000 (0.075) 212}{33{,}000}$$

$$= 595$$

The air horsepower is the horsepower required to move the air. Additional power must be supplied to overcome the resistance of the system. The actual or shaft horsepower can be expressed in the following manner:

$$\text{Shaft horsepower} = \frac{\text{Air Horsepower}}{\text{Total Mechanical Efficiency}}$$

Assuming an efficiency of 60 percent for propeller fans, gives

$$\text{Shaft horsepower} = \frac{595}{0.60} = 992$$

If four fans were used around a tree, each fan would be required to move air at 1,238,000/4 or 309,500 cfm. The horsepower requirement would be 248 horsepower per fan based on the above efficiency.

EXPERIMENTAL INVESTIGATION

Laboratory Tests

Before attempting design and construction of a field machine, laboratory tests were conducted to determine pertinent information. This section describes the procedure involved and discusses the results.

The objectives of the laboratory tests were to determine:

(1) The effect of a high velocity air stream on reducing impact forces occurring for falling fruit.

(2) The magnitude of the impact forces for fruit falling in an air stream at various velocities.

(3) The magnitude of air velocity required to minimize bruising incurred in falling.

Apparatus

Fans. Two backward curve centrifugal fans mounted together on the same base and driven by a single shaft were used to supply high velocity air movement. These fans with their outlets connected together by a transition section were capable of moving air through a ten inch square duct at 7,000 feet per minute.

Engine. Power to operate the fans was provided by a Wisconsin "V-4" air-cooled engine capable of providing approximately 24 horsepower at 2,200 revolutions per minute. This engine supplied power to the fans through V-belts connected to give a 3.81 step-up ratio. The step-up ratio was necessary to obtain desired fan speeds since the engine contained a two to one reduction unit on the drive shaft. A clutch unit was provided on the engine drive shaft for disengagement of the fans from the engine.

Duct. A duct ten inches square, conforming to A. S. M. E. Tests Code recommendations for fans, was constructed. These recommendations stated that the duct length should not be less than ten duct diameters, a straightener located at a distance not less that six duct diameters and pitot tube openings located at a distance not less than seven and one-half duct diamenters from the fan end of a straight and uniform section of the duct. The duct consisting of uniform cross section was 14-feet high with the lower eight feet constructed of three-eights inch plywood and the upper six feet constructed of three-sixteenths transparent plastic. A honeycomb type straightener with one inch cell spacings and three inches in length was constructed of sheet metal and located eight feet from the fan end of the straight section of the duct. Five holes seven-eights of an inch diameter were cut in one wall of the plastic section to facilitate entry of a pitot tube. These holes were located nine feet, five inches from the fan end of the straight section of the duct. The holes were tapped to permit closing with a threaded metal plug. A small door was constructed directly above the holes to provide entry into the duct. The plastic and plywood sections were butted together to form a joint with a smooth surface inside. The two sections were secured to each other by clamp tighteners. The entire length of duct was mounted atop a transition section connected to the fans. The transition section was constructed according to the Fan Test Code recommendations. These recommendations provided a transition section 42-inches in length with a taper of seven degrees from the fans to the inlet at the straight section of the duct.

Pitot Tube. The pitot tube used was the "combined" type having stagnation and static-pressure measuring devices. It was inserted through the holes in the plastic wall to obtain pressure differences. A small plastic plug, three inches long and seven-eights of an inch in diameter was bored lengthwise to accommodate the pitot tube and screw into the holes in the wall of the duct. This arrangement permitted traversing the duct in two directions with the pitot tube to obtain measurements at the center of 25 equal areas.

Manometer. A "U" tube type manometer was used to indicate difference between static- and stagnation pressures. Water was used as the manometer liquid and a drop of food coloring was added to make the water more distinguishable against the background. A meter stick mounted between the legs of the manometer was used to measure the difference in water levels. The manometer was connected to the pitot tube by rubber hoses.

Tachometer. An electronic tachometer was used to determine revolutions per minute of the engine drive shaft. This unit consisted of a small two-pole generator attached to the drive shaft by a flexible coupling. The generator produced an electric signal that was fed into a timing device (manufactured by Standard Electric Company) that indicated revolutions per minute directly.

Strain Gages. Type A-5, SR-4 strain gages were mounted on a cantilever beam to measure impact forces applied to the beam. Four gages were used to form a Wheatstone bridge arrangement for connection to an electronic recording device. The gages were mounted one inch from the support with two gages on the bottom and two on top of the beam.

Cantilever Bean. Calculations based on formulas of strength of materials yielded dimensions for a cold rolled steel beam three-sixteenth of an inch by one inch by fifteen inches as satisfactory design values. The beam was secured by strap iron clamps to a two inch angle iron frame. Small holes were drilled through the beam at distances of 13, 15, 17, 18, and 20-inches from the support. These holes made it possible to attach the fruit to the beam at different locations to minimize beam deflections for different sized fruits.

Recording equipment. A Brush Strain Analyzer and oscillograph were used for measuring impact forces. The recorder was calibrated physically by applying a known amount of weight to the beam and adjusting the pen deflection accordingly.

Procedure

An air duct was constructed, as previously described, and connected in a vertical position to the fans by the transition section as shown in Figure 13. Figure 14 shows the upper section of the duct protruding through the floor from the floor below. The engine speed was controlled from the upper floor level by a throttle arrangement on the small sawhorse device shown in Figure 14.

Air velocity measurements were made with the pitot tube for various fan speeds. For each fan speed, a series of 25 pressure differences were obtained by traversing the duct in two directions. This was accomplished by removing a plug from one of the openings in the duct wall and inserting the pitot tube. The plastic jacket around the pitot tube was screwed into the hole to insure an air tight fit and to hold the pitot tube rigid while being moved across the duct area. The plastic jacket contained sufficient tolerance in the bore to allow the pitot tube to slide through it. After the duct was traversed at one opening, the pitot tube was removed and placed in each of the other holes to obtain a complete traverse of the duct (25 measurements).

Average velocities were computed for the duct cross section at various fan speeds. Computations were based on standard air at 70 degrees Fahrenheit, 29.92 inches of mercury

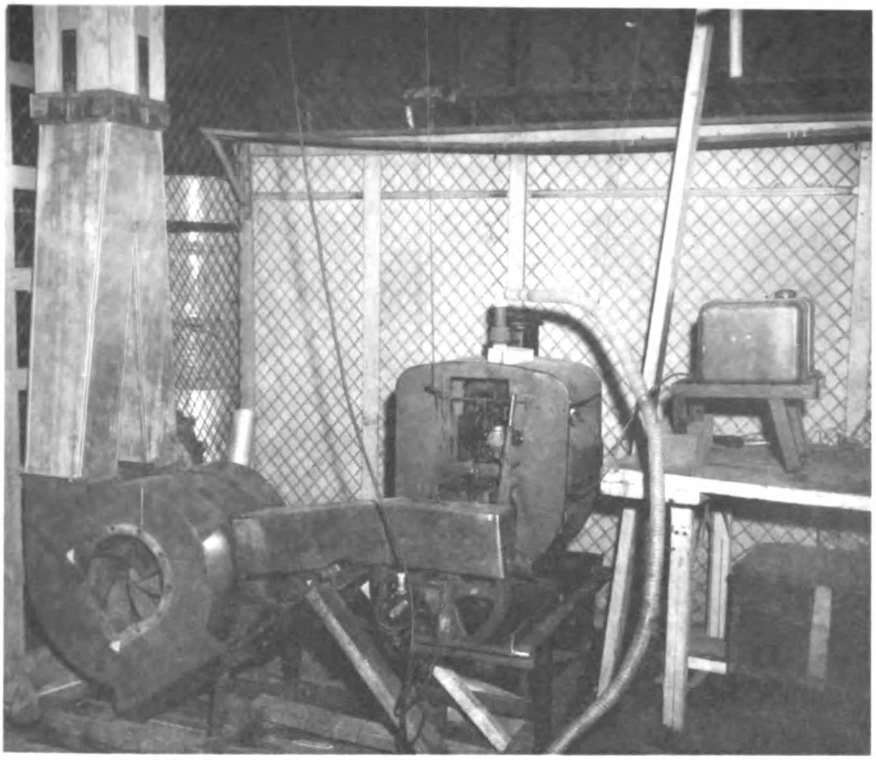

Figure 13. The engine, fans, and duct assembly used for laboratory tests.

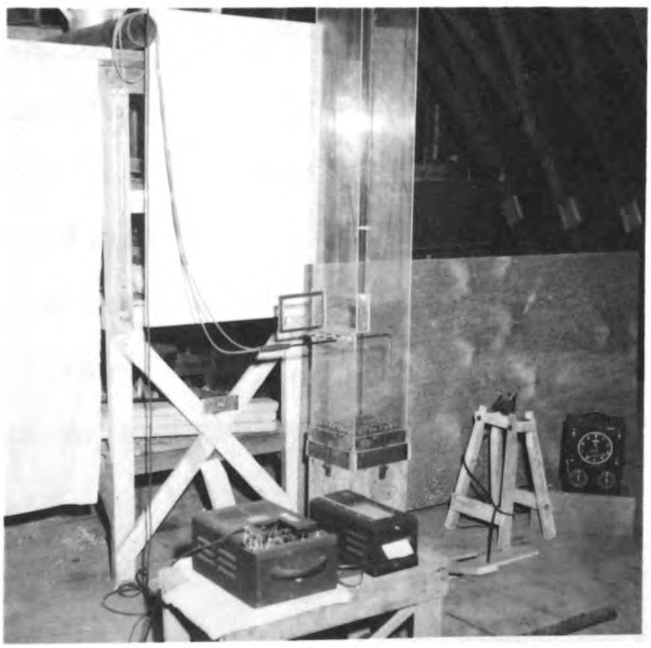

Figure 14. Upper portion of the duct extending from floor below and some of the equipment used.

and 50 percent relative humidity.[5] The equations involved are:

$$V = 1{,}096.5 \sqrt{\frac{p}{\gamma}} \quad \text{(Any air condition)}$$

and

$$V = 4{,}005 \sqrt{p} \quad \text{(Standard air conditions)}$$

where:

p = head or pressure in inches of water

γ = specific weight of air pounds per cubic foot (0.075 pounds per cubic foot for standard air)

V = air velocity, feet per minute

Figure 15 shows a graph of average velocities versus drive shaft revolutions per minute. This graph was used as a calibration curve for the tachometer. Fan speed was adjusted by the tachometer to give a desired air velocity. The tachometer is shown at the far right in Figure 14.

Directly above the duct outlet, a frame of wood and angle iron was constructed to provide a mounting for a cantilever beam. The beam was mounted onto this frame with the free end directly above the duct outlet. Figure 16 shows this arrangement. A V-shaped trough was placed beneath the beam to eliminate effects of the air stream on the beam. Figure 17 shows the under side of the trough as it appeared above the duct opening.

The fruit was attached to the bean with a nylon line

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[5]Madison, R. D. (1949).

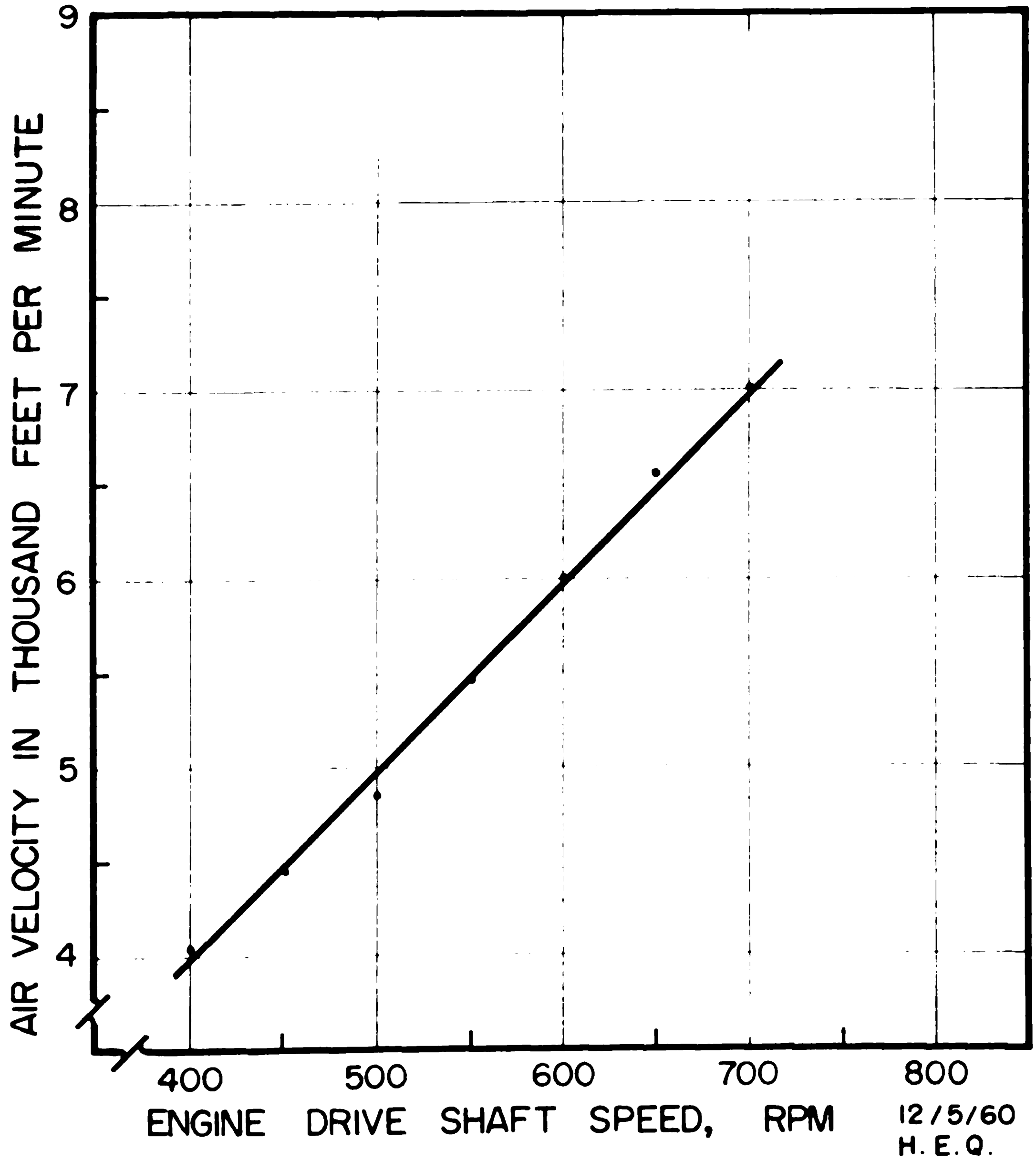

Figure 15. Relation of engine drive speed to air velocity in duct.

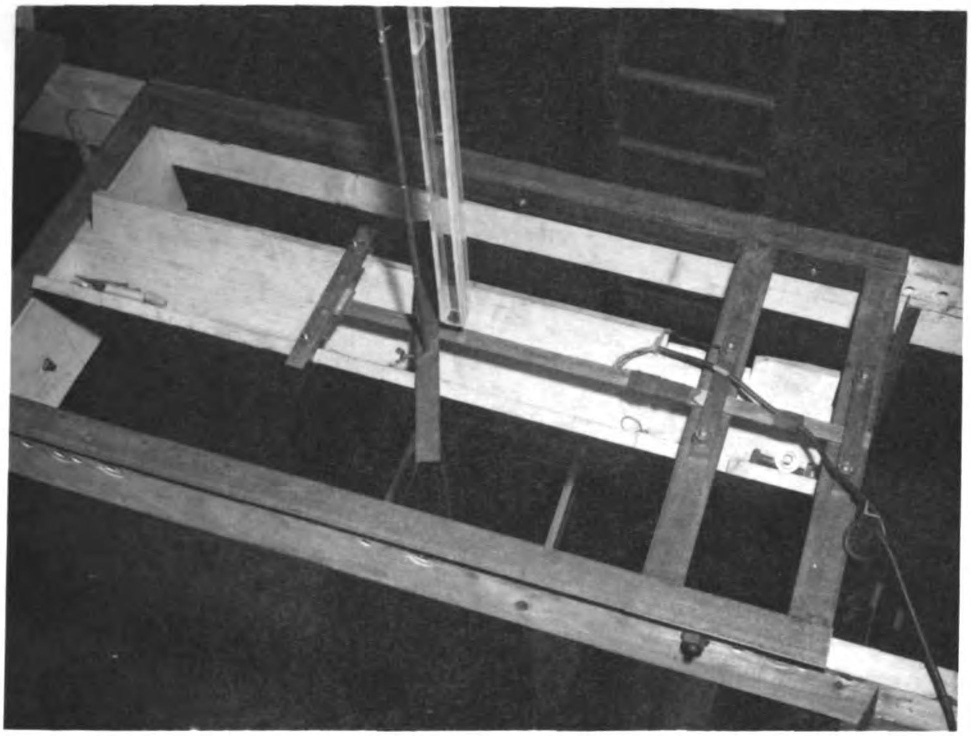

Figure 16. Cantilever beam with strain gages mounted above the duct outlet.

