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Produce Damage Simulator-Detector

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Abstract

A damage detector system for assessing the protective qualities of fruit shipping containers was developed and tested. It utilizes the immediate increase in carbon dioxide (CO₂) production characteristic of physically injured apples and oranges that is measurable within 6 hours following damage treatment. The CO₂ response of apples bruised by impact or compression forces was consistent for fruit ages and cultivars and is caused by decarboxylation of malic acid spilled from damaged cells. Damage to oranges caused by all types of physical force yielded similarly useful CO₂ responses for the 3 cultivars tested. Response changes in ethylene production were less useful than CO₂ for damage assessment of apples and oranges, but probably more useful than CO₂ for tomatoes.

A produce damage simulator system was developed and tested, providing a means to simulate and quantify mechanical injury in storage and distribution, in relation to typical produce handling and transportation environments.

The damage simulator system is based on especially developed mathematical models, quantifying mechanical injury as related to the biomechanical properties of the fruit, material properties and geometrical configurations of packaging systems and unit loads, and the expected mechanical inputs in the handling and transportation chain, e.g. compression, shock and vibration.

The database for simulating shock and vibration was derived from two instrumented surveys of typical transport routes of apples and citrus fruit. The combination of the DAMAGE SIMULATOR and DAMAGE DETECTOR provides a useful tool to quantitatively measure and rate the damage potential of different produce handling and transport modes and the protective properties of produce packaging systems in large scale commercial produce shipments from the packinghouse to the supermarket shelf.

OBJECTIVES OF RESEARCH

The main objective of this project was to develop a PRODUCE DAMAGE SIMULATOR DETECTOR SYSTEM, providing a means to quantitatively measure and rate the protective properties of produce packaging systems in commercial handling and transportation environments. This main objective may be subdivided as follows:

1. Simulate and quantify mechanical injury in storage and distribution, in relation to transportation environments and degree of protection provided by packaging.
2. Develop means and procedures for the systematic and objective detection and measurement of physical damage of two selected types of produce, citrus fruit and apples.
3. Combine the damage simulator and detector into a commercially useful test procedure for transportation damage simulation and detection of large scale produce distribution systems, (citrus and apples).

The first two objectives were successfully attained in full. The third objective was achieved only partially, although all the information for its implementation is now available. The reasons for this are threefold :

- a. The budget granted was considerably reduced in comparison to the requested sum; required for the completion of the entire project.
- b. Various technical delays slowed down the progress of the project.
- c. The need to schedule activities according to the seasons of the two fruit types selected.

A formal request to BARD to extend the duration and budget of the project by another year was turned down. This is most unfortunate, since this precludes realization of the full benefits to agriculture. In view of the above and based on the overall success of the project as reported herein, it is strongly suggested that BARD reconsider its previous decision and grant an extension, in order to enable practical implementation of the results in the field.

Expression of thanks

The investigators would like to express their gratitude to all persons who cooperated and assisted in obtaining fruit samples and arranging the transportation environment surveys.

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DAMAGE DETECTOR FOR FRUIT

Introduction

Several objective methods for readily identifying and evaluating physical damage to fresh fruit were suggested in the literature. One possibility was to electronically observe the physical symptoms of injury by scanning the fruit with infrared sensors (Danno et al., 1978); another was to measure aberrations in the gas exchange pattern of the product, particularly of carbon dioxide which is a normal respiratory product of living plant tissue (Eaks, 1961).

Preliminary trials indicated that infrared scanning offered little potential for achieving the needs of the project. Utilizing human medicine techniques and equipment¹, the infrared scanning of severely bruised apples and pears yielded negative results. Slight imaging of damaged areas was observed for fresh skin abrasions in pears, possibly a result of the cooling effect of water evaporating from the skinned areas. A possible heating effect at the site of damaged tissues due to increased respiratory activity was not detected. Other reported electronic scanning procedures (Brown, et al., 1974) were considered to be inappropriate.

Initial trials showed that an increase in carbon dioxide (CO₂) evolution was indicative that tissue damage could be readily and accurately measured by gas chromatography (GC) procedures. Likewise, a similar response in ethylene (C₂H₄) emanations following damage was evident. The identification of other volatiles emitted by physically damaged apple and tomato fruits utilizing various GC columns and a coupled GC-mass spectrometer was inconclusive. Research on the development of a detector system based on gaseous emanations was directed to:

1. quantifying the CO₂ and C₂H₄ responses of apples, oranges, and tomatoes to various types and degrees of physical injury;
2. describing the physiological nature and the factors affecting the CO₂ and C₂H₄ responses by apples;
3. examining procedures for measuring the gaseous response of fruit within shipping containers; and
4. developing a detector system that would provide a simple, standard means for evaluating the protective characteristics of shipping containers.

¹Courtesy of Mr. Phillip Hoekstra, Thermoscan, Inc. 21503 Harper Avenue, St. Clair Shores, MI 48080, U.S.A.

Methodology: Index of Damage Response

The change in production of CO_2 and C_2H_4 due to physical damage can be expressed as index values based on an appropriate control treatment of non-damaged fruit. Several methods of expression were examined.

1. Quotient of post-treatment rate of gas output for treated fruit divided by post-treatment rate for nontreated fruit, with the latter fruit handled in a comparable manner to the treated fruit except for the application of the injury under study. The nontreated has an index value of 1.00.
2. Quotient of the increase in the rate due to damage obtained by a pre-treatment reading subtracted from the post-treatment reading of the same sample, divided by the increase for the nontreated sample. The nontreated fruit has an index value of 1.00.
3. Quotient of the post-treatment rate of a sample (either treated or nontreated) divided by the pre-treatment rate of that particular sample or group of samples. The nontreated fruit has an index value above or below unity depending upon whether or not the post-treatment rate is greater or smaller than the pre-treatment rate.

A comparison of the index values obtained for four cultivars (cv.) of apples damaged by impact forces are given in Table 1. The three methods provided values considerably different in magnitude, yet consistent in trend, for expressing the effects of the damage responsible for increases in CO_2 production. Methods 1 and 2 give a base of unity for the nontreated or control fruit and thereby provide a more readily perceived concept of the effect of damage to the fruit. The greater magnitude of the index obtained by method 2 using the change in rate, provides emphasis on the role of the degree of damage. Method 3, giving the total response of a treatment relative to its pretreatment production, provides values for comparison, but the effects are not readily perceived because of the variable base values for the nontreated controls.

A valid assessment of the damage response by gas production is probably most likely for methods 2 and 3 because it is a measurement of the change due to damage for a specific sample, whereas with method 1, a comparative change is obtained by using a corresponding control treatment. There are limitations of methods 2 and 3 in that there may be a carry-over effect from the pre-treatment holding period while the fruit is sealed within the gas accumulation chamber and during the subsequent aeration period required for the fruit to equilibrate to the ambient atmosphere. The cause for the consistent increase in CO_2 rate for the post-treatment period over the pre-treatment period was not determined.

The simplicity and expediency of method 1 suggested its use for expressing the findings of a detector system. This method is used throughout this report for comparison of damage responses.

Tissue damage in bruised apples. Oxidative browning of apple fruit tissue damaged by impact bruising enables quantitative measurement of the damage 24 to 48 hours after injury. The data of Table 2 show that dropping fruit from a height of 50 and 100 cm onto a hard surface increases CO₂ evolution of the whole fruit, the area of the bruise measured at the surface of the fruit, and the weight of the bruised cortex tissue excised from the fruit excluding the epidermal tissues. Since the relative increases were no greater for CO₂ than for the bruised area or weight of tissue it was apparent that impacts affected the CO₂ production of the damaged tissue rather than the whole fruit. This was studied extensively by Klein (thesis, 1983) with the conclusion that the CO₂ increase resulted from decarboxylation of the malic acid spilled from the ruptured cells at the site of the bruise. *

A manuscript by Klein and Dewey (copy attached) submitted for publication in the Journal of the American Society for Horticultural Science presents evidence that:

- (a) The CO₂ evolved is positively correlated to drop height.
- (b) A greater number of drop impacts increases CO₂ evolution.
- (c) The CO₂ output of excised bruised tissue is similar to that of whole fruit.
- (d) The O₂ uptake rates are similar for bruised and nonbruised tissues.
- (e) The effects of atmospheres, vacuum infiltration with mannitol solutions, acid determinations, and temperature increases on bruised and nonbruised tissues verify that the CO₂ effect of bruising is not respiratory in nature, but rather to decarboxylation of malic acid.

Other studies by Brown (thesis, 1984) and Parker (thesis, 1984) provide further evidence that measurements of CO₂ increases within several hours following injury to apples reflect the extent of physical damage.

Electrical impedance as a measure of bruise damage. The studies of Loughheed et al. (1981) using a "Shigometer"¹ for in situ measurement of electrical resistance demonstrated that membrane breakdown and cellular disorganization in apple fruits result in decreased electrical impedance. We found with this instrument that apple fruit tissues damaged by impact had a lower impedance than nondamaged tissues. Using the technique illustrated in Fig. 1 it was found that the decrease in electrical resistance of bruised apple tissues was highly correlated to the radius of the bruised area visible at the fruit surface, see Fig. 2. Although possibly useful as an objective measure of the extent of damaged tissues caused by an impact force, the requirement of identifying the bruised area and then properly inserting the instrument probes into bruised and nonbruised tissues to obtain comparative resistance values would greatly limit its use. Further study of this method was discontinued.