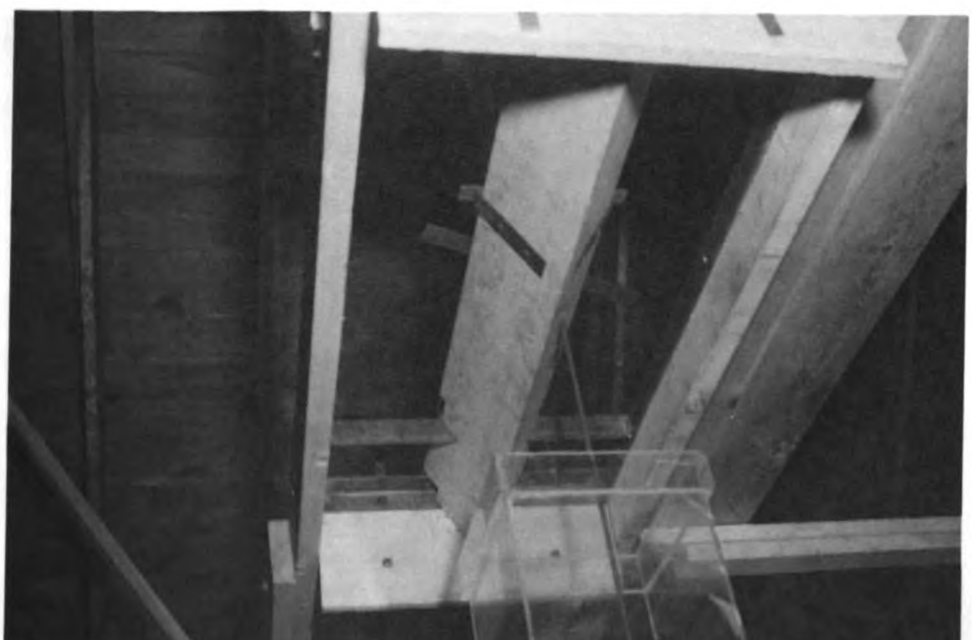

Figure 17. V-shaped trough above the duct outlet shielding the cantilever beam from the air stream.

threaded through a small opening in the trough, through a hole in the beam and secured by placing a knot in the end. The other end extended down into the duct for attachment of the fruit. Figure 18 shows the device used for attaching apples. The needle formed from a nail with an enlarged head was inserted through the apple from blossom end to stem end. Figure 19 shows an apple attached to the nylon line with this device. For those fruit with a pit in the center, a sewing needle was used to insert a short length of nylon line through the fruit on either side of the pit and equip it with a small disk on the bottom side. The disk prevented the line from pulling into the flesh of the fruit.

Tests were conducted by pulling the line with the fruit attached upward with the line placed inside the small plastic tube mounted above the beam. The small tube served to hold the line in a vertical position above the beam. When the fruit was released from different heights marked on the small plastic tube and allowed to fall, it was brought to a stop by contact of the knot in the line with the beam.

The beam was manually given an initial deflection before releasing the line to allow the fruit to fall. The purpose of this deflection was to indicate on the recorder an initial point from which the time required for the fruit to fall could be measured. Figure 20 shows a section of oscillograph tape with recorded results of a typical drop. The time required for the fruit to fall from the raised position to the position

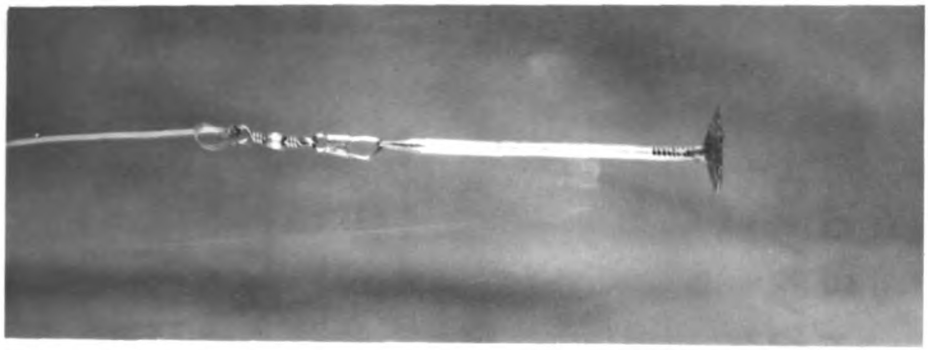

Figure 18. Device used for attaching apples to the cantilever beam.

Figure 19. An apple hanging inside the plastic duct from the cantilever beam.

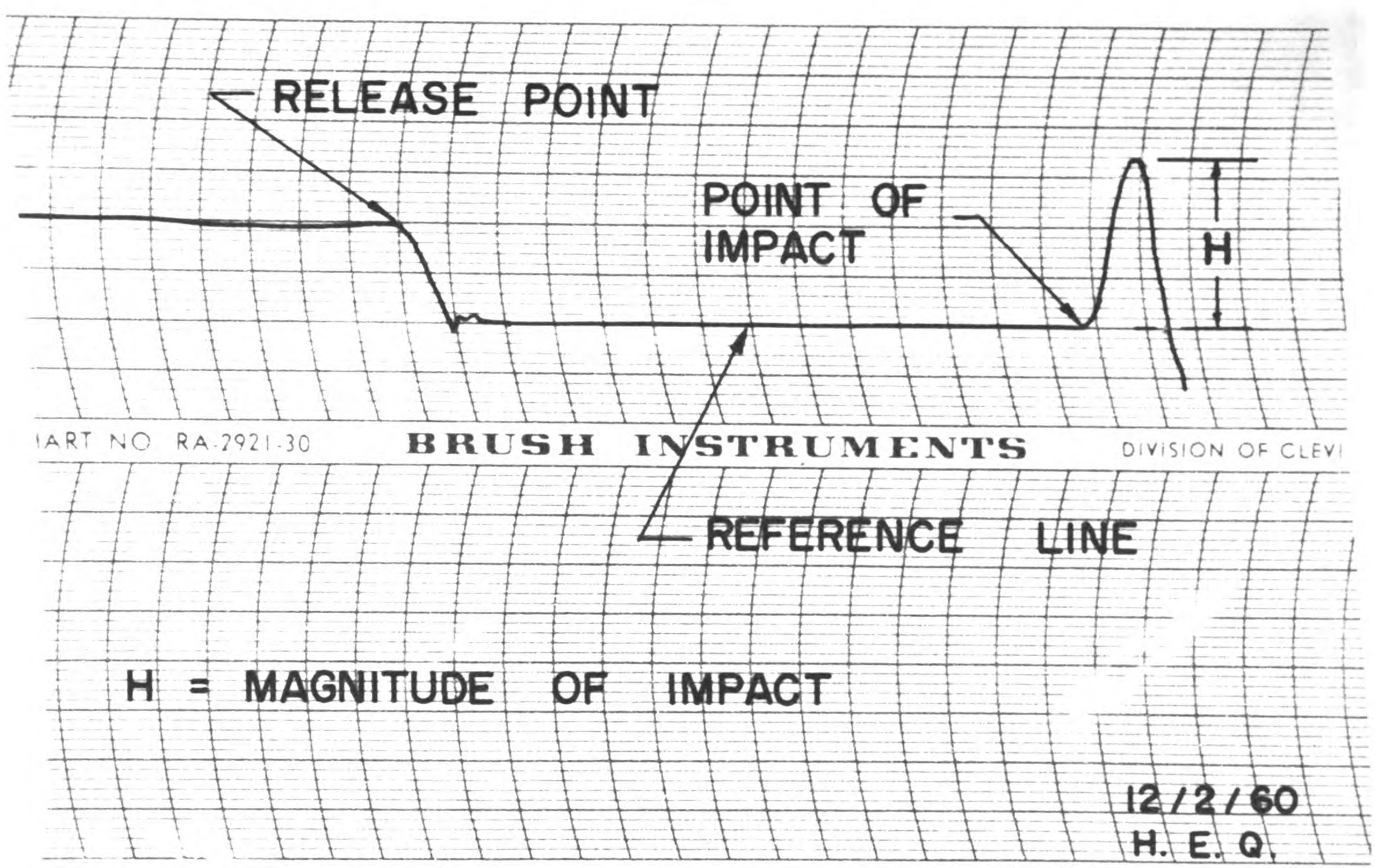

Figure 20. Section of oscillograph tape with recorded results of a typical drop.

occupied when fully supported by the beam was computed from the oscillograph tape. The oscillograph was operated at a speed of five inches per second which is one of the three standard speeds of an oscillograph. This speed was checked for accuracy with a stop watch. The time required for the fruit to fall was measured from the release point, shown in Figure 20, to the impact point. The magnitude of the impact force was determined by the lines of deflection from the reference line to the top of the deflection curve. A hard-rubber damper was mounted with slight contact to the beam at the free end. This damper eliminated beam vibration between the release point and impact point.

Experiments were performed with different species of fruit by dropping them from one-half, one, two, three, four, and five foot levels. Each fruit was dropped from these heights in air velocities ranging from zero to 6,500 feet per minute.

Results

The results obtained are presented on the graphs in Figures 21 through 24a. The graphs showing coordinate points were plotted directly from experimental data. The graphs showing curves with no coordinate points were obtained from the graphs of the experimental data.

The theoretical terminal velocities of the test fruit were computed by equation (4) and are shown in Table V.

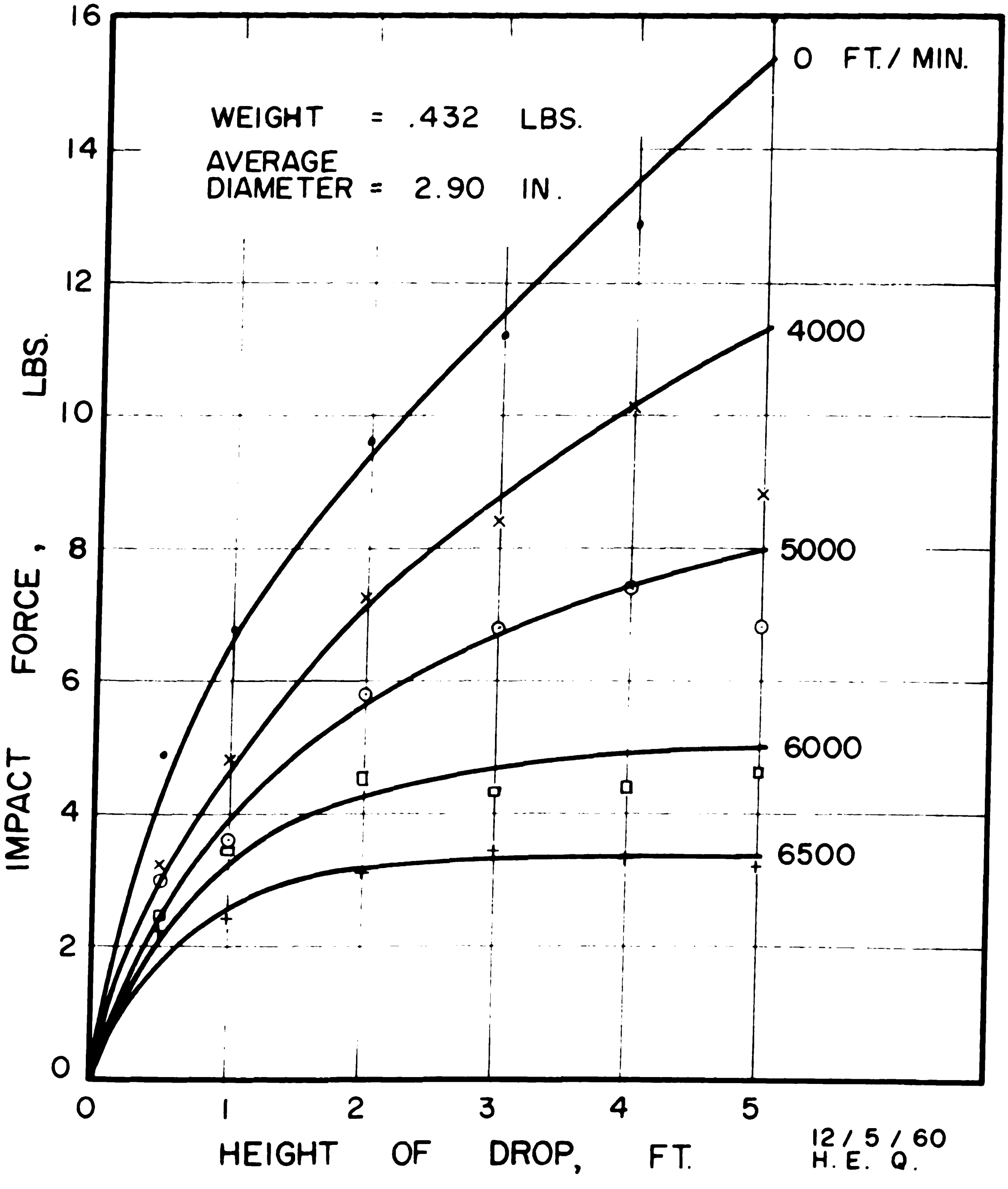

Figure 21. Relation of impact force to height of drop for a McIntosh apple.

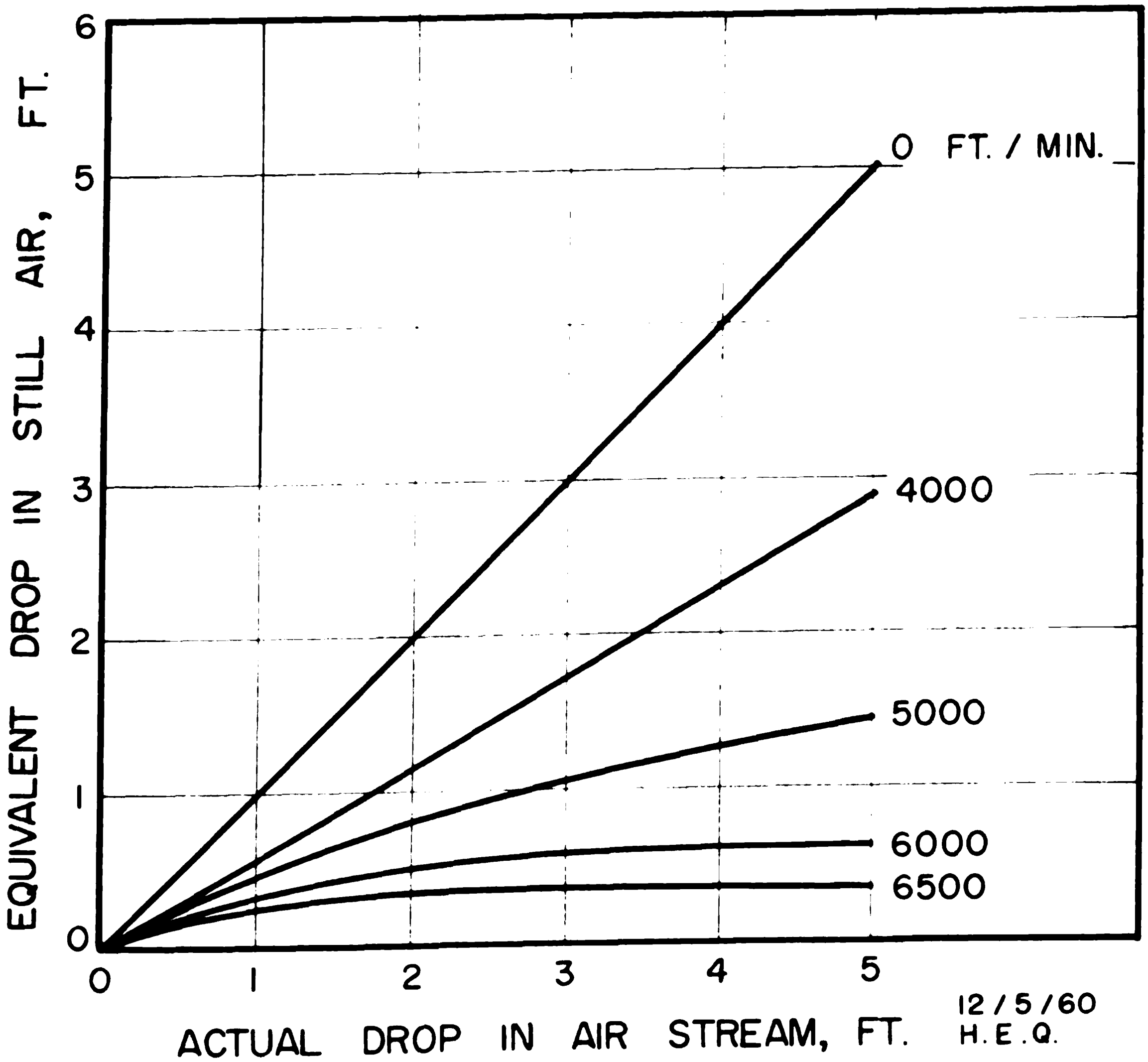

Figure 21a. Relation between the actual drop in an air stream and an equivalent drop in still air for a McIntosh apple.

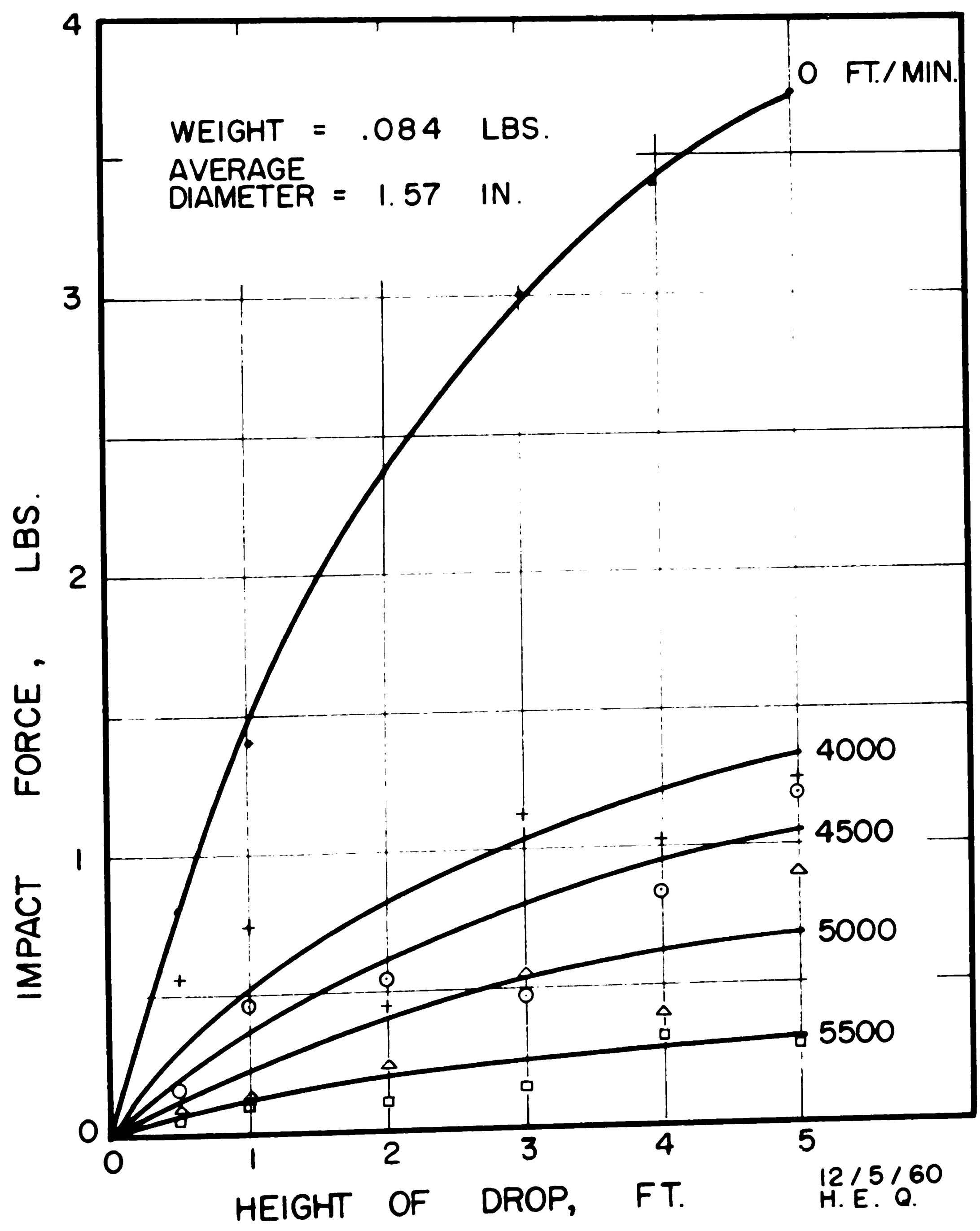

Figure 22. Relation of impact force to height of drop for a Montgamet apricot.

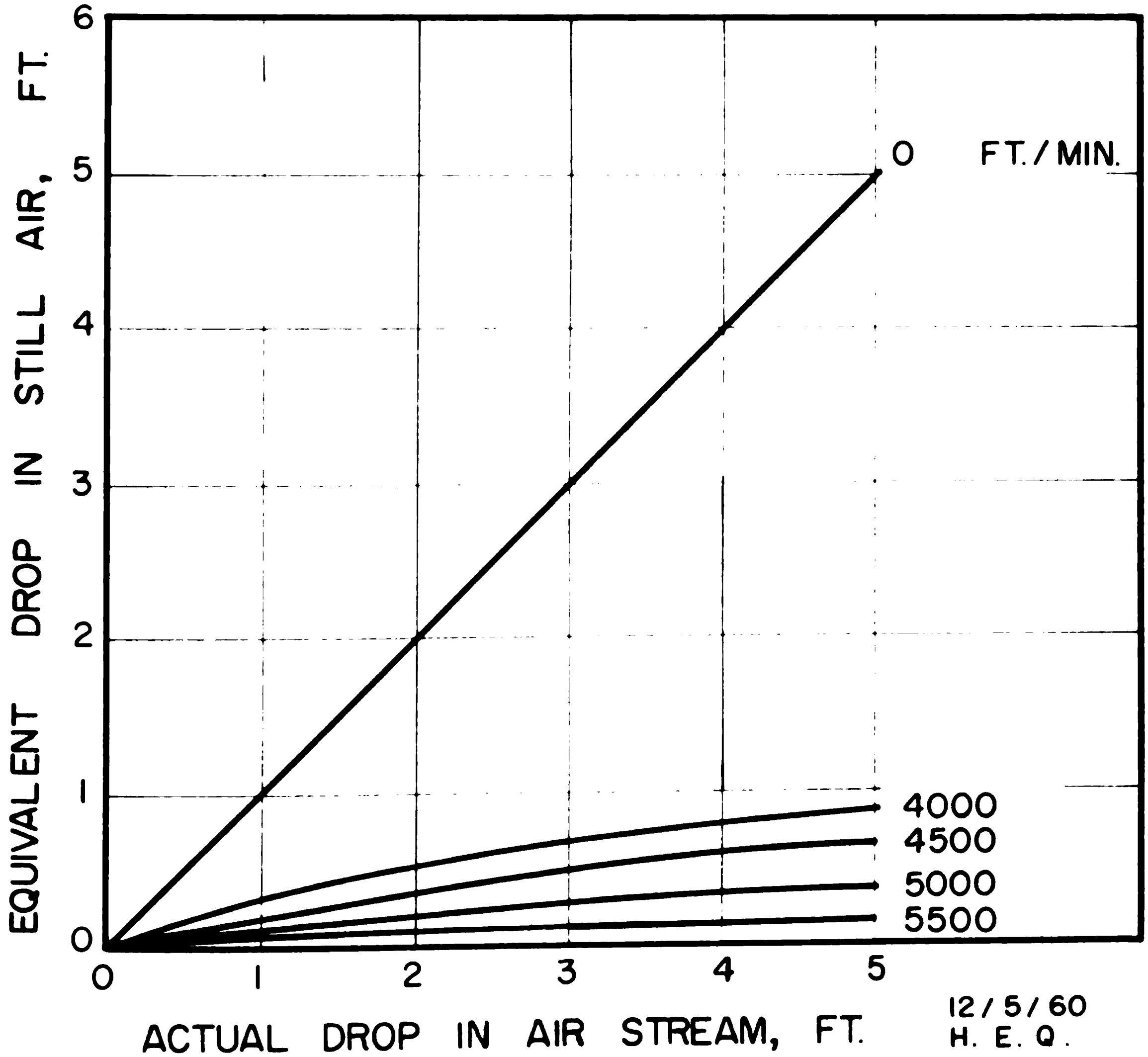

Figure 22a. Relation between the actual drop in an air stream and an equivalent drop in still air for a Montgamet apricot.

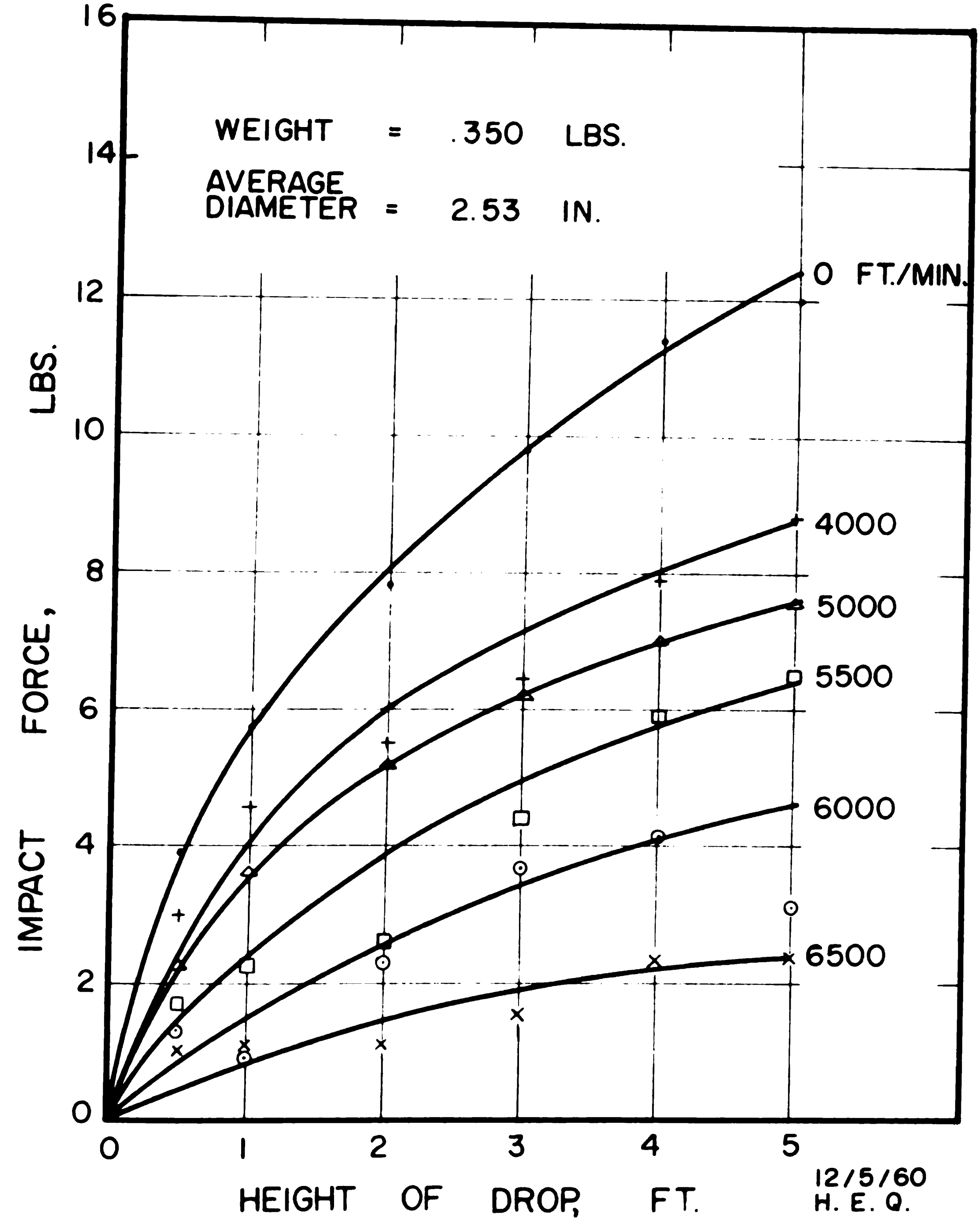

Figure 23. Relation of impact force to height of drop for a Red Haven peach.

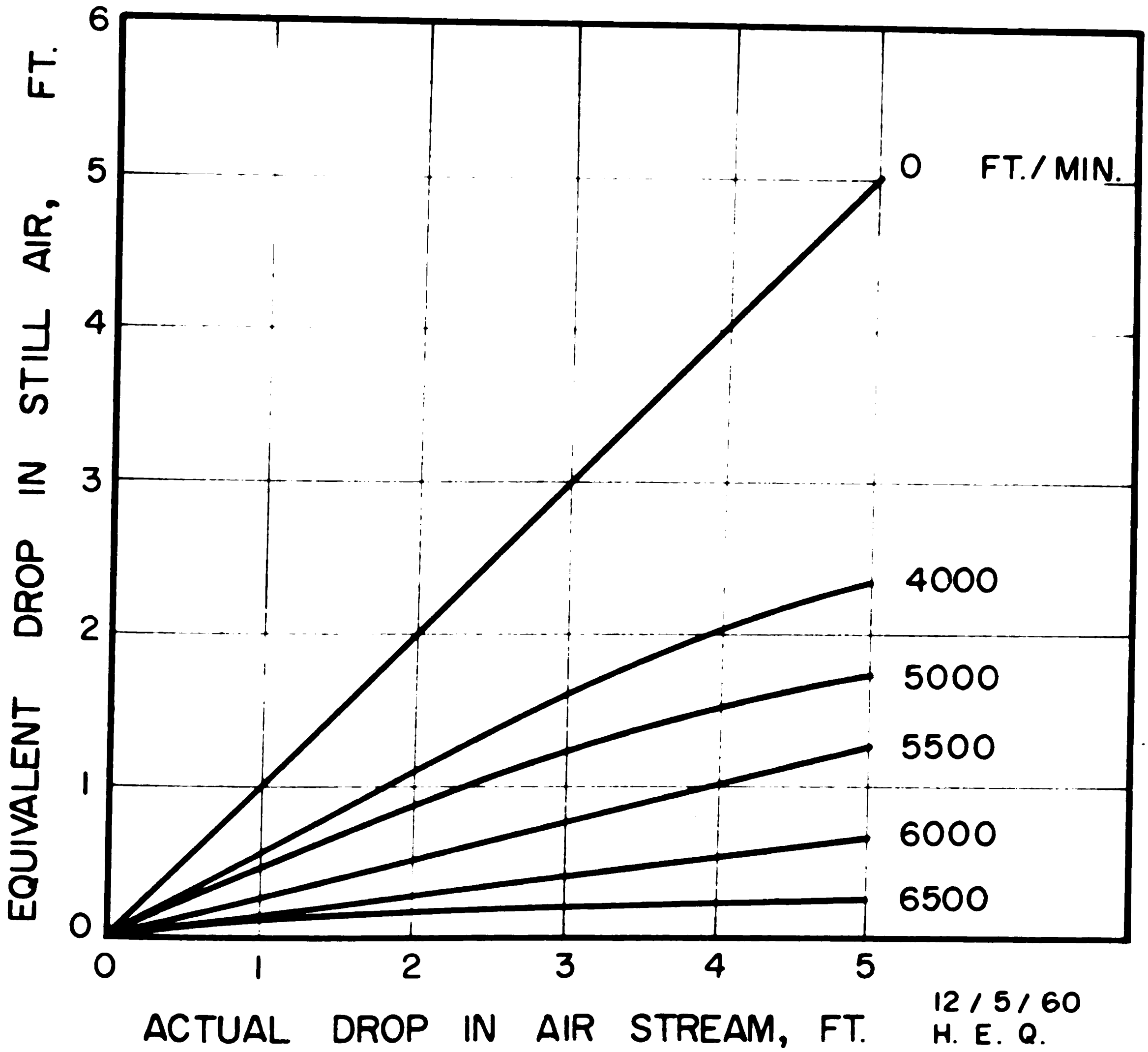

Figure 23a. Relation between the actual drop in an air stream and an equivalent drop in still air for a Red Haven peach.

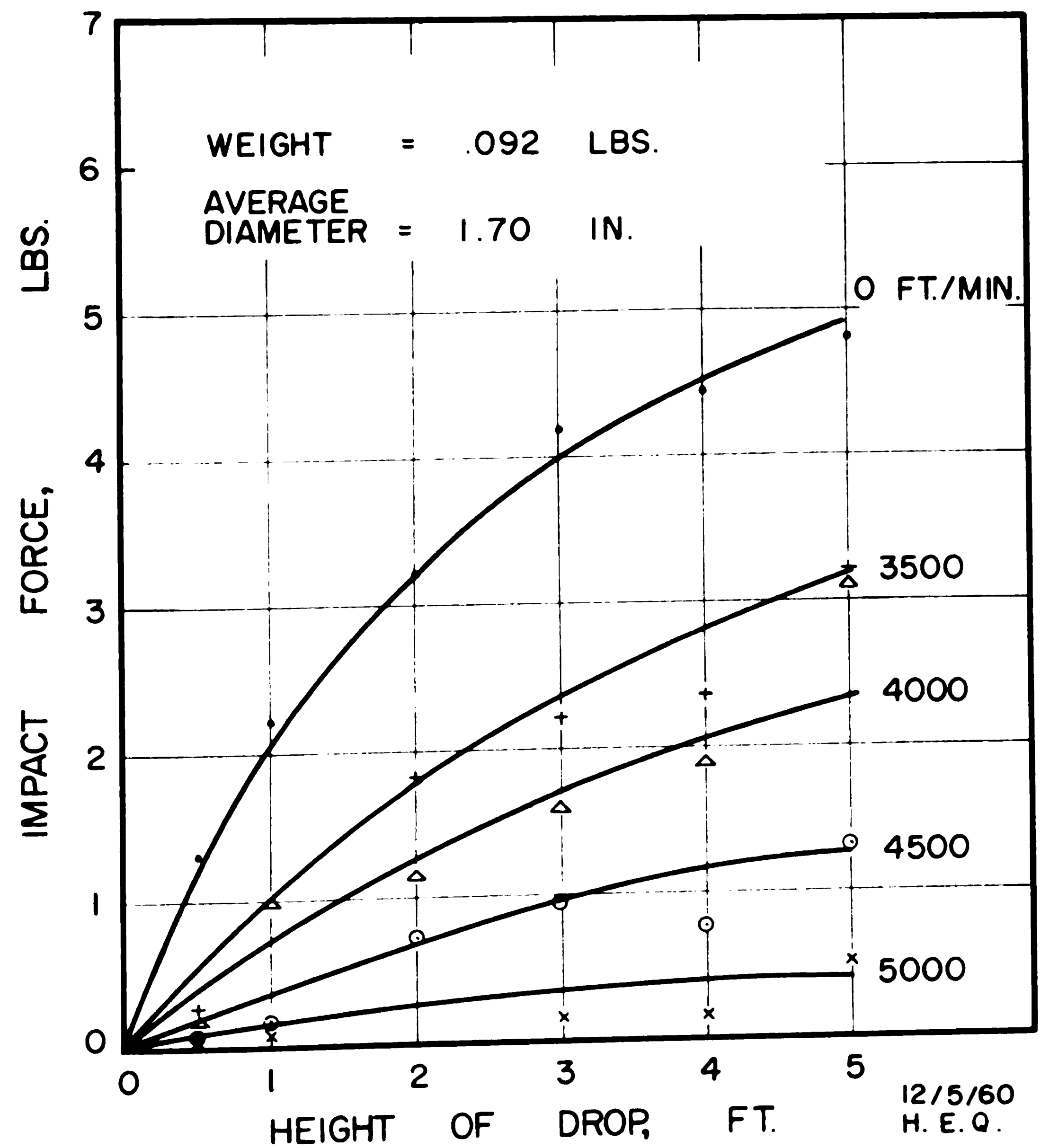

Figure 24. Relation of impact force to height of drop for a Stanley Prune plum.