¹ Product of Osmose Wood Preserving Co. of America, Inc., Buffalo, N.Y.

Damage Response of Apples

Extensive study of apples provided a wealth of basic information on CO_2 and C_2H_4 responses of damaged fruit. The apple was particularly suitable for study since bruise damage caused by impact and compression forces was relatively consistent and readily identified and measured by visual means. The fruit development stage of harvest maturity is identified by respiratory activity and endogenous C_2H_4 production. The ripening and senescence stages that follow harvest are markedly retarded by low temperature and controlled atmosphere storage so that a supply of fruit is available for testing over a period of 6 to 9 months.

All apple cultivars examined yielded a positive CO_2 response to damage. The response of cv. MacSpur (a strain of McIntosh), Empire and Rome Beauty, cultivars commonly grown in Michigan and marketed from storage, were studied in detail. The results summarized in Table 3 show their response patterns were similar. Empire was more extensively used than the others because of its good uniformity in physical characteristics and excellent storage quality.

Typical CO_2 damage response by apples is illustrated for cv. Empire in Fig. 3. The CO_2 evolution for mature fruit dropped onto a hard surface was positively correlated to drop height. An increased number of drops increased CO_2 output. The effect of bruising was apparent at 3 hours following injury and measurable for 24 hours. Similar responses occurred for damage by compression (see Klein, 1983).

Fruit age at the time of injury did not markedly affect the CO_2 response. Klein (1983) found that young Empire fruits harvested as early as 21 days following ontogeny increased in CO_2 production at 2 hours following damage. Market quality fruit from 3 times of harvest at weekly intervals had similar damage responses; fruit stored for 0, 100 or 199 days, likewise had similar damage responses, see Table 3.

Changes in C_2H_4 production by impact damaged apples were variable. They ranged from none to increases for less mature fruit and from none to decreases for ripened fruit. C_2H_4 production was considered to be unsuitable for use as a damage response for apples.

Conclusion. Apples, regardless of stage of development from ontogeny to senescence, yield an increase in CO_2 production as a result of the damage caused by impact and compression forces. Since the CO_2 increase arises from the decarboxylation of malic acid spilled from the damaged cells it provides a reliable measure of the amount of damaged tissue. The CO_2 response is immediate and reliable quantitative measurements are obtainable within 5 or 6 hours following the occurrence of damage. The C_2H_4 response is not a reliable indicator of fruit damage in apples.

Apple Shipping Containers

Measurement of the gaseous response by fruit damaged within shipping packages requires enclosure of the packaged fruit in an airtight container or the testing of damaged fruit samples removed from the package in a manner similar to that employed in basic laboratory tests. These procedures were examined and evaluated for suitability to a detector system.

Examination of Systems

Shipping packages constructed of 200-pound, C-fluted corrugated paper, filled with approximately 15 kg of apples were overwrapped with .75 mil thickness bioxically-oriented polyethylene film. The film was heat sealed at all joints, heat shrunk and the seams resealed with polyethylene adhesive tape. Trials with drop, compression and vibration forces were made. Although a CO₂ response to fruit damage was measured, it was either small or too variable to be statistically meaningful or useful. Further examination of leakage from sealed film enclosures plus modifications, indicated that this method was unsatisfactory for measuring differences in the CO₂ accumulation within shipper packages of apples. The next step was to examine rigid enclosures which could be positively sealed to prevent gas leakage. Cylindrical firm-walled tubs of ca. 38 L capacity with covers were fitted with closed-cell foam gaskets and tension cord lid clamps to hold the covers tightly and firmly in place. Tests with apples in which packaged fruit were dropped from a maximum height of 1 m or vibrated a maximum of 15 Hg and 0.5 G for 15 minutes yielded weak and inconsistent CO₂ and C₂H₄ responses.

Metal chambers fitted with airtight lids previously used for controlled atmosphere storage experiments were tested and found to be equally unsuitable as the tubs for measuring the CO₂ or C₂H₄ response of apples damaged in shipping packages.

A major difficulty was the amount of headspace within the enclosure. It was estimated that the free air space within the chambers amounted to at least 4 times the space occupied by fruit. Accordingly, there was great dilution of the gases evolved and the low concentrations exaggerated the errors and variations. The next step was to design and develop airtight enclosures which would provide a minimum of free air space surrounding the fruit, these are described by Brown (thesis, 1984).

Trials with shipping containers filled with apples or oranges and dropped, vibrated or compressed yielded index values of response that ranged from 1.0 to 1.72, and with considerable variation within treatments. It was concluded that more than 3 replications, as used here, would be needed in order to make reliable assessments of relative damage by gaseous emanations.

Still another approach to measuring the damage response of containerized fruit was to remove fruit samples from the shipping packages immediately following treatment, then enclose the fruit in laboratory containers and measure the accumulated gases in the same manner as employed in the basic studies of fruit response. This procedure offered several advantages over measuring responses of the entire package contents, namely: (a) the required quantity of test fruit is considerably smaller since only the test samples have to be initially damage-free; (b) test samples could be placed in various parts of the shipping package; (c) a greater number of replications could be employed; and (d) test samples could be placed in containers for gas accumulation that would provide a minimum of head space and more easily handled, weighted and analyzed for gas content. The results reported for apples in shipping packages were obtained in this manner.

Shipping Package Trials

Ten-fruit sample lots of cv. Empire apples previously selected for freedom from visible damage were randomly assigned in duplicate to the bottom, middle and top layers of fruit of 16 corrugated paper apple shipping packages. Two types of packing within a container, KP (Peleg, 1978) and tray, and three forces, impact by dropping twice from a height of 25 cm, compression by the force required to cause 70% depletion of the empty container, and vibration at 9.5 Hz and 0.8 G for 30 minutes, with all combinations of packing and forces applied. Upon completion of the force treatments the fruit samples were removed from the packages, placed in plastic containers, weighed, sealed and analyzed for CO₂ accumulation at 1, 2, 3 and 4 hours. The apples were subsequently held 2 to 4 days at 20°C in air prior to examination and rating of visible damage. A rating system of 1 to 5 for none to severe damage was utilized. A factorial design consisting of 4 replications applied on different days was employed.

Summations of the CO₂ production at the 4th hour and the presence of visible surface damage are given in Table 4. The lowest post-treatment production of CO₂, significantly less than force treatments except compression applied to the tray package, occurred for the nondamaged control; the greatest production of CO₂ occurred for the combination of all forces, being significantly greater than 6 of the other 14 treatments. The CO₂ values corresponded closely to the damage ratings. Index values for each treatment calculated from the appropriate nontreated control are listed in Table 5 showing significant changes (indicated by *) based on the factorial analysis of CO₂ production and damage rating. Significant index values for CO₂ ranged from a minimum of 1.11 for the containers of KP-pack fruit that was vibrated only to a maximum of 1.33 for tray-pack fruit receiving all three types of forces.

Each of the forces applied to the apples resulted in a significant increase in CO₂ production and visible damage (Table 5). Also, these methods of measurement showed that the tray pack offered more protection against damage than the KP pack.

Conclusion

The CO₂ response measured at the 4th hour following treatment provides reliable evidence of physical damage caused by drop, compression and vibration forces to apples in shipping packages. Differences in the protective characteristics of packing methods within the container are measurable in this manner.

Damage Response of Oranges

Preliminary trials in Israel prior to the initiation of the project demonstrated the possibility of employing fruit CO₂ production as an indicator of physical damage to cv. Shamouti oranges. This possibility for cv. Pineapple and Valencia oranges was confirmed by experiments conducted at the University of Florida Citrus Research and Education Center in cooperation with Dr. W. F. Wardowski during the 1982-83 and 1983-84 fruit harvest seasons.

Additionally, the effects of physical damage to oranges on ethylene production and the levels of damage that might be utilized in a detector system employing CO₂ evolution were examined. The presence of a CO₂ response of cv. Marsh grapefruit was recorded.

Laboratory Results

Impact damage to Shamouti oranges due to dropping the fruit onto a hard surface significantly increased CO₂ output to yield an index of 1.2 to 1.5 relative to the CO₂ produced by comparable nondamaged fruit. The application of vibration forces sufficient to cause fruit to rotate within test containers constructed of corrugated paperboard gave variable results. The CO₂ response following vibration had an index of 1.1 for 7.5 Hz at 1.1 G and up to an index of 2.4 for 7.5 Hz applied at 1.3 G. Fruit compression caused by static loads of approximately 5.3 to 7.8 kg per fruit increased fruit CO₂ output, whereas a smaller load of ca 3.7 kg per fruit was of no effect. Little or no visible damage to the fruit resulted from the impact, vibration or compression forces employed, nor were measureable changes in subsequent weight losses of the fruit observed.

The initial trials with Florida fruit of the 1982-83 harvest season showed that Pineapple, a popular early season cultivar for fresh market shipments, responded similarly to cv. Shamouti in CO₂ production following damage (see Table 6). Statistically valid results were obtained using at least 8 fruits per sample with 4 replications. It was found that the response measured at approximately 6 hours (Fig. 4) after enclosing the fruit samples in airtight containers following damage gave representative data for longer holding periods. The following types of damage resulted in significant (*, 5% level of probability) or highly significant (**, 1% level of probability) increases in CO₂ output as a result of the injuries incurred:

- (a) Abrasion caused by scraping each fruit with No. 220 silicone carbon emery paper to provide 4 areas of damage each about 1.25 cm in diameter yielded an index of 1.20* at 4 hours following enclosure.
- (b) Compression of each fruit once for ca 10 seconds with a 20 kg weight increased the CO₂ index to 1.31*; when applied 2 times, the index was 1.60**.
- (c) Impact by dropping each fruit from a height of 100 mm yielded an index of 1.65**.

Ethylene evolution from Pineapple oranges measured simultaneously with the accumulation of CO₂ within closed containers was stimulated by fruit damage, but there was considerable variation and inconsistency in the results (Table 6). Limited time and facilities prohibited further exploration of the ethylene response as a possible measure of damage to citrus.

A single experiment conducted with cv. Marsh grapefruit in which samples of damaged and nondamaged fruits (2 per sample replicated 5 times) were used indicated that this fruit yielded a marked CO₂ response to abrasion, which was the only type of damage tested, but as with oranges, the ethylene response was variable. Further study with grapefruit for use of the CO₂ response for measuring impact and compression damage should be considered for this fruit.

Tests with fruit of the 1983-84 harvest season showed that representative CO₂ responses to puncture, abrasion, compression or impact could be measured by the accumulation of CO₂ from oranges held continuously without aeration in closed airtight containers for 5 or more hours following the occurrence of injury. Accordingly, statistical comparisons of fruit responses at the 6th hour are summarized in Table 7.

Rind punctures to a depth of 7 mm with a sharp nail of 2 mm diameter at the rate of 2 per fruit caused no increase in CO₂ output, 4 per fruit did sometimes and 6 per fruit invariably caused an increase (index of 1.15** for Pineapple, 1.19** for Valencia).

Abrasion damage caused by scraping the fruit surface with silicone carbon emery paper to create a damaged area ca 1.25 cm in diameter yielded variable results. For one test, 2 and 4 abrasions per fruit increased CO₂ (index of 1.09* and 1.14*, respectively) for Pineapple fruit, whereas in two other tests there was no effect. Valencia oranges responded to 4 abrasions (index of 1.18*).

Compression of the fruit for 10 seconds with an 11.25 kg weight increased CO₂ production, index of 1.22** for Pineapple and 1.15** for Valencia. A force of 4.5 kg applied twice per fruit to Valencia caused a slight increase in CO₂ (1.05*); when applied once to Pineapple there was no measurable increase.

Impact damage to oranges resulted in CO₂ responses proportional to drop height and number applied. For cv. Pineapple a single drop from a height of 250 cm, the minimum distance employed for this cv. yielded a small CO₂ increase (index of 1.09*); 2 drops of 1000 mm increased CO₂ to 1.62**.

Fruit quality depreciation due to appearance changes, water losses and decay development for fruit held at 20°C for several days or up to one week following the conclusion of the gas evolution evaluations was negative for fruit damaged by impact and compression. Punctures and abrasions created visible damage, otherwise there were no consistent symptoms of quality deterioration.

Conclusion

Impact and compression forces that likely cause internal though invisible damage to oranges, as well as forces that cause visible damage, i.e., punctures and scars of the rind, increased fruit CO₂ production which was consistently measured within a few hours following injury. The extent of the CO₂ increase reflected the amount of force exerted and, apparently, the degree of injury inflicted on the fruit. The CO₂ response of damaged fruit, when compared to the normal CO₂ production of comparable nondamaged fruit, should provide a reliable means for evaluating the protective characteristics of shipping containers.

The C₂H₄ response to damage was variable and not extensively studied as a quantitative measure.

Detecting Fruit Damage in a Citrus Packinghouse Line

The possibilities for utilizing the CO₂ response of oranges for detecting the possible occurrence of invisible damage during passage through a sizing, sorting and packing line in preparation for shipping to fresh market outlets was suggested. Three trials were made; one to ascertain if samples of fruit taken during a normal run could be utilized, and the second and third to determine if previously selected oranges could be inserted and removed during a normal commercial run of grapefruit as a means of evaluating the degree of damage associated with individual operations in the line.

Results

Fruit taken at various points in the line during a commercial run of cv. Pineapple oranges had increased outputs of CO₂. Although there was no CO₂ increase upon dumping at the beginning, fruit from every subsequent operation, starting with washing, had highly significant increases in CO₂ production over fruit selected prior to dumping. However, there was no accumulative effect upon passage through every operation.

Except for waxing, all operations, including dumping, when individually and separately evaluated with Valencia oranges inserted into grapefruit runs produced significant increases in CO₂. The greatest increase, more than 50% over the control, occurred for fruit passing through a grading operation that required the greatest distance of travel (57 m) and time (198 sec) than other operations. Test fruit selected from bins of commercial fruit served as well for these tests as fruit carefully harvested and handled from the grove.

Conclusion

The increased evolution of CO₂ indicated that damage occurs in most packinghouse line operations. CO₂ measurements of oranges inserted and removed at various locations within a line during a run of grapefruit could be useful in detecting and correcting possible sources and causes of damage.

Damage Response of Tomatoes

Based on the findings of McLeod et al. (1976), exploratory tests were undertaken with mature green and slightly ripened field-grown tomatoes to determine the feasibility of using CO₂ and C₂H₄ damage responses for detector purposes. Fruit of uniform size, maturity and quality were field selected and carefully harvested and handled during transport to the laboratory. Further classification and assignment of test fruit into categories of uniform maturity by color were made prior to an experiment. Samples of 3 to 5 fruits were confined in sealed containers for measurement of gas output. A small packet of hydrated lime (Ca(OH)₂) was enclosed with the samples for C₂H₄ analysis to prevent the accumulation of CO₂ that might affect C₂H₄ production.

Results

Tomato fruits cv. Jackpot at the "breaker" stage of maturity (No. 2 on Michigan Color Chart), compressed by forces of 4 or 8 kg yielded immediate increases in C_2H_4 and CO_2 , with the increase for C_2H_4 more pronounced than for CO_2 (Fig. 4). Differences in magnitude in C_2H_4 and CO_2 relative to the extent of damage were evident for at least 60 hours following injury. Impact trials (3 drops of 33 cm) with cv. Ohio Hybrid showed the damage response for both C_2H_4 and CO_2 to be considerably greater for mature green fruit than for fruit at the "turning" or "red" stage of maturity, and as true for cv. Jackpot, the C_2H_4 response exceeded the CO_2 response. Impact, compression and abrasion injuries applied to cv. Independence fruit at the "breaker" stage of maturity provided further evidence that the C_2H_4 response was more definite and consistent than the CO_2 response. Accordingly, the CO_2 outputs were not examined in subsequent tests. As shown in Table 8, all types of forces yielded significant increases in C_2H_4 production of non-ripened tomatoes, with the magnitude of the force being a factor. For the most part, the responses of tomatoes to damage had to be of greater amount than the CO_2 responses of apples and oranges in order to be statistically sound. This was due to the greater variation in C_2H_4 of the replicated samples of tomatoes than the variation in CO_2 for other fruits.

Packaged Fruit

A series of 4 trials in which cv. Sonny tomatoes at the "breaker" and "turning" stages of maturity in corrugated paperboard shipping packages were exposed to impact and vibration forces yielded inconclusive results. In all instances the mean C_2H_4 outputs were increased by treatment, but the amounts were extremely variable. The CO_2 outputs increased in 2 trials, but decreased slightly in 2 others, again, by variable amounts. It was evident that the procedures for assessing the gaseous response of tomatoes in packages would have to be better standardized and properly replicated in order to provide suitable basic data for a detector system. These factors, together with procurement problems in obtaining a ready, reliable and adequate supply of fruit of suitable maturity, affected our decision to suspend further trials with tomatoes. The results with tomatoes, however, do suggest that the C_2H_4 response has a potential use in a damage detector system for tomatoes.

Conclusion

Damage causes a more marked increase in the C_2H_4 response than in the CO_2 response of tomatoes. The considerable variability in the tomato C_2H_4 response requires more study before it can be used as an indicator of injury.

Detector System

Extensive study of fruit responses to physical forces showed that increases in CO_2 evolution would serve for detecting and measuring damage to apples and oranges. Simulated transport and handling forces applied to shipping packages of apples yielded CO_2 responses similar to those applied directly to individual fruits. Although packaged oranges were not tested,

responses similar to those obtained for individually treated fruit are likely under simulated handling and shipping conditions. The damage detector principle applicable to apples should serve equally as well for oranges for assessing the protective characteristics of shipping containers in use or considered for use in the distribution and marketing of fresh fruit.

The application of C_2H_4 production as damage detector for fresh market tomatoes is recommended for further study.

Detector operation. The protection or lack of protection provided to fruit against physical injury by a shipping package and packing materials is measured by the CO_2 response of pre-selected damage-free fruit ("response" fruit) placed in the package. The rate of production of CO_2 is determined upon removal of the "response" fruit from the package following exposure to a standard set of programmed forces. The CO_2 evolved by damaged "response" fruit is compared to the CO_2 produced by control or nondamaged comparable "response" fruit packaged and handled similarly in every respect except for exposure to the damage forces.