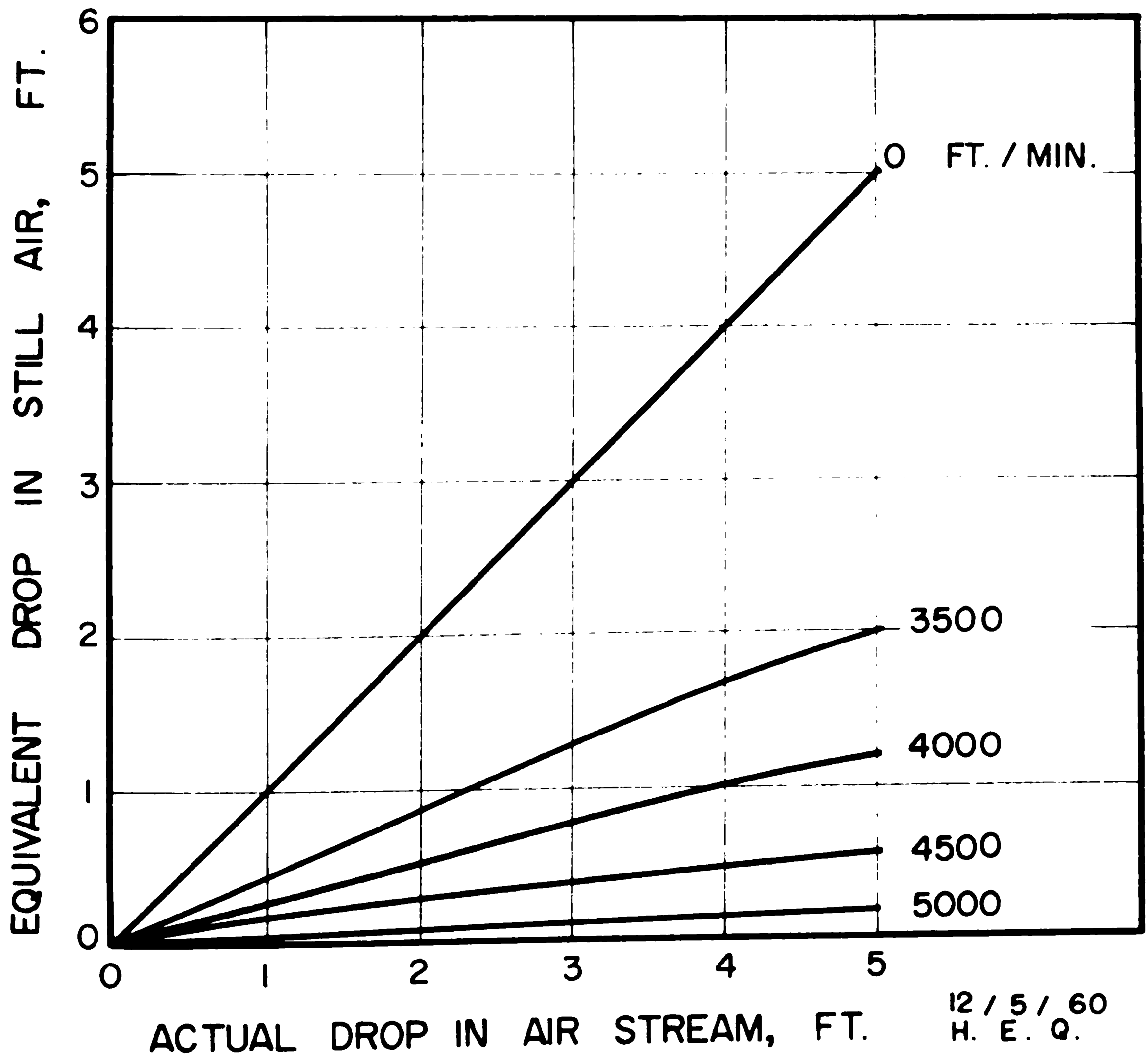

Figure 24a. Relation between the actual drop in an air stream and an equivalent drop in still air for a Stanley Prune plum.

TABLE V Theoretical terminal velocities computed with the results from samples of 50 fruits.

Fruit	Weight lb.	Ratio of Weight to Projected Area* lb./in.^{2}	Terminal Velocity ft./min.
APPLE			
McIntosh	0.432	0.0662	8180
APRICOT			
Montgamet	0.084	0.0432	6610
PEACH			
Red Haven	0.350	0.0624	7940
PLUM			
Stanley Prune	0.092	0.0411	6520

*Values obtained from Figures 1, 2, 7, and 10.

Air conditions of 70 degrees Fahrenheit at one atmosphere (γ = 0.075 pounds per cubic foot) were used in computing the terminal velocities in Table V.

Table VI has been prepared to concentrate the information provided by the graphs of Figures 21 through 24a. Only five foot drops have been considered since these represent the extreme case for this investigation.

The equivalent drop values in Table VI are the distances which fruit must be dropped in still air to produce an impact force equivalent to that obtained when the same fruit is dropped in air streams of the velocities shown.

TABLE VI Equivalent drop distances and corresponding impact forces*

Fruit	Air Velocities ft./min. 0		4,000		5,000		5,500		6,000		6,500	
	Equiv. Drop ft.	Impact Force lb.	Equiv. Drop ft.	Impact Force lb.	Equiv. Drop ft.	Impact Force lb.	Equiv. Drop ft.	Impact Force lb.	Equiv. Drop ft.	Impact Force lb.	Equiv. Drop ft.	Impact Force lb.
APPLE												
McIntosh	5	15.30	2.90	11.30	1.42	8.00	___	___	0.62	5.00	0.35	3.40
APRICOT												
Montgamet	5	3.72	0.85	1.32	0.35	0.68	0.15	0.30	___	___	___	___
PEACH												
Red Haven	5	12.40	2.35	8.70	1.75	7.60	1.25	6.40	0.65	4.60	0.25	2.40
PLUM												
Stanley Prune	5	4.90	1.20	2.35	0.17	0.40	___	___	___	___	___	___

*Data based on five foot drops.

Discussion

Comparisons were made for a portion of the values given in Table VI. The results of these comparisons are presented in Table VII.

The values presented in Table VII are valid for all fruit of the same species having similar weight and diameter measurements. The values given in Table VII represent in percent the amount of reduction in impact forces and heights of drop from the five foot values when an air stream was used to lower the fruit. The percentages were obtained by dividing the differences between values (Table VI) for zero and the various air velocities by the zero air velocity values. Percent reduction of impact forces and heights of fall increase for lighter weight fruit and decrease for heavier fruit experiencing a five foot drop. It is apparent, however, that the deviation in percentages from the values given in Table VII will not be large since the variation in fruit size among a species is relatively small.

The air velocities of Table VII, corresponding to the maximum percent reduction values, were compared with the terminal velocities of Table V. The results of this comparison indicated that 78 to 92 percent reduction of impact forces occurred for all species at air velocities ranging from 750 to 1,580 feet per minute below the theoretical terminal velocities.

If 78 to 92 percent reduction of impact forces will

TABLE VII Reduction of impact forces and equivalent heights of drop when using air to lower the fruit*

Fruit	Air Velocities (ft./min.) Used in Computing the Percentages					
	0 - 5,000		0 - 5,500		0 - 6,500	
	Impact Forces %	Height of Fall %	Impact Forces %	Height of Fall %	Impact Forces %	Height of Fall %
APPLE						
McIntosh	48	72	—	—	78	93
APRICOT						
Montgamet	82	93	92	97	—	—
PEACH						
Red Haven	39	65	48	75	81	95
PLUM						
Stanley Prune	92	97	—	—	—	—

*Data based on five foot drops.

sufficiently reduce bruising that occurs from fruit impact, then air velocities ranging from 750 to 1,580 feet per minute below theoretical terminal velocities could be used effectively in lowering the fruit from the tree. Table VI shows that equivalent drops in still air range from 0.15-to 0.35-feet corresponding to the 78 to 92 percent range discussed above. Fruit dropped from these equivalent drop heights would produce impact forces equivalent to those of fruit dropped in air from five feet at the velocities given. Gaston and Levin (1951) indicated that bruising occurred to apples when dropped on various surfaces from only one inch heights. The effective drop for McIntosh apples dropped five feet in an air stream of 6,500 feet per minute was 0.35-feet or 4.2-inches. This fact makes it evident that a greater air velocity should be used to effectively handle apples. It is evident that air velocities very nearly equal to terminal velocities will be required if pneumatic methods are to be effective.

Analysis of error involved

In the procedure, the method of determining impact forces was discussed. There was definitely instrument error and human error which is difficult to analyze but a portion of the experimental error can be accounted for. The portion referred to here is that occurring from the friction force encountered by the nylon line sliding through the hole in the cantilever beam and the wooden trough beneath the beam as the fruit descended.

Calculations, by established equations for free fall motion of the time required for an object to fall from different heights, were made. These calculations yielded values less than those obtained experimentally for all drops in still air, thus it was apparent that friction forces were significant.

The following procedure was used to analyze this error and express it in terms of percent error in impact force.

The following equation for velocity of a particle in free fall is given as:

$$V^2 = V_o^2 + 2\ aS \tag{5}$$

where:

V_o = initial velocity, feet per second

V = velocity of particle at distances S from initial point, feet per second

S = distance of fall, feet

a = acceleration of particle, feet per second per second ($a = g = 32.2$ feet per second per second for free fall)

Since $V_o = 0$ in this experiment,

$$V = \sqrt{2\ a\ S} \tag{6}$$

If it is assumed that (a) does not equal (g) for free fall, then the velocity of the particle at any time (t) must be computed independent of the acceleration. This is accomplished by solving the equation

$$S = V_o\ t + \frac{1}{2}\ g\ t^2 \tag{7}$$

for (g) and substituting into the equation

$$V = V_o + g\ t \tag{8}$$

to obtain

$$V = \frac{2\ S}{t} \tag{9}$$

where: t = time for fall, seconds

Equation (9) was used to compute, from the experimental data, the velocities of fruit in free fall using the time recorded from the oscillograph tape.

After obtaining the instantaneous velocity, graphs were made of velocity versus time. From these graphs the acceleration was computed by determining the slope of the straight lines obtained. The results are given in Table VIII.

TABLE VIII Acceleration of fruit in free fall with line attached

Species and Variety	Acceleration ft./sec.^{2}
Plum, Stanley Prune	22.2
Peach, Red Haven	26.6
Apple, McIntosh	26.4
Apricot, Montgamet	21.3

The present error in velocity can be computed by equation (6) in the following manner.

$$\%\ \text{error} = \frac{V_1 - V_2}{V_1}\ (100)$$

where:

V_1 = velocity for free fall, feet per second

V_2 = velocity with string attached, feet per second

Substituting for V_1 and V_2 gives

$$\% \text{ error} = \frac{\sqrt{2\,g\,S} - \sqrt{2\,a\,S}}{\sqrt{2\,g\,S}}$$

$$= \frac{\sqrt{g} - \sqrt{a}}{\sqrt{g}} \qquad (10)$$

The results from equation (10) are presented in Table IX.

TABLE IX Percent of error in velocity

Species and Variety	Percent Error
Plum, Stanley Prune	17.1
Peach, Red Haven	9.2
Apple, McIntosh	9.5
Apricot, Montgamet	18.8

If the impulse and momentum principle is considered, the impact force can be introduced and related to velocity. Writing an equation for momentum of a fruit in free fall and solving for impact force gives

$$F = \frac{m\,V_1}{t_1}$$

where:

F = impact force, pounds

m = mass of fruit

V_1 = velocity of fruit, feet per second

t_1 = impact time, seconds

Since t_1 is not affected appreciably by friction to the nylon line, the error in impact force (F) is caused by the error in velocity. These errors were presented in Table IX.

Compressibility considerations

Since air is a compressible gas, it was necessary to determine whether compressibility would cause any appreciable error if not considered.

Ower (1927) gives an analysis for compressible gasses. He has shown that a gas velocity may be as high as 200 feet per second before the effect of compressibility is significant.

This investigation involved air velocities of 6,500 feet per minute or 108 feet per second. Since these velocities were below the value of 200 feet per second, compressibility was not considered.

Fields Tests

Using the information obtained from the preliminary studies and the laboratory tests, a field machine was constructed and tested. Only a portion of a complete machine was constructed since the principle involved was the same.

Design of the machine

Plans for a field machine were initiated and apples chosen as the test fruit. The laboratory tests indicated that for apples an air velocity of 6,500 feet per minute or more would be desirable if bruising was to be minimized. The necessary information was supplied to a local fan company and arrangements made to obtain fans from them. The fan company was unable to provide fans which would meet all the necessary requirements since air velocities in this range are uncommon in commerical work. As a substitute, two 36-inch propeller fans were obtained. The fan company rated each of these fans capable of moving air through the fan ring area at a rate of 5,000 feet per minute at 2,200 revolutions per minute.

The air velocity obtainable was lower than that determined necessary, but it was felt that valuable information could be obtained from a field machine employing these fans.

The fans were mounted on a five inch channel iron frame with adjustable legs constructed of three and one-half inch pipe inside four inch pipe. At the bottom of each leg, a ten inch face plate was welded to prevent the legs from sinking into the ground. The fans were mounted in a horizontal position with their drive shafts extending downward.

The manufacturer indicated that 20 horsepower per fan was required when operating at 2,200 revolutions per minute. Thus, the power train design was based on 20 horsepower at 2,200 revolutions per minute since this was the fan speed necessary for air movement at 5,000 feet per minute.

Two designs for driving these fans were considered, (1) by V-belts and (2) by roller chain. Design calculations indicated that eight V-belts would be required using a C-section belt and 17 V-belts if a B-section was used. Design calculations with roller chain indicated that it was possible to use No. 50 double strand roller chain. This design was chosen as the most practical and was selected for the drive. To complete the power train on the machine, a 90-degree one to one ratio gear box was used. It was mounted on the side of the channel iron frame with one shaft extending downward and aligned with the fan shafts.

Two double strand roller chain sprockets (30 teeth each) were secured to the lower gear box shaft to drive the fans. A 1.2 step-up ratio was desired from the gear box to the fans to provide proper fan speed and maintain maximum output from the power source. To provide the step-up ratio, each fan was equipped with a 25-tooth double strand sprocket. Connection of the fans to the gear box was accomplished by placing double strand roller chain from the sprocket on one fan to the top sprocket at the gear box and the chain from the sprocket on the other fan to the lower sprocket at the gear box. The power train was completed by connecting a Continental, Red Seal six cylinder engine to the other shaft of the gear box. The connection was accomplished with a six foot drive shaft equipped with universal joints at each end.

A continuous rubber coated steel mesh fruit grading belt with one and one-half inch mesh (nine feet long and three feet wide) was placed over the fans. Figure 25 shows this belt and the fans beneath it. The function of this belt was to remove the fruit to a catching box and allow the air to move upward from the fans to the tree. The belt was driven on two, six inch steel pipe rollers. One roller ran idle while the other served as the driver. The driver was powered by a Farmall "340" tractor power-take-off. A seven foot drive shaft with universal joints on each end was used to connect the tractor to the drive roller.

As a safety precaution, a skirt ten inches wide of boiler plate metal was placed around the channel frame assembly to provide operator protection from the fans. Shields were provided over all drive shafts and drive chains.

A plywood container wall to confine the air stream was constructed, eight feet upward from the channel frame assembly. Three sides were enclosed leaving one side open to facilitate placement of a tree limb inside. A plastic window was placed in one wall for viewing purposes. This arrangement can be seen in Figure 26 which shows a side view of the machine with

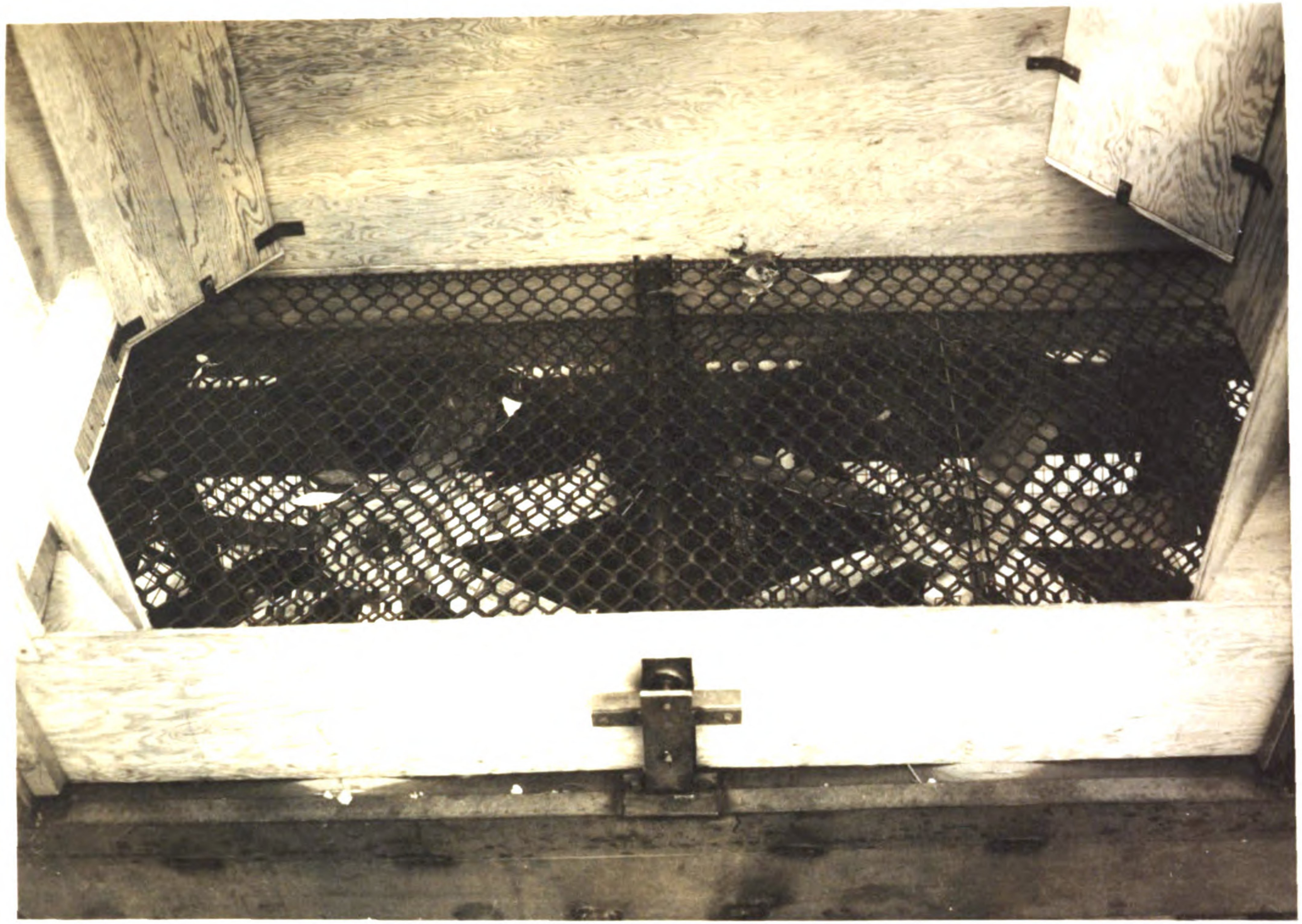

Figure 25. Position of fans beneath the fruit catching and conveyor belt.

Figure 26. Pneumatic fruit harvester with a limb inside the confining walls.

Figure 27. Over-all view of the pneumatic fruit harvesting machine with the author viewing a limb inside.

a limb inside the confining wall. Canvas, cut to fit around the limb, was used as a wall on the open side. This completely enclosed the area above the fans and confined the air to move upward through the limb and out the top. Figure 27 presents a more complete view of the confining wall. It also shows an over-all view of the entire machine with the power sources connected.

Transportation of the machine was accomplished by a fork-lift mounted on the rear of a Massey-Ferguson "35" tractor. Figure 28 shows a view of this operation. Two channel members were welded across the bottom of the machine with the channel legs pointing downward. These provided a track into which the forks of the fork-lift were inserted by backing the tractor into the machine.

Air velocity measurements

To determine the air velocity from the fans, a pitot tube was used in connection with a "U" tube manometer. Holes at one foot intervals beginning seven inches from each end were placed in opposite sides of the confining wall at a distance of six feet from the fan blade surface. The pitot tube was inserted through these holes and readings taken at positions of five and 14 1/2-inches from the wall. Figure 29 shows this operation being conducted for the area at one location. A traverse was made from each side in two directions for one-half of the confined area since the pitot tube would not reach across the total width. A total of 28

Figure 28. Method of transporting the harvesting machine.

Figure 29. Measurement of air velocity inside the walls with a pitot tube.

measurements were obtained. From these an average air velocity was computed. The results of this traverse indicated an air velocity of 2,610 feet per minute at a fan speed of 2,200 revolutions per minute. This value was considered too low to be effective; therefore, alterations were made to improve the air velocity. The alterations consisted of raising the entire machine three inches to provide greater intake area for the fans and decreasing the area within the confining walls. The initial area consisted of a rectangular enclosure of 20.7 square feet. This was altered by moving the wall, with the plastic window, inward eight inches and placing corner partitions in each corner. Figure 25 shows a view of these partitions. The alterations decreased the duct (confining wall) area by 3.8 square feet. The effective duct area was then 16.9 square feet as compared to the fan ring area of 14.12 square feet. The necessary air velocity, through the duct area, to give 5,000 feet per minute through the fan ring area would be 4,150 feet per minute.

The pitot tube holes in the duct walls were relocated to give points of measurements at the center of equal areas and another velocity traverse made. The results indicated an average velocity of 3,020 feet per minute at a fan speed of 2,200 revolutions per minute. This velocity was 27.2 percent less than the velocity of 4,150 feet per minute needed to give rated velocity of 5,000 feet per minute at this speed.

A traverse of the enclosed area was conducted with the mesh conveyor belt removed to determine its effect on the air velocity. The results indicated an average air velocity of 3,650 feet per minute at a fan speed of 2,200 revolutions per minute. This was an increase 15.2 percent leaving 12 percent to be accounted for by turbulence and other losses. It is apparent that a fan system employing a mesh conveyor belt of the type used on this machine would be required to provide 15.2 percent greater air velocity to account for losses due to resistance of the belt.

Test Procedure

Information obtained from the laboratory tests indicated that this machine, providing an air velocity of 3,020 feet per minute, would not effectively reduce impact forces of falling fruit. Tests were continued, however, to establish basic information of this harvest method.

A Jonathan apple tree was selected for test work. The machine was placed under a tree limb with the limb inside the enclosed area as shown in Figure 30. A canvas wall was attached and cut to fit around the limb support. Figure 31 shows a view of the machine with the canvas wall attached and the limb completely enclosed.

Once in place, the power sources were connected and the machine put into operation. Hand-shaking of the limb was employed to loosen the apples from the tree and allow them to fall in the air stream to the mesh conveyor where they were

Figure 30. Placement of a limb inside the confining walls.

Figure 31. Limb completely enclosed by use of a canvas flap over the opening.

carried out the end as shown in Figure 32. They were dropped from the conveyor onto a plywood incline covered with expanded polyethylene. The plywood incline was draped with a lightweight canvas to slow the apples down before they reached the box so as to prevent bruising. The box was lined with expanded polyethylene also to prevent damage from the sides of the box.

Figure 33 shows the results from the harvested limb. The seven apples at the far right in the picutre contained spurs left on when they were shaken loose from the tree. The remaining 73 apples contain numerous bruises which cannot be detected from the picture.

Evaluation of the machine

The apples shown in Figure 33 were inspected for bruises after one week of storage and each bruise given a numerical evaluation.

The bruise evaluation was based on a system of evaluating bruises by Schomer (1957). He used a numerical system based on bruise size, whereby the numerical values assigned the different bruises were roughly proportional to their areas. The numerical system used is outlined in Table X.

In addition to those values given in Table X, the following classification was also used:

Descriptive Term	Numerical Evaluation
No bruise	0
Skin break	cull

Figure 32. Apples being delivered to a box from the conveyor belt.

Figure 33. Apples that were harvested with the pneumatic fruit harvester.

TABLE X Classification of apple bruises*

Descriptive Term	Size of Bruise (dia.) inches	Numerical Evaluation
Very small	Less than 1/2	1
Small	1/2 to 3/4	2
Medium	3/4 to 1	4
Large	1 to 1 1/4	6
Very large	Greater than 1 1/4	12

*Table reproduced from "Bruising of Apples: Where does it occur and how can it be minimized"? (Schomer, 1957)

The results from the bruise evaluation are presented by the histogram in Figure 34. More than one-half (59.5 percent) were classified in the category of "cull" and "12." This indicated that severe bruising was present. Only two apples from the entire lot did not show visible bruises. These were two of the smallest fruit weighing 0.167 and 0.152 pound. If Figure 8 in Appendix I is extrapolated, the ratios of weight to projected area are found to be 0.0480 and 0.0469 respectively. The corresponding terminal velocities computed from equation (4) page 33 are 6,960 and 6,890 feet per minute respectively. Since these two apples were harvested in an air velocity of 3,020 feet per minute, which is less than half the velocities of 6,960 and 6,890 feet per minute necessary for flotation, it is evident that the air had little effect in preventing bruising. It is highly probable that these two

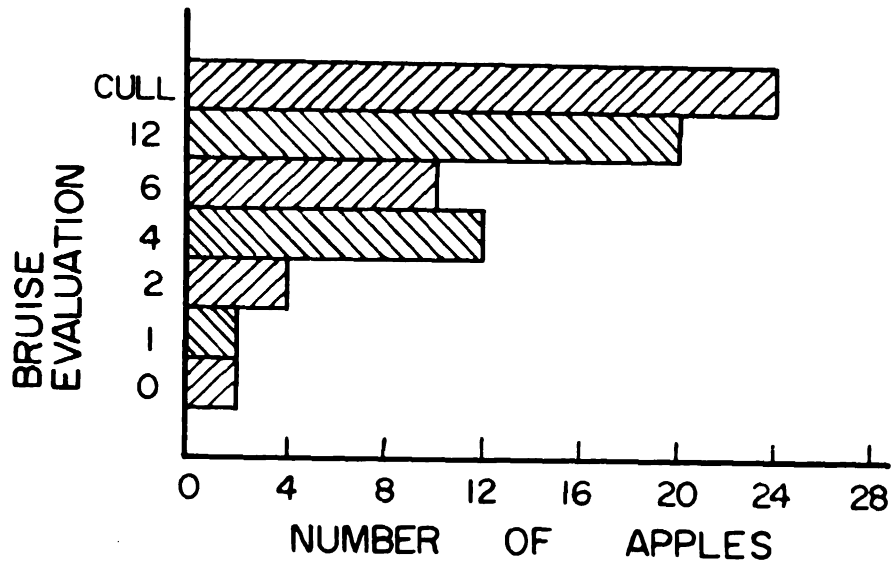

Figure 34. Number of apples receiving bruises when shaken loose by hand and lowered pneumatically

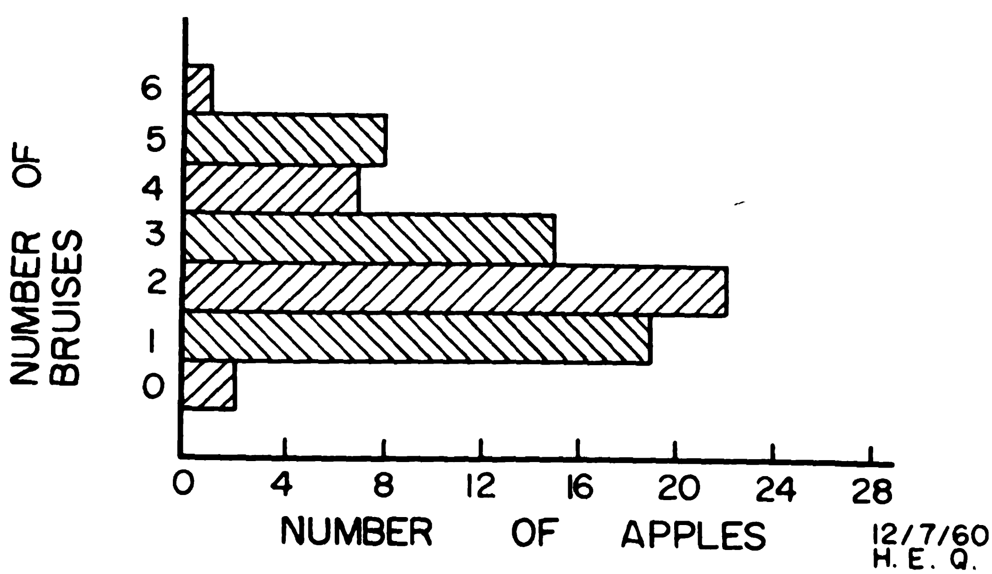

Figure 35. Number of bruises occurring on the apple when shaken loose by hand and lowered pneumatically.

apples were not bruised because they fell only a short distance to the mesh conveyor belt.

Figure 35 shows that a majority of the fruit harvested received one and two bruises. This fact could be accounted for in many ways and the author feels that more data is necessary before a definite cause can be established.

As an aid to further evaluate the field machine, drop-tests were conducted with Jonathan and Northern Spy apples on the machine. The drop-tests were conducted with samples of 50 apples from each variety. An adjustable platform was constructed above the mesh conveyor belt from which the apples were rolled off and allowed to fall to the conveyor below. Neither the conveyor nor the fans were operating during these tests. Ten apples, one at a time, were rolled from the platform at one-half, one, two, three, and four foot positions. This procedure was applied to both species.

The results of these tests are presented in Appendix III, however, only the Jonathan variety was used for evaluation purposes.

The data for both the harvested fruit (Figure 34) and the drop-test fruit were arranged to indicate percentage of total fruit occurring in each bruise category. These results are shown in Figures 36 and 37. Figure 36 gives the results of the harvested fruit and Figure 37 gives the results of the drop-test fruit.

Comparison of the two figures indicates that when no air

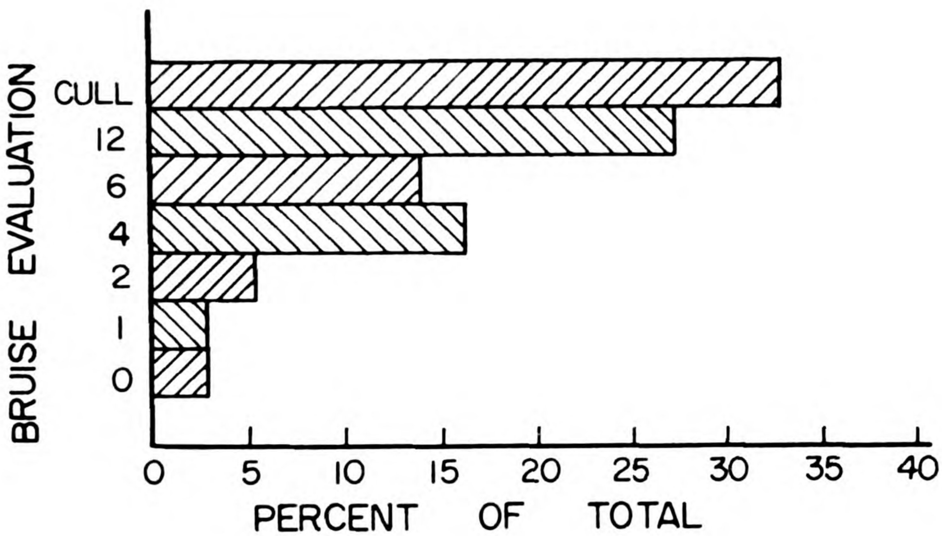

Figure 36. Percent of total apples (80) receiving bruises when shaken loose by hand and lowered pneumatically.

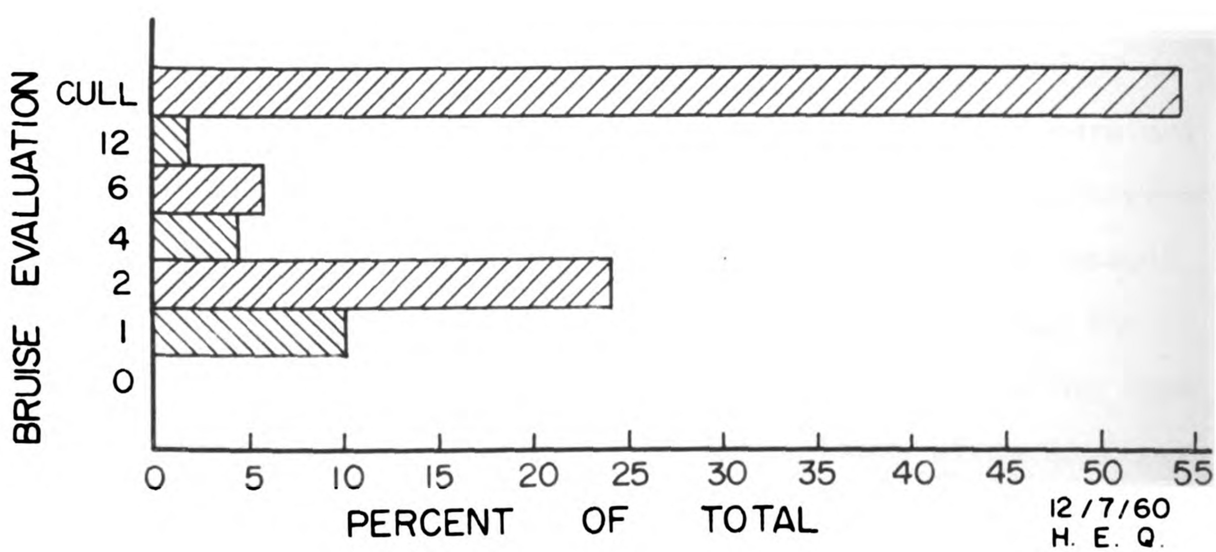

Figure 37. Percent of total apples (50) receiving bruises when dropped manually from various heights onto the machine with the fans not operating.

was present, 21.5 percent more fruit were contained in the "cull" category. The drop-test fruit (Figure 37) shows an increasing percentage of fruit occurring in bruise evaluations of 12 down to 2 while for the harvested fruit (Figure 36) the opposite was true.

This fact indicates that many of the apples harvested with the machine received an impact force of sufficient magnitude to only bruise the apples and not break the skin. The drop-test fruit received the entire impact force and as a result caused more skin breaks.

This comparison indicates that the air from the machine was capable of reducing the number of "cull" fruit, however, the remaining fruit contained considerable bruising and was not acceptable.

Comparison of the results given in Figures 36 and 37 is not completely justified since both samples of fruit were not harvested on the same date. The machine harvested fruit were harvested October 14 and the drop-test fruit were harvested October 19. Because of these different harvest dates, the drop-test fruit were more mature and softer, thus making them more susceptible to bruising. The percentages given in Figure 37, for fruit in each bruise category should be decreased to justify a comparison between Figures 36 and 37. The changes would probably be small and not affect the original comparison appreciably; therefore, this comparison is representative of the capabilities of this machine.

COST ANALYSIS

The economics of a pneumatic type fruit harvester were analyzed by a procedure given by Bainer, Kepner and Barger (1955) and are presented in this section. They stated that the total cost of performing a field operation includes charges for the machine, for the power utilized, and for labor. These costs are grouped under the headings of overhead costs and operating costs. Overhead costs include depreciation, interest on investment, taxes, insurance, and shelter. Operating costs include repairs, maintenance, lubrication, fuel and oil, and labor. Numerous assumptions were necessary for this analysis. They were based upon material given by Bainer, Kepner and Barger and material pertaining to semi-dwarf apples. The assumptions made are as follows:

(1) A pneumatic fruit harvester would have a service life of five years.

(2) There would be no salvage value.

(3) An acre contains 86 trees (semi-dwarf type).

(4) Each tree would require three minutes to harvest.

(5) The harvest season would be of 35 days duration.

(6) The harvester would operate ten hours per day.

(7) Fuel consumption would be 8.5 horsepower-hour per gallon.

(8) The horsepower requirement would be 1,000 and would

be utilized one-half of the total time.

(9) Field efficiency would be 60 percent.

(10) The initial cost of a machine would be $15,000.

(11) Interest on investment would amount to six percent.

(12) Fuel would cost $0.20 per gallon.

(13) Repairs, maintenance and lubrication would amount to 3.4 percent of the initial cost.

(14) Taxes insurance and shelter would amount to 1.5 percent of the initial cost.

(15) The cost of oil would be three precent of the fuel cost.

(16) Labor would cost $2.00 per hour and three men would be employed.

(17) Hand harvest would cost 14.2 cents per 40 pounds of apples.

(18) A acre of semi-dwarf apple trees would yield 1,000 bushels of apples.

(19) A bushel of apples weigh 50 pounds.

(20) The price received per bushel of apples would be $1.50.

The following values were computed with data from the assumptions:

Yield per tree = 11.6 bushels

Field capacity = 0.140 acres per hour

Annual use = 350 hours

Total acreage per year = 49

The annual overhead charges are:

Depreciation $\frac{(15,000 - 0)}{5}$	=	\$3,000.00
Interest $0.06 \frac{(15,000 + 0)}{2}$	=	450.00
Taxes, insurance, and shelter 0.015 (15,000)	=	225.00
Total annual overhead charge		\$3,675.00

The costs per acre are:

Overhead	$\frac{3,675.00}{49}$	=	\$ 75.00
Repairs, maintenance and lubrication	$\frac{0.034(15,000)}{49}$	=	10.04
Fuel, 8.5 hp-hr/gal.		=	84.00
Labor, 3 men @ \$2.00/hour		=	42.80
Oil cost (0.03) (84.00)		=	2.52
Total cost per acre			\$214.36

Thus the mechanical harvesting costs are given by this analysis as \$214.36 per acre.

The annual cost for hand harvesting would be equal to

$$\frac{\$0.142}{40 \text{ lb.}} \times \frac{50 \text{ lb.}}{\text{bu.}} \times \frac{86 \text{ trees}}{\text{acre}} \times \frac{11.6 \text{ bu.}}{\text{tree}}$$

$= \$177.00$ per acre

The value received by the grower for his apple crop would be equal to

$$\frac{86 \text{ trees}}{\text{acre}} \times \frac{11.6 \text{ bu.}}{\text{tree}} \times \frac{\$1.50}{\text{bu.}}$$

$= \$1,500.00$ per acre

The harvest costs expressed as a percent of the total value received per acre are given as follows:

(1) Mechanical harvesting:

$$\% = \frac{214.36}{1{,}500}(100) = 14.3$$ when three men are utilized.