The "response" fruits are selected for uniformity of cultivar, shape, size, maturity and freedom from visible damage. Ten fruits are assigned at random to each variable and replicate and placed in a standard position within each package, such as the top, middle or bottom layer, but preferably not adjacent to each other. A minimum of four replications of test packages are filled with "package" fruit that is of similar commercial grade, size, and quality to "response" fruit. It need not be damage-free. All "package" and "response" fruits are preconditioned to the same temperature (usually $20 \pm 5^\circ C$) prior to starting a test. The ambient atmosphere should be relatively free of C_2H_4 or other gases which could affect fruit respiration and CO_2 production. Careful and equivalent handling of all "response" fruit is essential in order to avoid an incidental CO_2 damage response.

Measurement of damage response. Immediately following a damage treatment the "response" fruits are carefully removed from each shipping container and placed in a corresponding airtight container (plastic tub) and weighed. The randomization established for package treatments is maintained throughout. The analysis procedure is as follows:

(a) The tubs are closed with snap-on lids within approximately one hour after application of the damage. The tubs are sealed by applying the snap-on lids in the same order and time sequence that are followed for sampling the tub head space atmosphere for CO_2 content.

(b) At a standard time, usually four or five hours after sealing, a gas sample is withdrawn from the tub through the analyzer. To take a gas sample, each of the two needles of the analyzer is inserted into a separate hole in the lid covered by gas-proof tape. Atmosphere circulation through the analyzer and the tub requires approximately 15 to 20 seconds to provide a stable CO_2 reading.

(c) The analyzer provides a reading of percentage carbon dioxide. The percent values are adjusted for fruit weight and headspace volume of the tubs, and converted to milliliters of CO_2 produced by each gram of fruit each hour as follows:

$$\text{CO}_2 \text{ (ml/g/hr)} = \frac{(\text{CO}_2) (.01) (\Delta \text{ volume})}{(\text{fruit weight}) (\text{time})}$$

CO_2 = reading from analyzer (%)

Δ volume = Gross volume of containers (ml) - fruit weight (grams)
fruit weight = weight of fruit in tubs (grams)

time = length of time the tubs are actually sealed (hours)

(d) The CO_2 outputs (ml CO_2 /g·hr) are statistically analyzed by appropriate procedures such as analysis of variance, regression analysis, multiple range tests, or standard deviation. A simple statistical comparison by standard deviations shows whether or not a treatment is dissimilar to the control. An index value for CO_2 production of treated fruit relative to the CO_2 production of nontreated fruit (control) is useful for making a comparison of a treatment to the control:

$$\text{CO}_2 \text{ index value} = \frac{\text{mean CO}_2/\text{g/hr of treatment}}{\text{mean CO}_2/\text{g/hr of control}}$$

Statistical evaluation of index values, however, is based on actual CO_2 outputs relative to that of the nontreated fruit.

Materials and equipment. The following materials and equipment for measurement of a CO_2 damage response are required.

(a) "Response" fruit selected from a particular standardized source. Ideally the fruit should be selected on the tree, then carefully harvested, handled and packed in padded containers for transport to the testing site. This is necessary to avoid damage that could affect the subsequent damage response to be measured. It is more practical, however, to obtain fruit from commercially harvested lots by selecting fruits free of visible damage due to compression, impact or abrasion from the upper several layers of fruit in orchard bins. The selected fruit should be carefully handled to avoid inflicting damage that would interfere with the treatment response.

(b) "Package" fruit used as filler fruit in the shipping packages under test can be taken from normally handled commercial fruit intended for fresh market. It should be comparable as to cultivar, size, maturity and firmness to the "response" fruit, but does not need to be free of damage.

(c) Plastic tub containers fitted with snap-on self-sealing airtight lids (commonly used as freezer containers for foods), or similar airtight containers, that can be easily and reliably closed are used for collecting the evolved CO_2 (see Fig. 5). The lids are modified with holes and septums to permit sampling of the headspace atmosphere without contamination with outside air or leakage. A container capacity of 6000 ml holds 10 apples or oranges of medium size with a minimum of headspace for collection of the accumulated CO_2 .

(d) An analyzer utilizing an infrared detector and a digital percentage readout provides rapid determinations of CO_2 with good accuracy. The ADC

Carbon Dioxide Analyser manufactured by The Analytical Development Co., Ltd., England proved particularly suitable for our research (Fig. 5). A 5 to 10% CO₂ range of the instrument is adequate. A laboratory model gas chromatograph fitted for CO₂ can be employed for gas samples taken by syringe from the fruit containers and injected. An integrator, as shown in Fig. 6, used in conjunction with the GC instrument improves accuracy and simplifies determination of the quantity of CO₂.

PRODUCE PACKAGE DAMAGE SIMULATOR

Introduction

In this age of highly mechanized produce harvesting, processing, packaging, and distribution, the average shrinkage due to mechanical damage (between the grower and consumer) is reportedly estimated at around 30-40% on a global scale. The economic loss associated with this damage is enormous. Hence, reducing mechanical produce injury is a major concern of produce industries worldwide. As more and more mechanization is introduced, new potential damage sources appear.

A prerequisite for solving mechanical problems of fresh produce is a thorough understanding of the nature and mechanical properties of fruits and vegetables, as well as modern harvesting processing, storage packaging, distribution and marketing systems.

A basic step in this direction is development of mathematical models quantifying mechanical injury as related to the biomechanical properties of the fruit, material properties and geometrical configurations of packaging systems, and the expected mechanical inputs in the production chain, from harvesting to the supermarket shelf.

Modern distribution and marketing of fresh fruits and vegetables comprise multiple stage processes, including storage handling and transportation, by land sea or air, to markets which are sometimes thousands of kilometers away from the field or orchard where the produce was grown. The diversity of transport modes in general and distribution of fresh produce in particular, renders the dynamic environment conditions extremely complex. It may be loosely described as a mixture of continuous excitation with intermittent transients or superimposed discrete excitation.

Accordingly, the damage simulator part of the project had to address the following problems:

- a. Mathematical models of produce damage mechanisms.
- b. Measurement and quantification of produce transportation environments.
- c. Simulation of transportation environments, (compression, shock and vibration).
- d. Simulation of damage in containers and unit loads of fresh produce.

These four parts of the project are discussed next.

Mathematical models of fruit damage

Most fruits and vegetables are spherical or spheroidal in shape. Mechanical injury in distribution is primarily a phenomenon of permanent deformation at the contact points between fruits, fruits and container sides, or container bottom. If fruits are packed in plastic or pulp trays incorporating cups, the contact is between a spherical cup and the spheroidal fruit inside it.

If we assume that fruits in a container are perfectly elastic spheres, i.e., all deformation is totally recovered upon removal of compressive load. Then, the Hertz law for a static load acting on two spheres in contact may be directly applied as described by Timoshenko and Goodier (1951) and Goldsmith (1960). Unfortunately real fruits are not made of perfectly elastic material.

In most general terms fruit and vegetable flesh may be considered as a non-linear viscoelastic or viscoplastic material possessing both properties of a liquid and of a solid to different degrees. Thus the texture of a tomato (Miles et al. 1969) is more like a liquid than an apple, while the viscous composition of an orange may be classified somewhere in between.

Preliminary investigations showed that using existing linear elastic or viscoelastic models for quantification of mechanical properties of fruits and vegetables, leads to significant contradictions to experimentally observed phenomena, (Pitt and Chen 1983 and Peleg 1978). Thus it was necessary to develop a new theoretical body whereby improved prediction of the behavior of non linear viscoplastic materials such as fruits and vegetables and packaging systems, could be realized. Mathematical models and procedures were developed for static and dynamic testing of non-linear viscoplastic materials, as well as a general rheological model quantifying force deformation loading curves, creep and relaxation.

This theoretical body has been published in two articles attached herewith; Peleg K. 1983, A rheological model of nonlinear viscoplastic solids. J. of Rheology 27(5):411-431. Peleg K. 1984, A mathematical model of produce damage mechanisms. Transactions ASAE 27(1):287-293. These two articles should be considered as an integral part of this report. A condensed summary of these two articles follows.

Rheological properties were quantified in terms of three types of curves obtained by tests, as commonly used for description of mechanical material properties: quasistatic constant rate force deformation, creep and relaxation.

The mathematical model was based on a characteristic non-linear differential equation of the form:

$$(1) \quad F = K_0 X + R X^3 + C \dot{X} + F(\text{sgn} \dot{X})$$

This equation defines the force F , acting on a test specimen as composed of a cubic elasticity force $K_0 X + R X^3$, viscous damping force $C \dot{X}$ and internal friction force $F(\text{sgn} \dot{X})$.

The elastic parameter K_0 , quantifies linear elasticity while the strain hardening (or softening when negative) parameter R predicts non-linear behavior of the material. Local linearization of the characteristic equation permitted a closed form solution for creep at constant loading force and

relaxation at constant deformation.

Fruits may then be pictured as composed of a non-linear viscoplastic material quantified by this characteristic equation. The approximate solution of the above equation also permitted definition of a non-linear relaxation modulus $E(t)$:

$$(2) \quad E(t) = E_0[\exp(-t/T) + E_{\infty}[1 - \exp(-t/T)]]$$

where; E_0 is the instantaneous non-linear elasticity modulus at time $t = 0$, which reverts to the regular linear modulus of elasticity when $R = 0$, E_{∞} is the asymptotic or residual relaxation modulus after a time $t \gg T$ has elapsed, since application of the external load on the specimen, while T is a relaxation time constant.