(2) Hand harvesting:

$$\% = \frac{177}{1{,}500}(100) = 11.8$$

Comparison of harvesting costs for the conditions assumed indicate that harvesting apples with a pneumatic harvester would cost 2.5 percent more than hand harvesting. Even though the results of this analysis do not favor pneumatic fruit harvesting, the cost analysis has disclosed that a pneumatic fruit harvester may be economically feasible. With a few improvements, mainly in overhead and fuel consumption, mechanical harvesting costs could possibly be reduced below hand harvesting costs to make pneumatic fruit harvesting practical for commercial use.

CONCLUSIONS

The conclusions derived from this study may be stated as follows:

(1) An air column moving at a velocity very nearly equal to the terminal velocity of the fruit is necessary for pneumatic harvesting to be effective. It was found that an air velocity of 6,500 feet per minute reduced the impact force received from a drop of five feet to a value equivalent to that obtained from a drop in still air of 4.2-inches for an apple, and three inches for a peach.

An air velocity of 5,500 feet per minute gave an impact force for a drop of five feet equivalent to a drop of 1.8-inches in still air for an apricot.

An air velocity of 5,000 feet per minute gave an impact force for a drop of five feet equivalent to a drop of 2.04-inches in still air for a plum.

These velocities ranged from 750 to 1,580 feet per minute below the theoretical terminal velocities of these fruits.

(2) A greater air velocity is needed to float heavier fruit than is needed to float lighter fruit of the same species because the ratio (W/A) increases for heavier fruit (Equation 4).

(3) Fans capable of supplying air at a velocity greater than the velocity needed to effectively lower the fruit are necessary to overcome head losses. A survey of fan companies indicated that fans of this size are not readily available and would probably require special design.

(4) Horsepower requirements for fans capable of providing the terminal velocities discussed in the manuscript were found to be large. This means that the initial cost of a machine of this type, covering the complete tree, would be large; therefore, high efficiency would be a necessary requirement.

(5) A theoretical cost analysis indicated that a pneumatic fruit harvester for apples has possibilities of being economically justified on a cost per acre basis.

RECOMMENDATIONS FOR FUTURE STUDY

1. Further study would be advisable to determine if fans other than propeller fans could be used for harvesting fruit with air.
2. An investigation, made with the Magness-Taylor pressure tester to determine what value it may have toward handling techniques used in harvesting fruit, is suggested.
3. It is suggested that a study be conducted to determine fruit velocities when falling in an air stream and relate these by an equation to impact forces. With this information, an exact air velocity could be computed which would lower various species and varieties of fruit effectively.
4. The conclusions from this study indicated that it would be desirable to decrease the air velocities needed to float various species of fruit. Based on this fact, the recommendation is made that the possibility of coating the fruit with a lightweight material should be investigated. Since terminal velocity is dependent upon the square root of the ratio of fruit weight to projected area (Equation 4), it is evident that if this ratio can be decreased the terminal velocity will decrease. The material should have a low density and add considerable bulk to the fruit to provide a large projected area. It

should be non-toxic, easy to apply and remove and possess enough rigidity to withstand the required air velocity. A material of this nature would also greatly reduce chances of damage occurring to fruit from impact forces while falling. A foam material, produced by Dow Chemical Company, used to spray on plants for frost protection was investigated by the author for use on fruit. A letter from Dow Chemical indicated that this material was undesirable. The letter also stated that most of their products meeting these specifications would be toxic to the fruit and, therefore, could not offer a product of this nature.

5. Another recommendation involves a method of harvesting fruit with flexible fingers. This method would employ a multiplicity of slender rods mounted very closely together on a single frame. The rods would be of sufficient length to protrude into the branch area to the center of the tree. With the fruit positioned among the rods, the tree would be shaken to loosen the fruit and allow it to fall to the rods to be caught from only a two or three inch fall. A slight tilt to the rods and possibly some vibration would cause the fruit to slide toward the rod mountings where they could be deposited in a storage container.

SUMMARY

Samples of 50 fruits each were obtained for various species and varieties of tree fruits. Basic data for diameters, weights, firmness and forces to remove the fruit from the tree were recorded.

An air duct was constructed and used in the laboratory to determine the effect of a high velocity air stream in reducing impact forces received to fruit from a fall.

A theoretical analysis was made for a particle in an air stream. The analysis provided information regarding the terminal velocities of the fruit and horsepower requirements for the required volume flow rate of air.

Using the information obtained from the laboratory tests and theoretical analysis, a field machine was constructed and tested on a Jonathan apple tree.

A correlation and regression analysis of data obtained from the various species and varieties of fruit indicated a high degree of association between fruit weight and the ratio of fruit weight to projected area. A correlation analysis, conducted for Red Haven peaches and McIntosh apples, for the fruit weight and force required to remove the fruit from the tree indicated a definite association did not exist between these variables. Also, graphs of fruit weight versus force to remove the fruit from the tree for each species gave very

little indication of any relationship existing. It was concluded from the scatter of points on the graphs that other factors were present and probably the most predominant one was maturity of the fruit.

The theoretical analysis indicated that horsepower requirements to move air at a velocity of 7,000 feet per minute through a 15-foot diameter duct would be 992 if the efficiency of the fan was 60 percent. Additional horsepower would be required to overcome head loss from the duct system and turbulence. The reduction in velocity due to turbulence and harvester design for the field machine constructed in this study was 27.2 percent.

The laboratory tests with various species of fruit indicated that air velocities very nearly equal to the terminal velocities of fruit are necessary to appreciably reduce impact forces occurring to falling fruit. Terminal velocities for large fruit such as apples and peaches were calculated to be in the range of 7,000 to 8,000 feet per minute while for smaller fruit the range was from 3,400 to 7,000 feet per minute. These velocities are theoretical and were based on assumptions.

Tests conducted with the field machine indicated that an air velocity of 3,020 feet per minute was not effective for Jonathan apples. The number of apples with skin breaks was reduced considerably as compared with still air conditions on the machine, however, a majority of the apples received large bruises that were undesirable.

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APPENDICES

APPENDIX I

Figures 3 through 10 are presented in this section. The reader is cautioned that the regression lines presented on the following graphs have not been computed by established methods, but have been estimated.

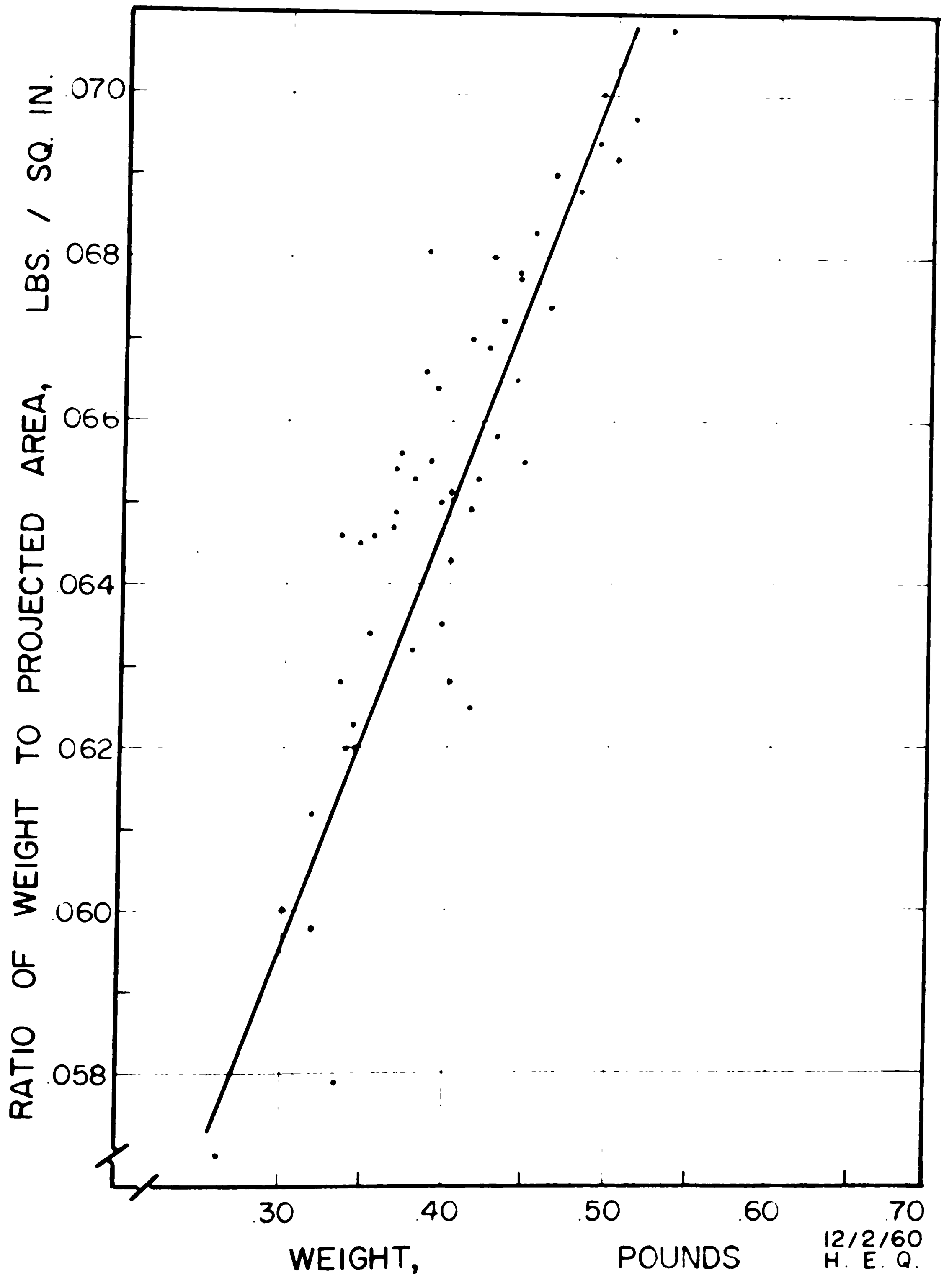


Figure 3. Relation between weight and projected area for Northern Spy apples.

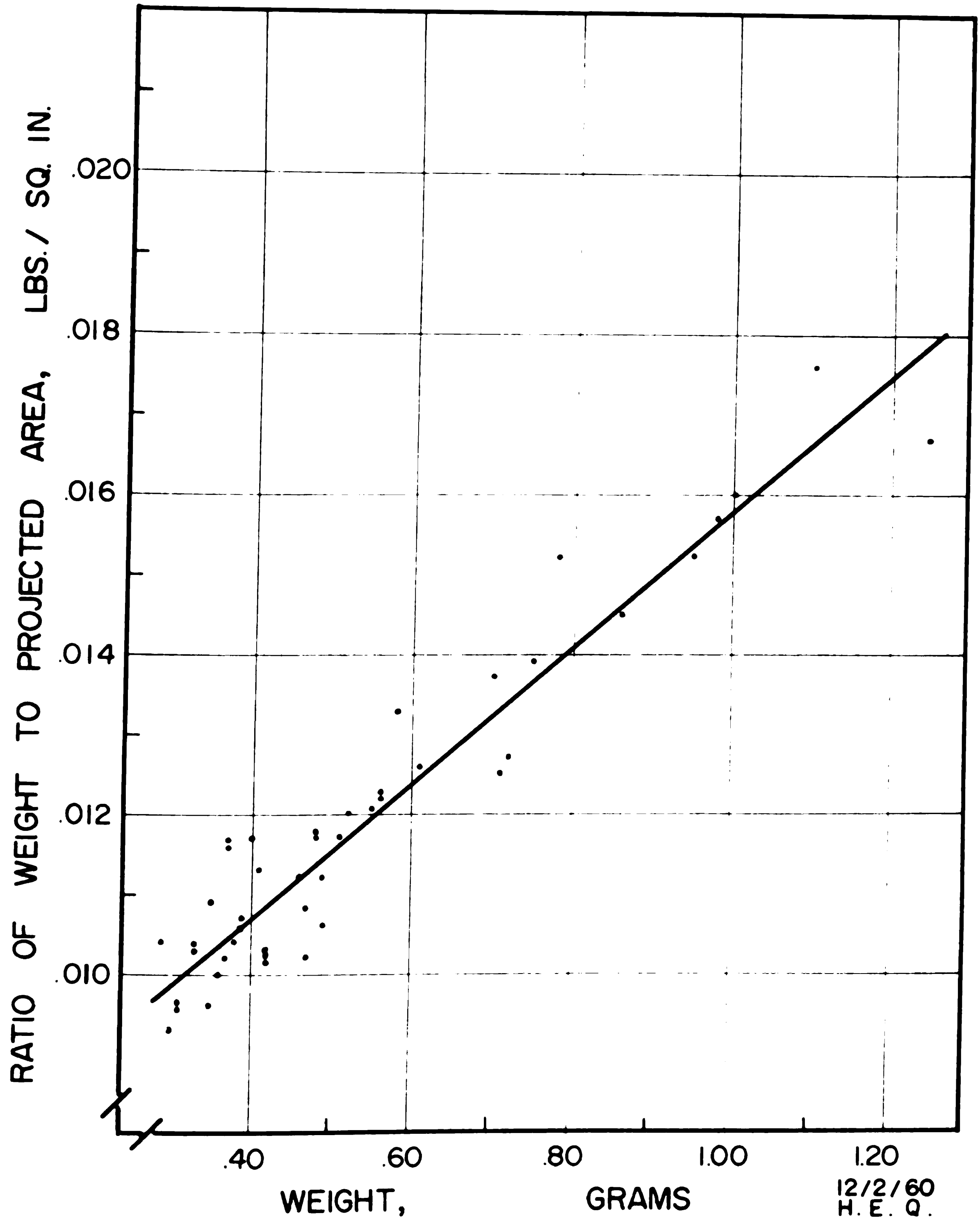


Figure 4. Relation between weight and projected area for Jersey blueberries.

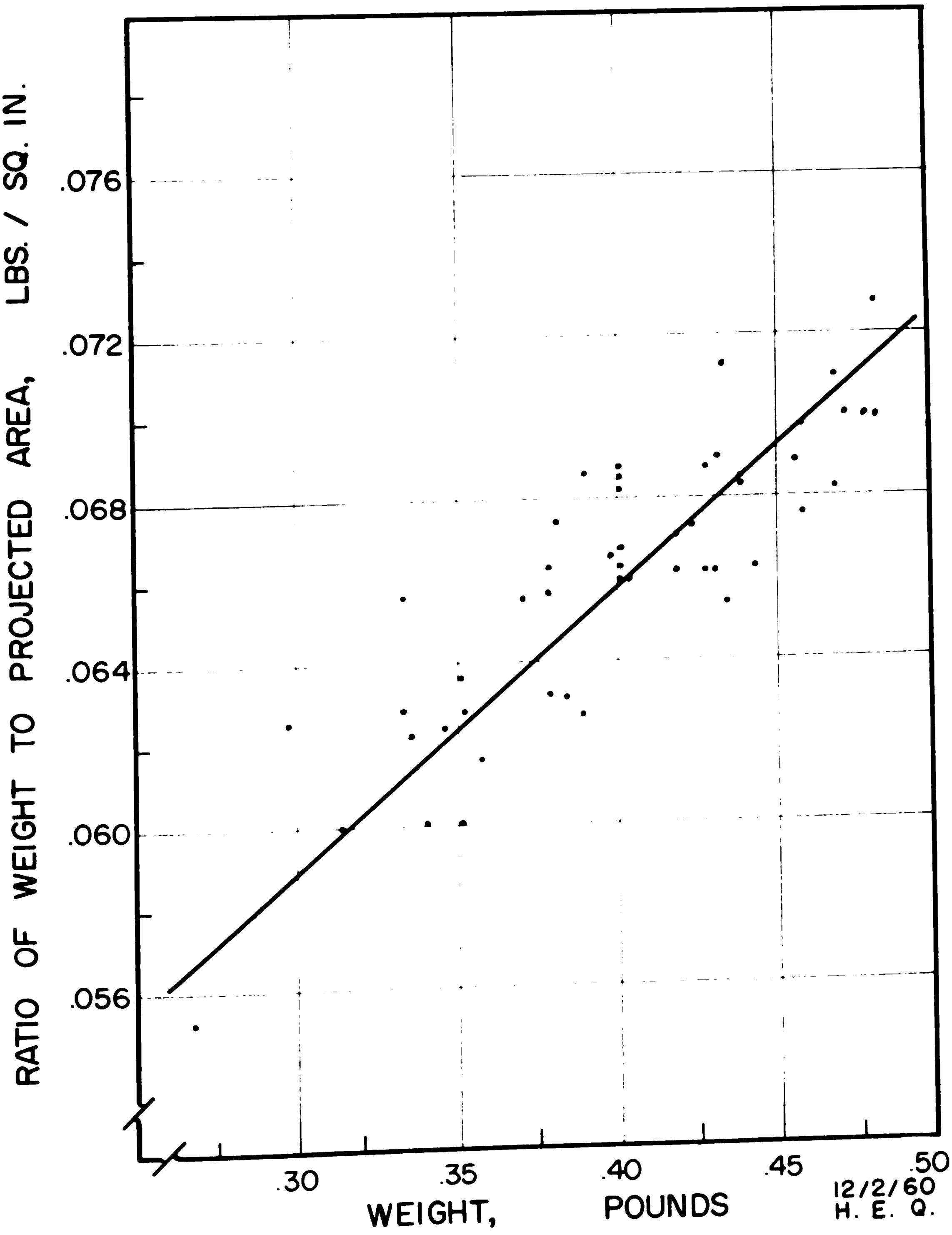


Figure 5. Relation between weight and projected area for Elberta peaches.