This method of defining a relaxation modulus of elasticity was employed by Yang (1966) for the purpose of extending the Hertz contact problem solution to viscoelastic bodies. However, whereas Yang (1966) used the conventional three parameter linear viscoelastic model, Peleg (1983) extended the solution to non-linear viscoplastic bodies as well while the linear solution is retained as a special case thereof.

Note that $E(t)$ may be viewed as a time and deformation dependent spring rate or as a time and strain dependent stress strain ratio. Thus, $E(t)$ may be expressed in either force per unit length or force per unit area.

Following the line set by Pao (1955), Goldsmith (1960) and Yang (1966), Peleg (1983, 1984) showed that a good approximation of the Hertz contact problem may be obtained for non-linear viscoplastic bodies by using $E(t)$ from equation (2) instead of the linear three parameter relaxation modulus. This is possible because the geometry of the elastic and viscoelastic cases are identical, but the dimensions of the indentation in the viscoelastic case is time dependent.

Using this non-linear relaxation modulus, Peleg (1984) developed equations for prediction of produce bruise size parameters, e.g., contact circle diameter and depth of fruit deformation at constant loading force, varying loading force and combination thereof. The maximal pressure at the center of the contact circle was also computed.

The above equations, predicting contact pressure, bruise diameter and bruise depth, are valid only for as long as the loading force F is applied. Upon removal of the external force F some portion of the fruit deformation will be recovered. Since only the residual deformation constitutes the actual bruise size of the fruit, the above equations lead to conservative design, by neglecting the recovered deformation. Nevertheless, using the creep curve loading and unloading equations, one can also predict the amount of recovered and residual deformation if so desired.

Observe also that the values of E_0 , E_{∞} and T are not true constants, since they are associated with some mean deformation X_0 . Thus we must either use their mean values, or have a predetermined estimate of the mean deformations at hand. The former is simple but less accurate, while the latter requires recursive computations. Using experimentally determined, mean values of E_0 , E_{∞} and T for estimating $E(t)$, will usually provide results of sufficient accuracy.

Summary of general transportation surveys

A quantitative knowledge of the environment of different transportation modes of fresh produce is essential for optimal design of packaging systems and maximal protection of produce in the distribution chain. The average spectra and the extreme values of the different transportation environment variables are the stresses and inputs which have to be born and attenuated by the packaging system in order to protect the produce inside. The main function of the damage simulator is to simulate these inputs by controlled laboratory tests as described in the next sections. The simulation process does not strive to exactly duplicate these inputs, but to imitate their damage capability. Furthermore, the duration of the test must be much shorter, say 20-30 minutes, in comparison to the actual time of transporting the produce to its destination, which may take several days.

Extensive transportation environment surveys have been conducted previously for general and military cargo types in different transport vehicles.

Of all the transportation environment surveys reviewed, the publications of Foley et.al. (1973) and Ostrem and Rumerman (1965), seem to be widest in scope, and there is considerable agreement between their values although the presentation formats are different. In Foley et. al. (1973), transportation vibration environments in trucks, railcars, and turbo-jet airplanes are presented as one standard deviation level acceleration versus frequency bar graphs. Ostrem and Rumerman (1965), reported shock and vibration transportation environment data in continuous graph form of peak acceleration envelopes, for truck, rail, ship and turbo-jet aircraft. In Foley's survey the one standard deviation levels were obtained after the discrete and some continuous single frequency excitation has been filtered out. Thus, his data may be considered as almost normally distributed, hence the one standard deviation levels may be assumed to approximate the RMS value of zero to peak acceleration amplitudes.

It is well known that in a normal (Gaussian) distribution, the peak values are distributed according to the Rayleigh distribution, wherein 99.7% of the population is included within four standard deviations. Thus, one may compare the results of the two surveys by assuming that the peak acceleration levels reported by Ostrem and Rumerman (1965), should be equal to about four times the RMS acceleration levels reported by Foley et. al.(1973).

Although fresh produce rarely travels by all four transport modes, a total envelope encompassing composite spectra of trucks, railroad, marine and cargo aircraft, may be useful as a distributive database for conservative design, and background for comparison to the results of the produce transportation environment survey which was an integral part of this project.

A combined analysis of the above surveys showed that the vibration environment of all transport modes as regards potential damage to produce-package systems, may be delimited as follows:

- a. Non-stationary random vibration with discrete and intermittent excitation buried within.
- b. Frequency band 1-200 HZ.
- c. Acceleration amplitudes 0.1 to 0.7g RMS, and 1 to 4g envelope of peaks, including intermittent transients.

Survey of apple and citrus fruit transportation environments

This part of the project involved design development and construction of two systems:

- a. Portable transportation environment data recording system.
- b. Data analysis reduction and presentation system.

Data recording system.

The data recording system is shown in fig. 7, a-c. It consists of a state of the art, 15 channel, Kiowa RTP- 600A, FM tape recorder using a standard video cassette as recording medium. The frequency response of this recorder at a tape speed of 2.38 cm./sec is DC to 625 Hz, whereby uninterrupted recording of about three hours is possible on a single cassette. Miniature Piezoresistive Acceleration Transducers, (Entran Devices EGA - series, 10 g's and 50 g's range) were used to sense the acceleration levels in container columns of citrus and apple pallet loads. A special electronic network was designed and constructed for calibrating and conditioning these transducers. In addition to the excitation of the transducer's bridges and amplification of the output signals, this network also performed dynamic compensation and matching of all the transducers, effectively extending their flat frequency response beyond 300 Hz and exactly equalizing their voltage output per g. The transducer conditioning hardware, tape recorder and portable power supplies were cushioned inside two rigid containers, as shown in fig. 7. These containers were integrated within citrus and apple shipping container pallet loads and sent on regular transportation routes by truck and ship. A 20 m. tether cable with mike and control box enabled remote control of the recording system and voice remarks records from the truck's cabin on the go. The instrumented pallet load was stowed in the rear right side position of the truck bed where the acceleration levels are most severe. In each case a whole column of shipping containers in the pallet load was instrumented with acceleration transducers. The input acceleration to this container column was monitored by an acceleration transducer attached to the pallet deck, while transducers attached to the bottoms of the containers measured the input levels to each individual container in its respective tier of the column. Additional accelerometers were imbedded inside fruits approximately placed in the centers of the shipping containers.

Data analysis system.

The hardware of the data analysis, reduction and presentation system comprises a microcomputer, fast 8 bit A/D converter with adjustable sampling rate, digital storage oscilloscope, signal level trigger electronics and adjustable anti - aliasing low pass filter, with 96 dB/octave roll off.

The software consists of a set of programs for semiautomatic sampling of the data recorder's channels, Fast Fourier Transform (FFT) processing of 1024 size samples and graphical display of results.

This system enables representative sampling of long transportation vibration records, digitizing and transforming each sampled record segment into the frequency domain, whereby amplitude versus frequency domain plots, are obtained. These frequency domain plots can then be averaged or a plot

enveloping all the individual plots may be prepared, representing the largest amplitudes encountered in the entire record at each frequency.

Description of transports and routes.

The data recorded and analyzed was compiled from two typical commercial shipments of apples and oranges.

The apple pallet load, fig. 7.b. was part of a truckload shipped, (Dec. 12. 1983) from a packinghouse in Kiriat Shemona to Tel Aviv wholesale market, about 200 km. distance, over a mixture of different road conditions ranging from badly rutted pothole filled old two way road, to newly paved smooth divided highway. A double rear axle, 15 ton fully loaded Mack truck was used on this trip. On each type of road conditions, three ranges of traveling speeds were employed.

The citrus pallet load, fig. 7.a. was part of a commercial shipment of Valencia oranges count 88, from a packinghouse in central Israel (Rhovot), to Ashdod port by truck (about 45 km.), then by ship to Haifa port, where the ship took on a complementary load before sailing to Marseille France. From Marseille, the instrumented citrus pallet load was transported by semitrailer truck to a wholesale market in Paris France, (about 1000 km). The ship, ("Iris", 7000 tons) was of the ROLL ON - ROLL OFF type, i.e. it took on whole semitrailer truck bed loads whereby the whole trip from the packinghouse to Paris, including stopover in Haifa port, was accomplished in seven days, beginning March 3 1984. A 9 ton, Layland single rear axle truck was used to transport the load from the packinghouse to Ashdod port, there it was transferred onto a semitrailer truck bed which was stowed aboard ship and went intact all the way to the wholesale market in Paris.

In both shipments, records were taken during loading and unloading operations as well as during the different legs of the transportation route. Thus the records include both steady state vibration, intermittent and handling shocks.

The mixture of trucks and road conditions used in both runs may be regarded as a representative range of typical produce ground transportation modes.

Data Processing.

The main objective of the transportation environment study was to compile a database for generating synthetic environments for produce - package damage simulation on commercially available shock and vibration testing equipment. To this end, the transient data was separated from the steady state vibration during the sampling process by adjusting the level of the electronic trigger. Acceleration transients higher than 7 g's were classified as shocks while those below 7 g's were considered as steady state vibration including intermittent transients. This rather arbitrary segregation is consonant with the procedures used by Foley et. al.(1973) and Ostrem and Rumerman(1965). It is moreover necessary, inasmuch as acceleration levels higher than 7 g's can not be reproduced on most vibration machines in the required frequency band, (3 - 200 Hz). The data segregation process was further facilitated by observing each sample of 1024 readings on the digital memory oscilloscope screen, whereby it could be visually verified as a transient shock or part of the continuous steady state vibration record. The two datasets thus created were then processed by two different methods as follows:

The steady state vibration signals were first passed through the low pass antialiasing filter, sampled by the A/D converter at 1024 samples per sec. (1 sec. sampling window), and processed by the FFT algorithm which was implemented on the microcomputer. The results, e.g., RMS acceleration and spectral content of each processed sample, as well as the cumulative envelope acceleration spectrum were stored on disc for further processing by the graphics program and digital plotter.

The transient datasets were sampled directly from the tape recorder channels (without passage through the antialiasing filter), at 2048 samples per sec. (.5 sec. sampling window), and stored on disc for further preprocessing by a shock pulse extraction program. Each half second sample of 1024 acceleration readings representing the transient signal typically contained several shock pulses spaced more or less closely by low level data belonging to the steady state category. The pulse extraction program separated these distinct pulses from the low level background noise. Each subdataset thus created was then padded with zeros (front and back), and processed separately by a slightly modified FFT algorithm which evaluated the discrete Fourier integral of each shock pulse. The main results logged for each pulse include; Peak Acceleration, Velocity Change (Area underneath the pulse), Pulse Duration and Rise Time (to peak acceleration). A cumulative envelope representing the Maxi-Max frequency content of all the processed shock pulses was also generated and stored on disc for further processing by the graphics program, similarly to the steady state spectrum envelopes.

Transportation environment envelopes

The results of the transportation environment survey are summarized in concise form by the graphs in figs. 8, 9 and 10. These comprise maximal value envelopes of input acceleration levels in the frequency domain. Logarithmic scales are used on both axes in order to increase the resolution in the lower frequency range, while including the entire frequency band of interest.

The top curve A. in fig. 8 envelopes all peak steady state input accelerations (on the pallet deck), as recorded in the apple transport survey including records on badly rutted pothole filled road, while the lower curve B. envelopes records taken only on the smooth, divided highway part of the trip. The top curve A. in fig. 9, similarly envelopes all peak steady state input accelerations on the pallet deck, as recorded in the citrus transport survey, while the lower curve B. envelopes only the records taken on board ship during the sea journey from Ashdod port in Israel to Marseille France.

The top curve A. in fig. 10, comprises the frequency domain envelope of all intermittent transients whose peak accelerations exceeded 7 g's, i.e. shock pulses, which were extracted from the vibration records as described above, while the lower curve B. envelopes the shocks recorded during handling operations of the pallet load, e.g. loading and unloading by forklift. In order to increase the scope and number of handling shocks, the forklift operators were asked to lift and suddenly lower the pallet loads several times from different heights, (5, 10, 20, and 30 cm.), in addition to the regular loading and unloading operations. Thus, curve B. in fig 10. may be assumed to represent an envelope of maximal forklift handling shocks as encountered in normal produce transport, wherewith both motor driven large forklift, as well as handling shocks of hand operated forklift carts were

recorded. In spite of this, it looks like the shock inputs due potholes in a badly rutted road (curve A.) are significantly more severe than those incurred during forklift handling operations, (curve B).

Note that whereas the steady state acceleration is expressed in g's, the shock intensity is expressed in terms of velocity change in m/sec. This is due to the well known difference of interpretation of the Fourier Transform of a steady state, implicitly periodic vibration signal and its transient counterpart, i.e. Fourier integral of a single short duration pulse.

In both the steady state and transient cases, the above curves represent estimates of peak values of a population, hence they may be assumed to be statistically distributed by the Rayleigh distribution, i.e. the above envelopes encompass about four standard deviations, that is 99.7% of the population of peak accelerations or velocity changes at each frequency. This means that a spectrum composed of quarter values of the envelope ordinates, in figs. 8 A. (subtracting .602 on the log scale), predicts the RMS level of steady state accelerations, whereas an average velocity change curve may be similarly obtained from the transient spectrum envelope in fig. 10 A. Theoretically the above approach is valid only for Gaussian populations, however for practical purposes, even if population normalcy was not rigorously proved, quarter value envelope curves represent a fairly good estimate of the actual values, and permit a calculated risk oriented design.

Frequency response of fruits and containers in pallet loads

From fig. 7 a. and b. it may be observed that the citrus pallet loads were stacked 7 high while the apple pallet loads had only 6 container tiers. In addition to recording and processing the accelerations of pallet decks, as described in the previous section, accelerometers were also attached to the bottoms of selected containers and some were also imbedded inside fruits, located approximately in the centers of containers. Although interlocking patterns were used in both shipments, the lateral positions of the instrumented containers were chosen to form a vertical column in a corner of the pallet load.

Envelope spectra curves such as in fig. 8 were drawn for each accelerometer, channel by channel. The results of this part of the study are summarized in Table 9. in terms of steady state vibration, RMS acceleration levels of these envelope spectra. The leftmost two columns show the RMS acceleration levels as recorded inside fruits or on the bottoms of containers in the apple pallet load shipment. The numbers in the two center columns summarize RMS values of the citrus pallet load shipment by truck, while the rightmost two columns similarly show the RMS levels of the envelope spectrum during the sea voyage.

The following conclusions may be drawn from the figures in table 9.:

a. Since the apple transport envelopes include the worst road conditions of the survey, all acceleration levels in the apple run were much higher than in the citrus shipment. Actually, the apple transport envelope spectrum envelopes all other spectra of the survey, i.e. the overall envelope curve in fig. 8 A. is composed of data from the apple run only.

b. The acceleration levels on a smooth highway are about 1/5 of what one

may encounter on a badly rutted sideroad.

c. The acceleration levels on board ship were quite low, which is contrary to the values reported by Foley et. al (1973) and Ostrem and Rumerman (1965).

However, whereis their data is based on a wide range of mostly military ship types and various sea conditions, the data in table 9 represents but one particular ship. Moreover, we found out too late that this RO - RO ship was especially equipped with automatic stabilizers, which may explain the low acceleration levels in spite of the relatively rough storm encountered during this voyage. Unfortunately, the project budget could not carry more than one overseas trip, as required for compilation of a more reliable database.

d. The acceleration levels of the fruits show a definite attenuation of the values recorded on the respective container bottoms. Nevertheless significant amplification of input levels was recorded in the apple run, (apples in tiers 3 and 5), but none in the citrus pallet load. This indicates better vibration energy dissipation by citrus fruit, i.e. more damping.

e. There does not seem to be a definite trend of increasing or decreasing acceleration levels from the bottom to the top container tiers. This may be due to the multi degree of freedom mode response of the container stack or loose bouncing fruits in particularly underfilled containers. Probably both effects are intermixed. Thus one cannot predict in which container tiers the vibration levels will be most severe. Furthermore, the shape of the envelope spectral curves is quite similar among fruits and containers of the same column and transport mode. This justifies the line taken in designing the transportation damage simulation test jig (described later), whereby only one container is used rather than a stackfull.

Vibration damage simulation

In this section we describe the modus operandi of creating a synthetic vibration test environment whereby produce - package damage simulation is based on the steady state vibration envelope developed in the produce transportation environment survey, fig. 8 A.

The main objective is to subject the test specimen to the maximal acceleration amplitudes at corresponding frequencies as encountered in real produce transports. Thus we want to generate a command signal which will drive a vibration testing machine (with test specimen on it) to reproduce a wide band random vibration test, whose acceleration spectrum resembles the top curve A. in fig. 8 as closely as possible. Such a test scheme, subjects the specimen to most of the severest inputs of the real journey in a fraction of the real time.

The test scheme must also allow overall intensity control, i.e. enable a calculated risk, test level selection, of less than four RMS level envelopes. Thus if the intensity level is adjusted to reproduce a one - level RMS curve, only about 40% of the peak accelerations of the transport environment will be reproduced, 87% for 2 RMS levels and about 99% for 3 RMS levels, while the top curve representing the 4 RMS level adds only 1% of the population, of very rare but very high acceleration levels.

A random vibration whose spectrum is constant at all frequencies is called white noise. In a white noise signal the amplitudes of the Fourier expansion component sinusoids are equal at all frequencies, i.e. its spectrum

is flat over the entire frequency range of interest.

Using banks of low and high pass filters one can construct a spectrum shaping filter whose transfer function approximately matches the shape of a frequency response curve, such as the envelopes in fig. 8 A. Passing a signal from a white noise generator through this filter yields a signal in the time domain whose frequency domain spectrum is the desired envelope curve.

The time domain signal obtained as described above may be considered as a synthetic transportation environment compressed in time, and representing the peak vibration intensity of one or several transportation modes.

Thus it may serve as a control signal for driving a vibration testing machine to reproduce the desired environment, if appropriate steps are taken to compensate for the frequency response characteristics of the vibration machine and the specimen mounted thereon. In other words, the transfer function of the spectrum shaping filter should be derived from the ratio of the desired transportation environment envelope spectrum and the transfer function, i.e. frequency response curve of the vibration machine and specimen thereon.