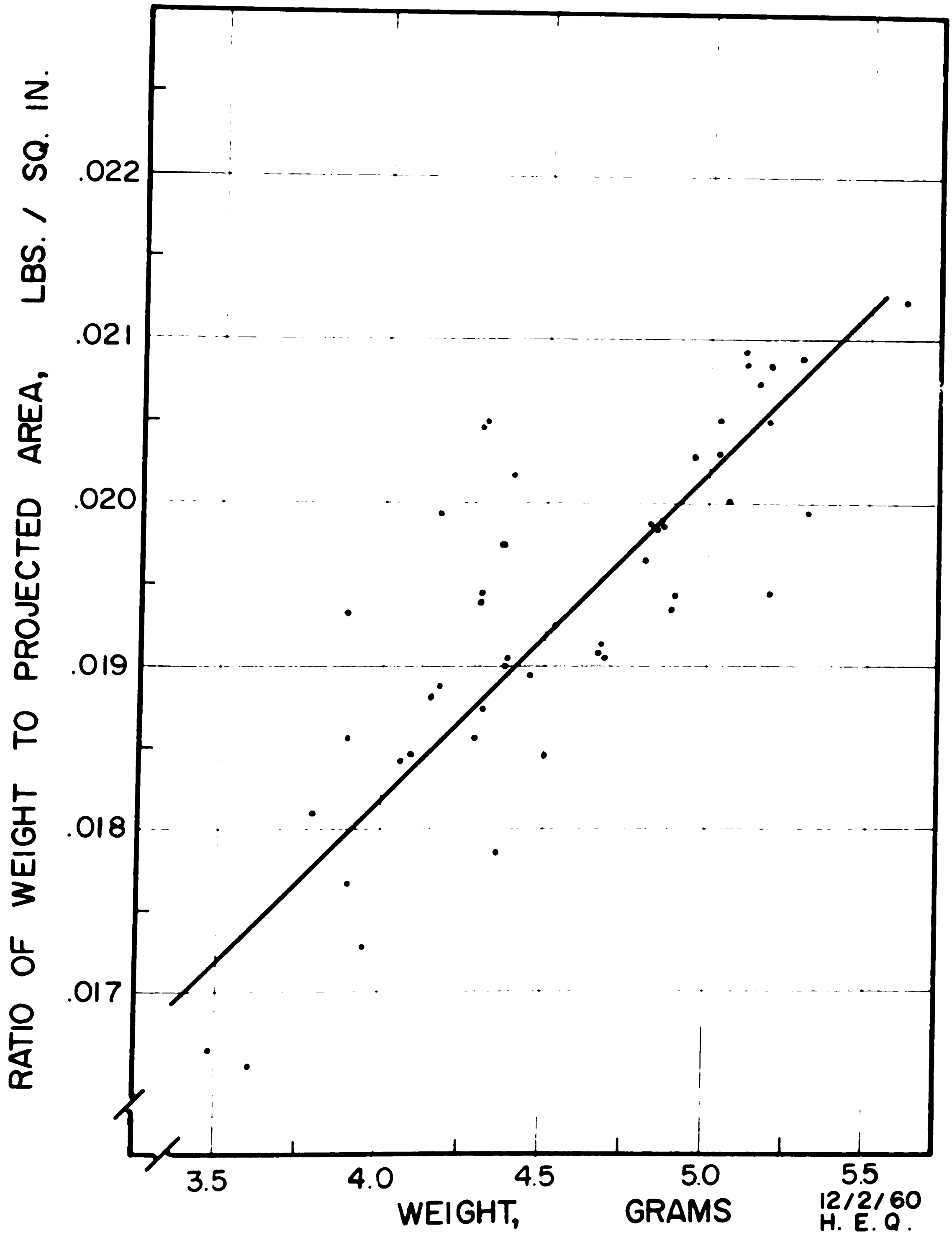


Figure 6. Relation between weight and projected area for Montmorency cherries.

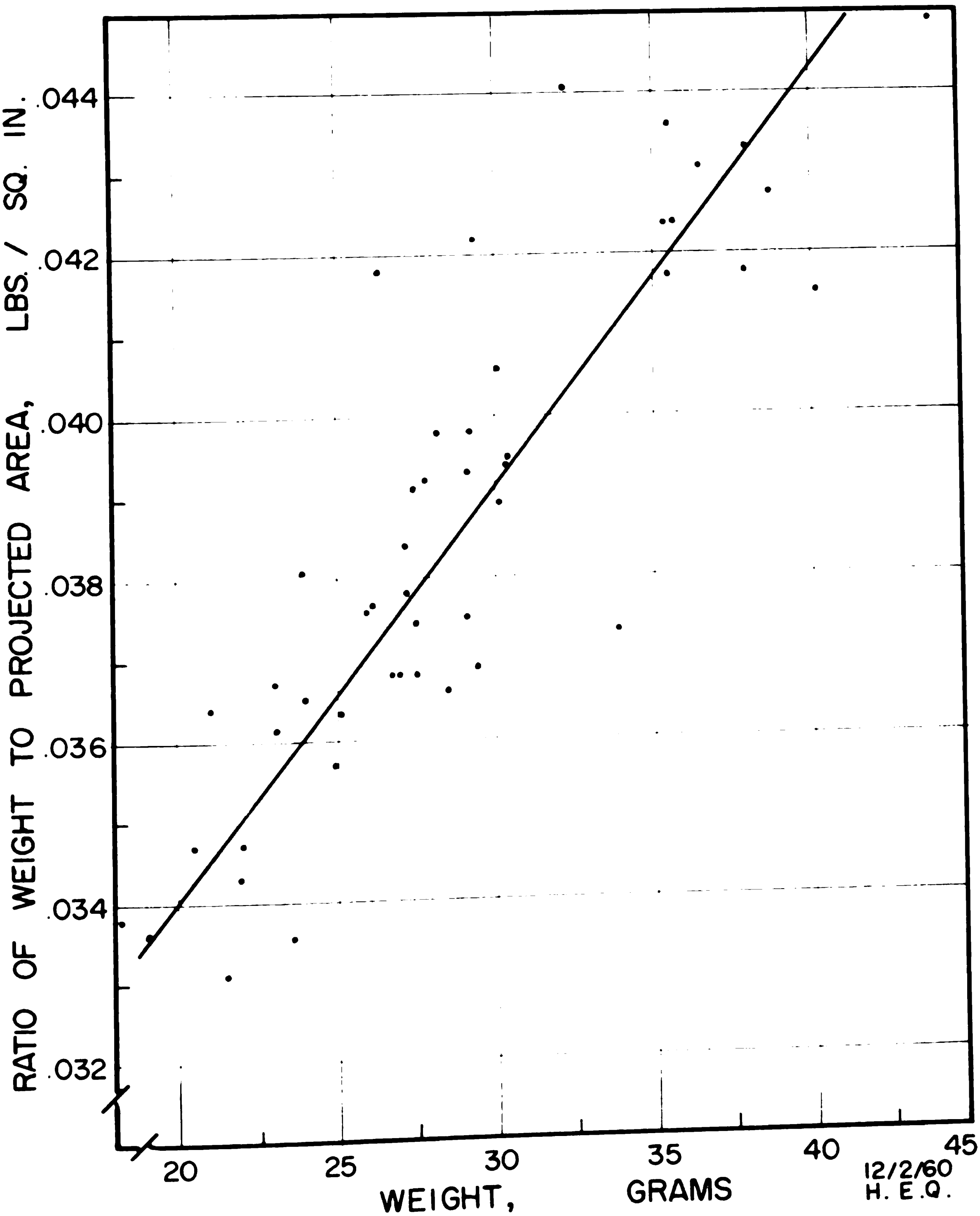


Figure 7. Relation between weight and projected area for Montgamet apricots.

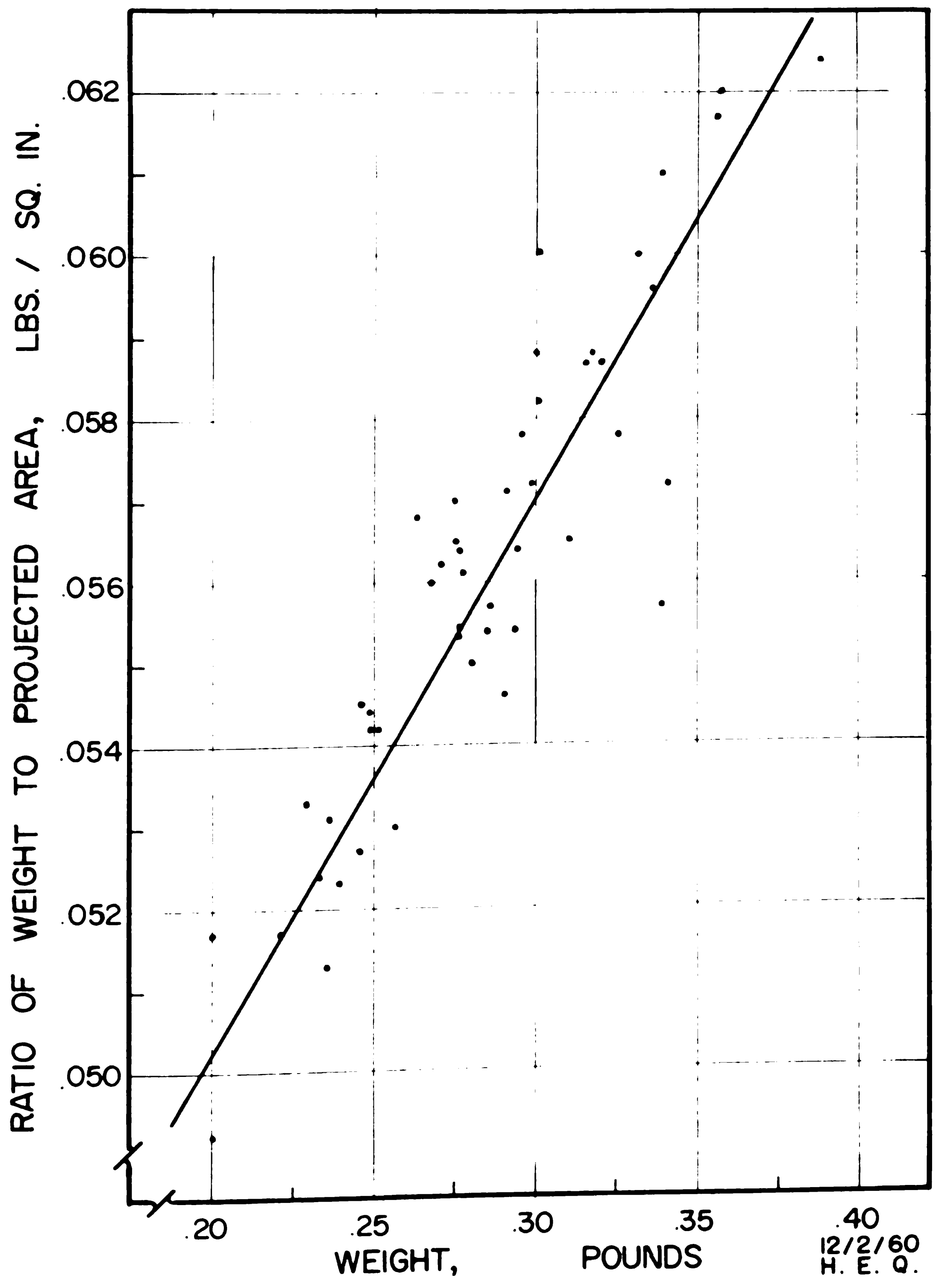


Figure 8. Relation between weight and projected area for Jonathan apples.

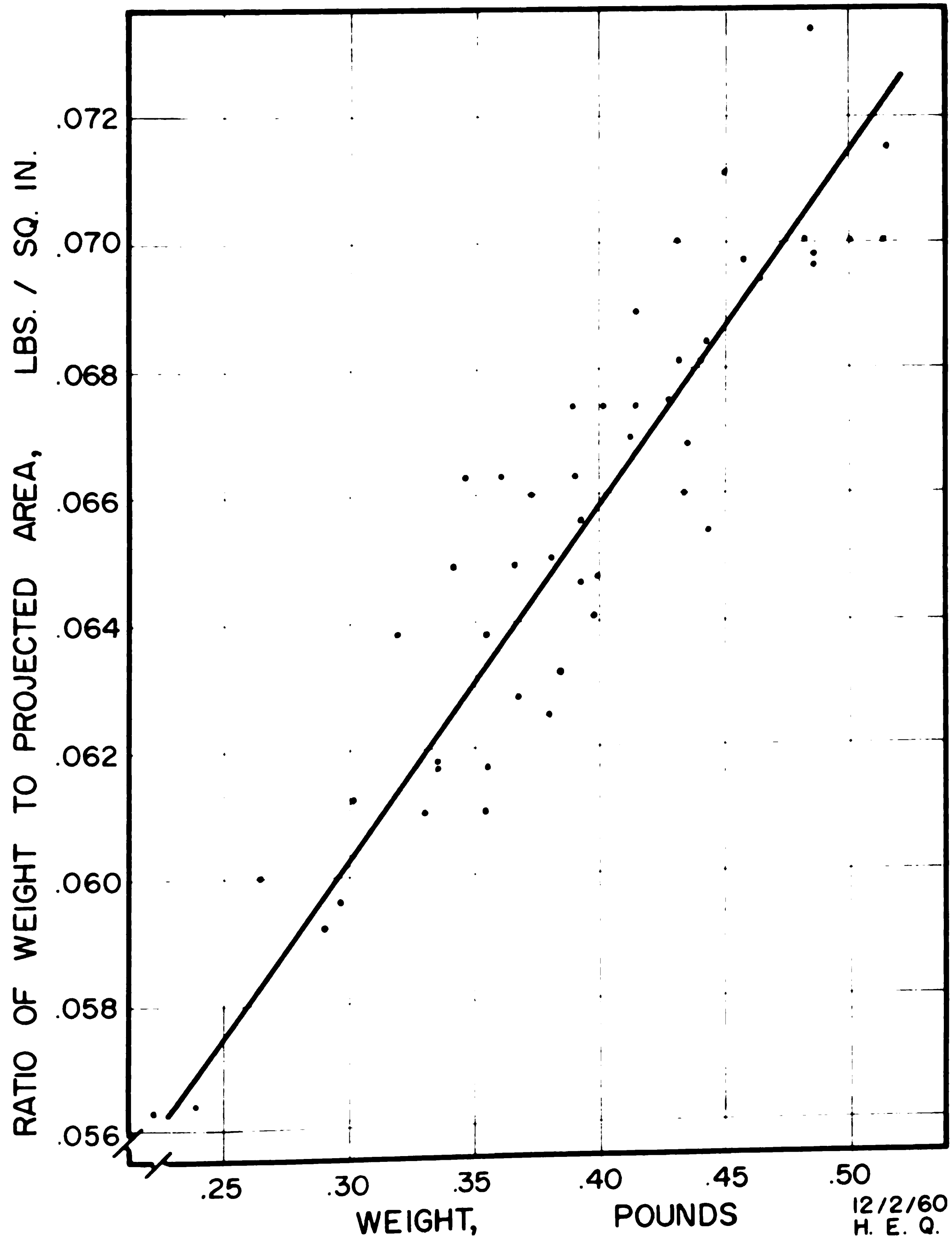


Figure 9. Relation between weight and projected area for Cortland apples.

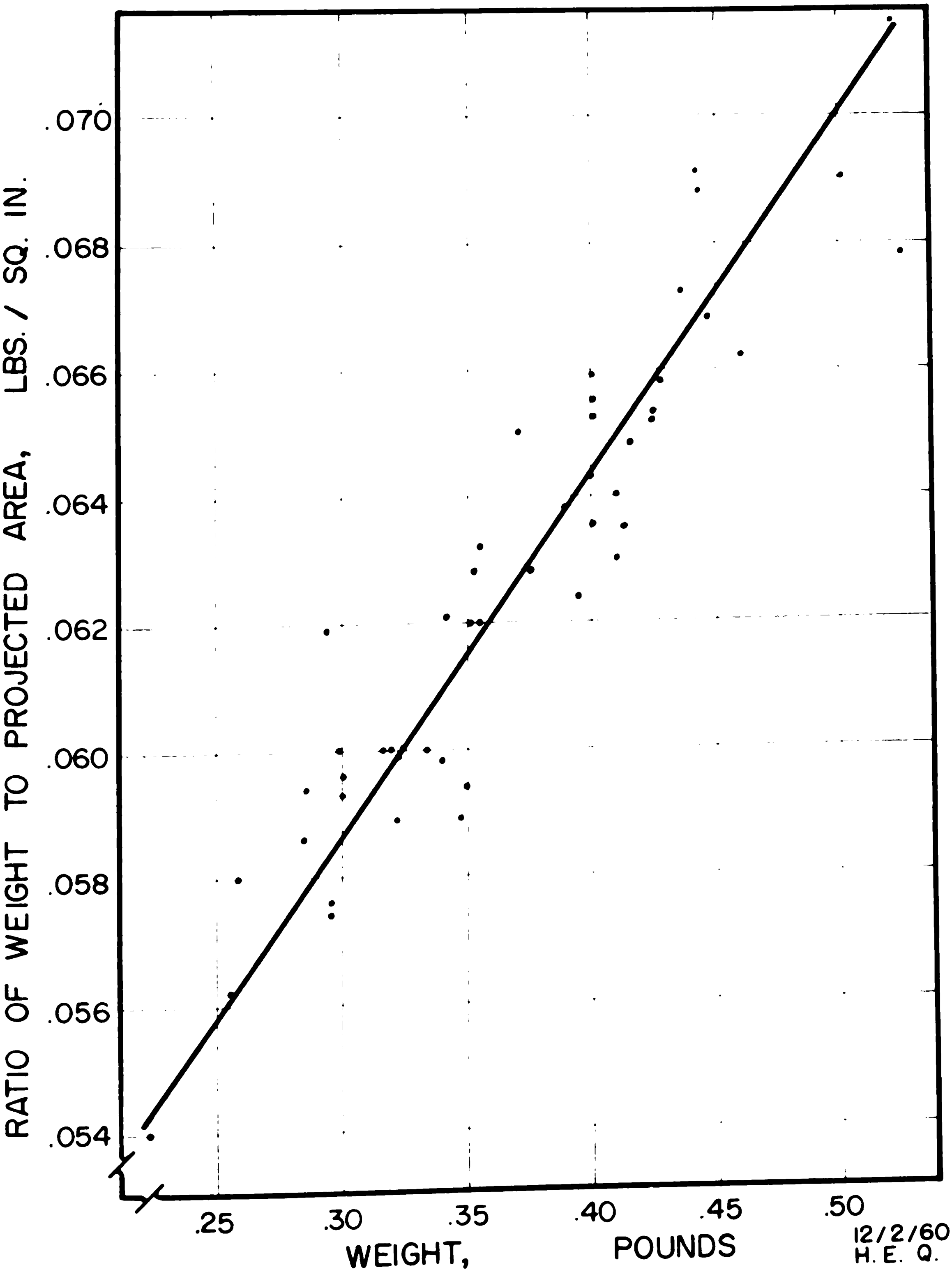


Figure 10. Relation between weight and projected area for McIntosh apples.