In our tests, we used an Electrohydraulic Vibration Testing Machine manufactured by MTS systems corporation model 840.03B, a Bruel & Kjaer function generator model 1027, for generating the white noise signal, while the spectrum shaping filter and accompanying amplification electronics was especially designed and built for our purpose. This instrumentation and the vibration machine are shown in fig. 11. The specimen comprised a column of five regular citrus shipping containers, pattern packed with Navel oranges count 88, similarly to the instrumented container columns in the transport environment survey pallet loads described above. Preliminary tests were run with wooden fruit models, packed in similar containers, while real oranges were used for fine tuning of the system in the final runs. The tape recorder was used to record all signals, for off line computerized analysis, e.g. FFT processing and graphics display and hardcopy generation.

The main steps of the procedure employed may be summarized as follows:

1. Run the vibration machine with specimen thereon, using the appropriately amplified white noise signal to control the vibration machine, while monitoring and recording the acceleration on the table of the vibration machine.
2. Obtain the frequency response curve of the vibration machine and specimen thereon, by averaging FFT processed samples of the recorded signal.
3. Obtain the required transfer function of the spectrum shaping filter by dividing the transportation environment envelope spectrum by the frequency response curve of the vibration machine derived in step 2.
4. Adjust the spectrum shaping filter by averaging FFT processed samples of its output while the input is the white noise signal, such that the resultant mean frequency response curve resembles the shape of the required transfer function obtained in step 3.
5. Run the vibration machine as in step 1. while interposing the adjusted

spectrum shaping filter between the white noise source and the control signal input to the vibration machine. Monitor and record the resultant accelerations on the vibration machine table.

6. Obtain the resultant acceleration spectrum by averaging FFT processed samples of the signal recorded in step 5. Compare this spectrum to the desired transportation environment envelope.

Ideally these should match exactly, however in practice this is very difficult to achieve because the spectrum shaping filter can never be adjusted to exactly reproduce the required frequency response curve. Nevertheless one may obtain improved results by iterating steps 4. to 6. while fine tuning the filter according to the differences between the desired envelope and the shape of the resultant acceleration spectrum obtained after each iteration.

The results of this process are shown in fig. 12, where the desired transportation vibration envelope A. in fig. 8. is redrawn, alongside the resultant acceleration spectrum B. as sampled on the vibration machine table. Although the matching between the curves is far from perfect, this is the best we could do with the first prototype of the spectrum shaping filter. Much better results could be obtained by redesigning and improving the electronics performance characteristics of the filter, based on the experience gained from the first prototype. Unfortunately, this could not be done within the budget and time frame of this project.

Shock damage simulation

In this section we describe the modus operandi of creating a synthetic shock test environment whereby produce - package damage simulation is based on the shock pulse envelope developed in the produce transportation environment survey, fig. 10.

The main objective is to subject the test specimen to one or more shock pulses whose damage potential is quantified by the maximal velocity change and peak acceleration (Peleg 1972), as encountered in real produce handling and transport modes.

Such a test scheme, subjects the specimen to most of the severest shock inputs of the real journey in a fraction of the real time, while enabling a calculated risk, test level selection, of less than the four standard deviation levels envelope in fig 10 A. Similarly to the vibration test scheme here too, choosing a one standard deviation envelope level will reproduce only about 40% of the peak accelerations, and velocity changes of the transport environment, 87% for two standard deviation levels and about 99% for three standard deviation levels, while going to the four standard deviation level adds only 1% of the population, of very rare but very high shock pulses.

For best results, a shock testing machine should be used for generating the shock pulses of the specified velocity change, peak acceleration, pulse duration and shape. If a shock machine is not available one may make do with simple drop tests onto a hard or variously padded floor, wherewith the drop height H may be calculated to approximately reproduce the required velocity

change ΔV by $H = \Delta V^2 / (2g)$. However this is not recommended since the peak acceleration pulse duration and shape could not be adequately controlled, hence it would be impossible to subject the specimen to a pulse whose Fourier spectrum closely approximates the envelope of fig. 10 A.

Most modern package testing laboratories have shock testing machines, whereby classical shock pulse shapes can be approximately reproduced in a controlled and repeatable manner. The most common pulses are: Halfsine, Rectangular and Terminal Peak Sawtooth, or Ramp pulse. Their time and frequency domain Fourier spectra equations can be derived analytically and are well known, Harris and Crede (1961). If a Fourier spectrum of one of the above analytical pulses can be approximately fitted to a given Fourier spectrum, such as the shock envelope in fig. 10 A, its time domain characteristics can be reproduced on the shock machine.

A mathematical model and computer program have been developed to perform this task, wherewith the four standard deviations Fourier spectrum envelope in fig. 10 A. was fitted to a rectangular and ramp pulse, as shown in fig. 13. and fig. 14. respectively.

The duration of both enveloping pulses is 30.7 ms. while the peak acceleration of the ramp pulse is 32 g's as compared to 16 g's for the rectangular pulse, in order to reproduce the same service velocity change of 4.85 m/s in both cases.

Note that the ramp pulse envelopes the service spectrum quite well up to about 150 Hz while the square pulse leaves some parts exposed inbetween its sidelobes. Both pulses do not envelope the service spectrum beyond 150 Hz, too well however, the very low intensities in the high frequency range are insignificant as related to the damage potential of the pulses.

The test drop height as calculated from the above velocity change is 120 cm. for both pulses wherewith the four standard deviations spectrum is approximately reproduced during each shock test.

A less conservative pulse may also be implemented, if one wants to reproduce only two standard deviations of the maximal envelope to cover only 87% of the service pulse population. To this end, the computerized enveloping process should be repeated as above after reducing the ordinates of the service spectrum by half.

Damage simulation test jig

The most realistic transport damage simulation mode may be obtained by compressing, vibrating and drop testing of whole pallet load specimens. Equipment to do so is commercially available. Testing columns of fruit filled shipping containers as described above, (fig. 11) is the next best choice. In view of the considerable expense and technical difficulties involved in performing pallet load or column stack tests, these should be employed primarily for research and development of new packaging systems, in a well equipped modern packaging laboratory, where package engineering expertise is readily available.

One of the premises of this project was that the damage simulator should be simple and inexpensive for routine testing, while using single fruit filled container specimens. To this end, a special transportation damage

simulator test jig was developed as shown schematically in fig. 15. This jig may be mounted on a shock or vibration testing machine table, while using the shock and vibration transportation simulation environments described in the previous sections.

An empty or fruit filled container is placed on the table, whereupon a ballast mass simulating the dead weight of a container column is slowly lowered onto it by a double acting pneumatic cylinder. The ball joint connecting the ballast mass to the piston rod keeps it centered on the container during the test, while permitting free vertical movement. The pneumatic cylinder may also provide top pressure simulating strapping forces. Input and output accelerations $\ddot{X}_1$ and $\ddot{X}_0$ are recorded by instrumenting the table and ballast mass with acceleration transducers. Dynamic container deflection X is recorded by means of an LVDT measuring the piston rod movements as the ballast mass swings up and down during the test. The container deflection can also be obtained by double integration of the relative acceleration signal $\ddot{X} = \ddot{X}_0 - \ddot{X}_1$.

The theoretical considerations enabling the approximation of a pallet load by a single degree of freedom system, as implemented in the test jig, are described in an article published by the principal investigator; Peleg K. (1984), "Impact and vibration testing of shipping containers", Journal of sound and vibration 93(3):371-388. This article should be considered as an integral part of this report.

The approximation is based on a non linear lumped parameter mathematical model, as shown schematically in fig. 16. The forces acting on a fruit filled container in the bottom tier of a pallet load are lumped into a concentrated mass, non linear restoring force, combined with two dissipating forces, e.g. viscous damping and friction force. Pallet load strapping forces, are also included in the model.

The above article describes in detail, procedures for testing empty as well as fruit filled containers, using either electrohydraulic or mechanically driven vibration machines. Some of the problems and remedies, when using the latter are also discussed.

Benefits to agriculture

The direct benefits of the Produce Damage Simulator Detector system as developed in this research project, may be grouped into:

1. Enables a quantitative and objective evaluation of the protective and functional qualities of produce packages.
2. Provides a tool for estimating produce package compatibility, e.g., possible mechanical damage due to storage stacking and dynamic loads in distribution and overall produce package strength. Individual containers or whole unit loads may be tested.
3. Aids in development of new and improvement of existing produce packaging and distribution systems, evaluate parameters in mathematical models, qualify alternative materials and containers by simulating storage and

transportation conditions. This permits faster market entry with better package-produce compatibility, reduced produce damage and overall packaging and distribution costs.

4. Provides means for quality control of packaging materials and shipping containers by large scale produce packers and distributing organizations.

6. Aids in meeting mandatory regulations and specifications, national standards and international standards, when produce export is involved.

Some of the indirect benefits are:

1. Publication of eight articles in professional journals, as per attached list.

2. Training of four graduate students, three M.S. and one Ph.D. degree, as per attached list.

Theses

Hinga Shalom. 1985. Quantification of produce transportation environments. M.Sc. degree thesis, Technion Israel Institute of Technology. Department of Agricultural Engineering. Haifa Israel. (In preparation).

Brown, James. 1984. The carbon dioxide response of apples damaged in shipping containers. M.S. degree thesis, Michigan State University (School of Packaging), East Lansing. (In preparation.)