APPENDIX II

The regression and correlation analyses for Figures 1 and 2 are presented as follows:

Let: y = ratio of weight per projected area

x = weight of the fruit.

The regression analysis using the symbols above consists of finding the regression of "y on x." The following equations are solved simultaneously to obtain the regression line.

$$\Sigma y = Na + b\ \Sigma x \qquad (11)$$

$$\Sigma xy = a\ \Sigma x + b\ \Sigma x^2 \qquad (12)$$

where:

a = the intercept on y-axis

b = slope of the regression line

N = number in sample

The correlation coefficient is given by the formula

$$r = \frac{P}{\sigma_x\ \sigma_y} \qquad -1 < r < 1 \qquad (13)$$

where:

$$P = \frac{\Sigma xy}{N} - \left(\frac{\Sigma x}{N}\right)\left(\frac{\Sigma y}{N}\right)$$

$$\sigma_x = \sqrt{\frac{\Sigma x^2}{N} - \left(\frac{\Sigma x}{N}\right)^2}$$ Standard deviation in x-direction

$$\sigma_y = \sqrt{\frac{\Sigma y^2}{N} - \left(\frac{\Sigma y}{N}\right)^2}$$ Standard deviation in y-direction

The following information was computed from the original data which is on file with Dr. B. A. Stout.

For plums (Figure 1):

$$\sum x = 1761.59$$

$$\sum y = 1.9602$$

$$\sum xy = 69.5217$$

$$\sum x^2 = 63{,}574.08$$

$$\sum y^2 = 0.077044$$

$$N = 50$$

For peaches (Figure 2):

$$\sum x = 19.928$$

$$\sum y = 3.2568$$

$$\sum xy = 1.3263$$

$$\sum x^2 = 8.4721$$

$$\sum y^2 = 0.213647$$

$$N = 50$$

The computations for plums (Figure 1) are:

$$\sigma_x = \sqrt{\frac{\sum x^2}{N} - \left(\frac{\sum x}{N}\right)^2} = \sqrt{\frac{63{,}574.08}{50} - \left(\frac{1761.59}{50}\right)^2}$$

$$= 5.5$$

$$\sigma_y = \sqrt{\frac{\sum y^2}{N} - \left(\frac{\sum y}{N}\right)^2} = \sqrt{\frac{0.077044}{50} - \left(\frac{1.9602}{50}\right)^2}$$

$$= 0.00198$$

$$P = \frac{\sum xy}{N} - \left(\frac{\sum x}{N}\right)\left(\frac{\sum y}{N}\right) = \frac{69.5217}{50} - \left(\frac{1761.59}{50}\right)\left(\frac{1.9602}{50}\right)$$

$$= 0.00921$$

$$r = \frac{P}{\sigma_x\ \sigma_y} = \frac{0.00921}{(5.5)(0.00921)} = 0.844^{**}$$

Substituting values into equations (11) and (12) gives

$$1.9602 = 50\ a + 1761.59\ b \tag{14}$$

$$69.5217 = 1761.59\ a + 63{,}574.08\ b \tag{15}$$

Multiplying equation (14) by 1,761.59 and equation (15) by minus 50, then adding these equations algebraically gives

$$-23.00 = -75,505.67\ b$$

$$b = \frac{23.00}{75,505.67} = 0.000304$$

Substituting the value of (b) into equation (14) gives

$$1.9602 = 50\ a + 1761.59\ (0.000304)$$

$$50\ a = 1.9602 - 0.5355$$

$$a = \frac{1.4247}{50}$$

$$= 0.0285$$

The equation of the regression line for Figure 1 is

$$y = 0.0285 + 0.000304\ (x)$$

To establish the limits of this equation, the standard error of estimate (S_e) was calculated as follows:

$$S_e = \sqrt{\frac{\Sigma y^2 - a\Sigma y - b\Sigma xy}{N-2}}$$

Substituting values into this equation gives

$$S_e = \sqrt{\frac{0.0770440 - 0.0285(1.9602) - 0.000304(69.5217)}{50 - 2}}$$

$$= 0.000954$$

The final equation of the regression line is given as follows:

$$\hat{y} = 0.0285 + 0.000304\ (x) \pm 0.000954 \qquad (16)$$

where:

$\hat{y}$ = an estimate of y

The computations for peaches (Figure 2) are:

$$\sigma_x = \sqrt{\frac{\Sigma x^2}{N} - \left(\frac{\Sigma x}{N}\right)^2} = \sqrt{\frac{8.4721}{50} - \left(\frac{19.928}{50}\right)^2}$$

$$= 0.1029$$

$$\sigma_y = \sqrt{\frac{\Sigma y^2}{N} - \left(\frac{\Sigma y}{N}\right)^2} = \sqrt{\frac{0.2136470}{50} - \left(\frac{3.2568}{50}\right)^2}$$

$$= 0.00552$$

$$P = \frac{\Sigma xy}{N} - \left(\frac{\Sigma x}{N}\right)\left(\frac{\Sigma y}{N}\right) = \frac{1.32633}{50} - \left(\frac{19.928}{50}\right)\left(\frac{3.2568}{50}\right)$$

$$= 0.000566$$

$$r = \frac{P}{\sigma x \; \sigma y} = \frac{0.000566}{(0.1029)(0.00552)} = 0.995^{**}$$

Substituting values into equations 11 and 12 **gives**

$$3.2568 = 50\ a + 19.928\ b \qquad (17)$$

$$1.3263 = 19.928\ a + 8.4721\ b \qquad (18)$$

Multiplying equation (17) by 19.928 and equation (18) by minus 50, then adding these equations algebraically gives

$$-\ 1.4135 = -\ 26.4798\ b$$

$$b = \frac{1.4135}{26.4798} = 0.0534$$

Substituting the value of (b) into equation (17) gives

$$3.2568 = 50\ a + 19.928\ (0.0534)$$

$$50\ a = 3.2568 - 1.0638$$

$$a = \frac{2.1930}{50}$$

$$a = 0.0438$$

The equation of the regression line for Figure 2 is

$$y = 0.0438 + 0.0534\ (x)$$

To establish the limits of this equation, the standard error of estimate (S_e) was calculated as follows:

$$S_e = \sqrt{\frac{\Sigma y^2 - a\Sigma y - b\Sigma xy}{N - 2}}$$

Substituting values into this equation gives

$$S_e = \sqrt{\frac{0.213647 - 0.0438(3.2568) - 0.05338(1.3263)}{N - 2}}$$

$$= 0.00205$$

The final equation of the regression line is given as follows:

$$\hat{y} = 0.0438 + 0.0534\ (x) \pm 0.00205 \qquad (19)$$

where:

$\hat{y}$ = an estimate of y

APPENDIX III

Figures 11 and 12 and a correlation analyses for these data are presented in this section.

The regression of "force to remove fruit from the tree on weight of fruit" was investigated by letting

y = force to remove the fruit from the tree

and x = weight of the fruit

The following values were obtained from the data collected on these samples.

For McIntosh apples (Figure 11)

$$\sum x = 18.539$$

$$\sum y = 224.0$$

$$\sum xy = 81.169$$

$$\sum x^2 = 7.1121$$

$$\sum y^2 = 1,118.50$$

For Red Haven peaches (Figure 12)

$$\sum x = 19.928$$

$$\sum y = 301.50$$

$$\sum xy = 119.554$$

$$\sum x^2 = 8.4721$$

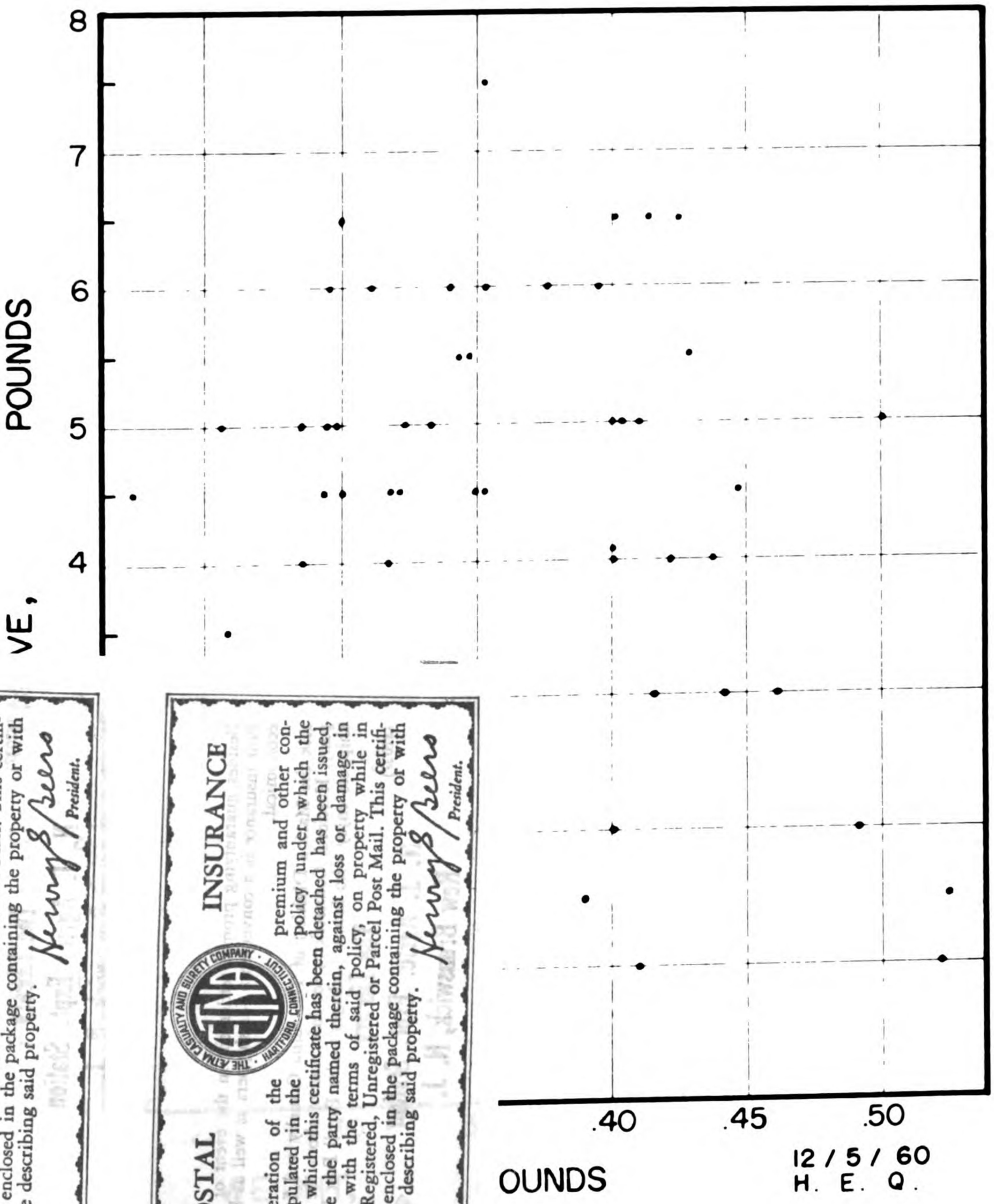
$$\sum y^2 = 2,000.25$$

For Figure 11:

The standard deviation in the x-direction is

$$\sigma_x = \sqrt{\frac{\sum x^2}{N} - \left(\frac{\sum x}{N}\right)^2} = \sqrt{\frac{7.1121}{50} - \left(\frac{18.539}{50}\right)^2}$$

$$= 0.069$$



...tween the weight and the force
...e McIntosh apples from the tree.

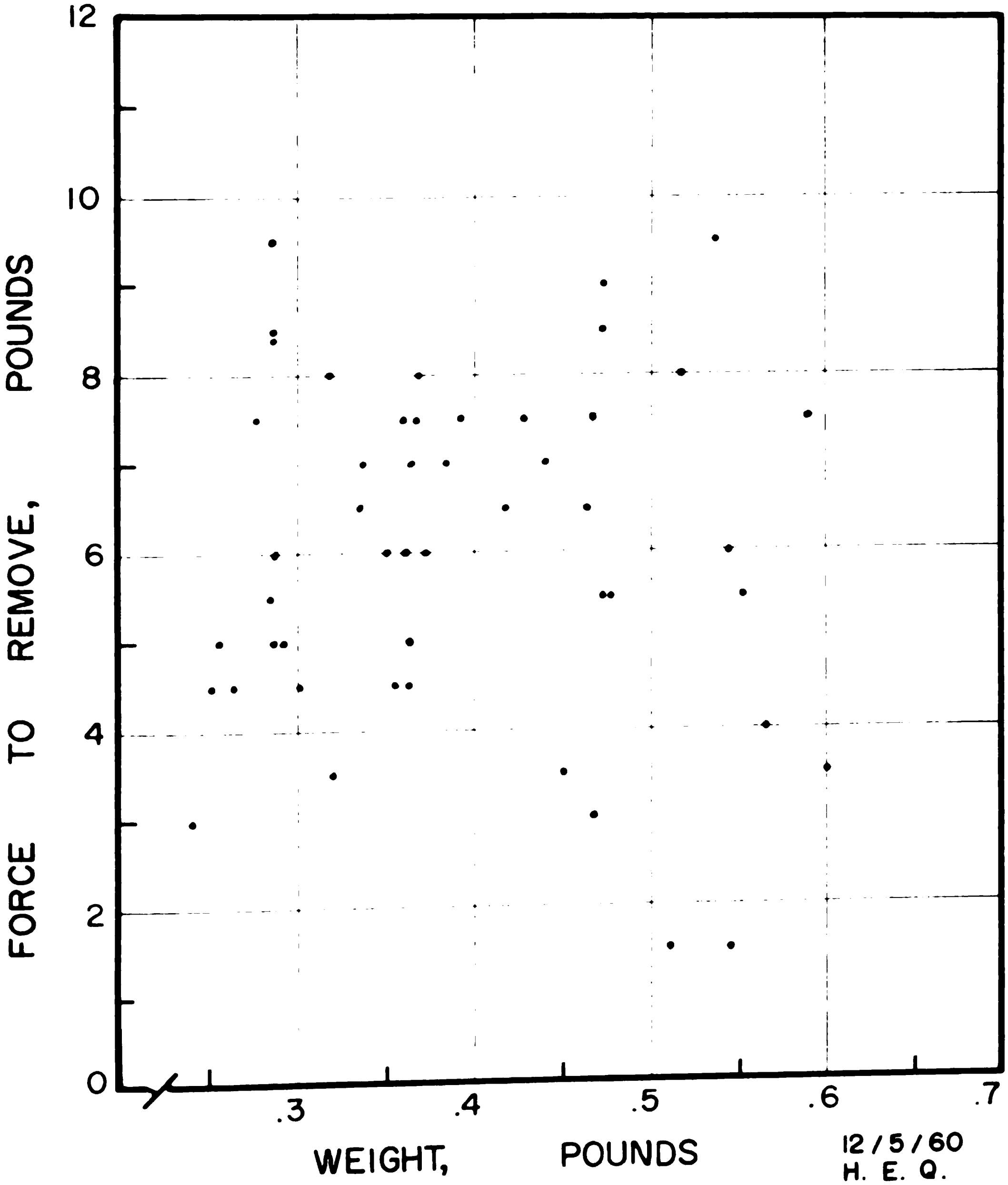


Figure 12. Relation between the weight and the force to remove Red Haven peaches from the tree.

The standard deviation in the y-direction is

$$\sigma_y = \sqrt{\frac{\Sigma y^2}{N} - \left(\frac{\Sigma y}{N}\right)^2} = \sqrt{\frac{1,118.50}{50} - \left(\frac{224}{50}\right)^2}$$

$$= 1.516$$

$$P = \frac{\Sigma xy}{N} - \left(\frac{\Sigma x}{N}\right)\left(\frac{\Sigma y}{N}\right) = \frac{81.169}{50} - \left(\frac{18.539}{50}\right)\left(\frac{224}{50}\right)$$

$$= -0.0377144$$

The correlation coefficient is

$$r = \frac{P}{\sigma_x \sigma_y} = \frac{-0.0377}{(0.069)(1.516)} = -0.3605$$

For Figure 12:

The standard deviation in the x-direction is

$$\sigma_x = \sqrt{\frac{\Sigma x^2}{N} - \left(\frac{\Sigma x}{N}\right)^2} = \sqrt{\frac{8.4721}{50} - \left(\frac{19.928}{50}\right)^2}$$

$$= 0.1029$$

The standard deviation in the y-direction is

$$\sigma_y = \sqrt{\frac{\Sigma y^2}{N} - \left(\frac{\Sigma y}{N}\right)^2} = \sqrt{\frac{2000.25}{50} - \left(\frac{301.50}{50}\right)^2}$$

$$= 1.91$$

$$P = \frac{\Sigma xy}{N} - \left(\frac{\Sigma x}{N}\right)\left(\frac{\Sigma y}{N}\right) = \frac{119.554}{50} - \left(\frac{19.928}{50}\right)\left(\frac{301.50}{50}\right)$$

$$= -0.0122368$$

The correlation coefficient is

$$r = \frac{P}{\sigma_x \sigma_y} = \frac{-0.0122}{(0.1029)(1.91)} = -0.0623$$

APPENDIX IV

Drop-test data for Jonathan and Northern Spy apple varieties are presented in Tables XI and XII below.

TABLE XI Number of Jonathan apples contained in each bruise category for various drops

Bruise Evaluation	6 - Inch Drop	1 - Foot Drop	2 - Foot Drop	3 - Foot Drop	4 - Foot Drop
0					
1	5				
2	5	6	1		
4			2		
6			1	2	
12			1		
cull		4	5	8	12

TABLE XII Number of Northern Spy apples contained in each bruise category for various drops

Bruise Evaluation	6 - Inch Drop	1 - Foot Drop	2 - Foot Drop	3 - Foot Drop	4 - Foot Drop
0					
1	2				
2	8	1			
4		5	1		
6		4	4	4	
12			2	1	2
cull			3	5	8