Klein, Joshua D. 1983. Physiological causes for changes in carbon dioxide and ethylene production by bruised apple fruit tissues. Ph.D. degree thesis, Michigan State University (Department of Horticulture), East Lansing. 76 pp. (copy attached).

Parker, Michael L. 1984. The effect of cultivar, harvest date and storage period on the carbon dioxide damage response of apples. M.S. degree thesis, Michigan State University (Department of Horticulture), East Lansing. (In preparation).

List of publications (copies attached).

Peleg K. 1984. Impact and Vibration Testing of Shipping Containers. The Journal of Sound and Vibration. 93(3):371-388.

Peleg, K. 1984. A mathematical model of produce damage mechanisms. Transactions of the ASAE. 27(1):287-293

Peleg, K. 1983. A Rheological model of nonlinear viscoplastic solids. Journal of Rheology 27(5):411-431.

Dewey, D. and J. Klein. 1982. Measuring bruise damage by physiological responses. Proc. 21st Int. Hort. Congress. I: 1230a. (Abstract of poster paper.)

Dewey, D.H., K. Peleg and J.D. Klein. 1981. Carbon dioxide as a possible measure of handling injury. HortScience. 16(3):60. (Abstract of poster paper.)

Klein, J.D., A.C. Cameron and D.H. Dewey. 1984. Cell destruction as a cause of decreased ethylene production by bruised apple fruit tissue. HortScience. (Submitted for publication, Nov. 1984).

Klein, J.D. and D.H. Dewey. 1984. Mechanism of carbon dioxide production by bruised 'Empire' apple fruit. J. Amer. Soc. Hort.Sci. (Submitted for publication, Oct. 1984).

Parker, M.L., W.F. Wardowski and D.H. Dewey. 1984. A fruit damage test for oranges in a commercial packinghouse line. Proc. Florida State Hort.Soc. (accepted for publication, Nov., 1984).

References on damage simulation

1. Broch J.T. Mechanical Vibration and Shock Measurements Bruel and Kjaer 1980 2nd edition.

2. Baca T.J. 1984 Alternative shock characterizations for consistent shock test specifications. Shock and Vibration Bulletin. 54(2):109-130.

3. Curtis A.J. 1984. Impact of 810D on dynamic test laboratories. Shock and Vibration Bulletin. 54(1):101-111.

4. Chappell T.W. and Hamann D.D. 1968 Poisson's ratio and Young's modulus for apple flesh. Trans. ASAE 11(5):608-610,612.

5. Chen P. and Fridley R.B. 1972. Analytical methods for determining viscoelastic constants of agricultural materials. Trans. ASAE 15(6):1103-1106.
6. Diener R.G., Elliot K.C., Nesselroad P.E. Ingle M. Adams R.E. and Blizzard S.H. 1979. Bruise Energy of Peaches and Apples. Trans. ASAE 22(2):287-290.
7. Dal Fabbro I. M. Murase H. and Segerlind L.J. 1980. Strain failure of apple, pear, and tomato tissue. ASAE paper No 80-3048. ASAE, St. Joseph, MI 49085.
8. Duffy J. 1959. A Differential Stress-Strain Relation for the Hexagonal Close-Packed array of Elastic Spheres. Journal of Applied Mechanics. March, pp 88-94.
9. Favour J.D. 1974. Transient waveform control- a review of current techniques. The Journal of Environmental Sciences. Nov/Dec:9-19.
10. Foley J.T. et al. 1973. Current predictive models of the dynamic environment of transportation. Journal of environmental studies. January.
11. Geers T.L. 1984. An objective measure for comparison of calculated and measured transient response histories. Shock and Vibration Bulletin. 54(2):99-107.
12. Goldsmith W. 1960. Impact, the theory and physical behaviour of colliding solids. Edward Arnold London.
13. Harris C.M. and Crede C.E. 1961 Shock and Vibration Handbook McGraw-Hill. Chapter 4.
14. Harris F.J. 1977 Trigonometric Transforms, a unique introduction to the FFT. Technical publication DSP-005 10/77. Spectral Dynamics Corp. San Diego CA.
15. Hamann D.D. 1969 Dynamic mechanical properties of apple fruit flesh. Trans. ASAE 12(2): 170-174.
16. Hinsch R.T. and Rij R.E. 1980. Mechanical Damage and Losses to Crisphead Lettuce During Marketing. USDA Paper AAT-W-9/April.pp15.
17. Hertz H. 1881. The contact of elastic solids. Journal of Mathematics (Grelle) Vol. 92.
18. Holt J.E and Schoorl D. 1977. Bruising and energy dissipation in apples. Journal of texture studies. 7:421-432.
19. Holt J.E., Schoorl D. and Lucas C. 1981. Prediction of bruising in impacted multilayered apple packs. Transactions of the ASAE 24(1):242-247.
20. Keller A.C. 1976. Signal Analysis Using Digital Techniques.

Application Manual DSP-004 3/76 Spectral Dynamics Corp. San Diego. CA.

21. Kelly R.D. and Richman G. 1969. Principles and Techniques of Shock Data Analysis. SVM-5. The Shock and Vibration Information Center Washington DC.
22. McLoughlin N.B. and Pitt R.E. 1984 Failure Characteristics of Apple Tissue Under Cyclic Loading. Trans. ASAE 27(1):311-319.
23. Miles J.A. and Rehkugler G.E. 1973. A failure criterion for apple flesh. Trans. ASAE 16(6):1148-1153.
24. Miles J.A., Fridley R.B. and Lorenzen C. 1969. Strength characteristics of tomatoes subjected to quasistatic loading. Transactions of the ASAE 12(5):627-630.
25. Mohsenin N.N. 1970. Physical properties of plant and animal materials. Gordon and Breach.
26. O'Brien M. et. al. 1960. Effects of mechanical vibrations on fruit damage during transportation. ASAE paper No. 60-311.
27. O'Brien M. et al. 1963. Causes of fruit bruises in transport trucks. Hilgardia 35(6):113-124.
28. O'Brien M., Gentry J.P. and Gibson R.C. 1965. Vibrating characteristics of fruits as related to in transit injury. Transactions of the ASAE. 8(2):241-243.
29. Ostrem F.E. and Rumerman M.L. 1965. Shock and vibration transportation environmental criteria. National aeronautics and space administration. George C. Marshall space flight center. Final report NAS-8-11451. September. pp.64.
30. Ostrem F.E. and Rumerman M.L. 1967. Transportation and handling shock and vibration environmental criteria. National aeronautics and space administration. George C. marshal space flight center. Final report. NAS-8-11451 April, pp. 98.
31. Peleg K. Analog Double Integration of Shock Pulses. Shock and Vibration Bulletin. 49 (2) september 1979.
32. Peleg K. 1984. Impact and Vibration Testing of Shipping Containers. The Journal of Sound and Vibration. 93(3):371-388.
33. Papoulis A. 1962. The Fourier Integral and its Applications. McGraw-Hill. NY
34. Peleg, K. 1984. A mathematical model of produce damage mechanisms. Transactions of the ASAE. 27(1):287-293
35. Pao Y.H. 1955. Extension of the Hertz theory of impact to the viscoelastic case. Journal of applied mechanics. 26(9):1083-1089.

36. Robinson J. 1984 The changing vibration simulation for military ground vehicles. Shock and Vibration Bulletin. 54(1):113-124.

37. Rumsey T. R. and Fridley R.B. 1977. Analysis of viscoelastic contact stresses in agricultural products using a finite-element method. Trans. ASAE 20(1):162-167, 171.

38. Schoorl D. and Holt J.E. 1974. Bruising and acceleration measurements in apple packs. Queensland journal of agriculture and animal sciences. 31(1):83-92.

39. Schoorl D. and Holt J.E. 1980. Bruise resistance measurements in apples: Journal of texture studies. 11:389-394.

40. Timoshenko S. and Goodier J.N. 1951. Theory of elasticity. McGraw Hill, N.Y.

References on damage detection.

1. Brown G. K., Segerlind L. J. and Summitt R. 1974. Near - Infrared reflectance of bruised apples. Transactions ASAE 17:17-19.

2. Danno A., Miyagoto M. and Ishiguro E. 1978. Quality evaluation of agricultural products by infrared imaging method. Memoirs Fac. Agric. Kogoshima Univ. 14(23):123-138.

3. Eaks I. L. 1961. Techniques for detecting damage to citrus fruit. Proc. Amer. Soc. Hort. Sci. 78:190-196.

4. Graf G.L., Rehkugler G.E., Miller W.F. and Throop J.A. 1981. Automatic Detection of Surface Flaws on apples using Digital Image Processing. ASAE Paper No. 81-353. St. Joseph, MI. 49085.

5. Loughheed E.C., Miller S.R., Ripley B.D. and Cline R.C. 1981. Electrical impedance of daminazide- and calcium- treated McIntosh apples. Experientia 37:835-836.

6. McLeod R.F., Kader A.A. and Morris L.L. 1976. Stimulation of ethylene and CO₂ production of mature-green tomatoes by impact bruising. Hort. Science. 11:604-606.

7. Peleg K. 1978. The K.P. produce packing system. ASAE Paper No. 78-6538.

Fig. 1. Diagram showing insertion of Shigometer probes into bruised portion of an apple for measurement by electrical impedance.

Fig. 2. Relation of decrease in resistance (impedance) and bruise radius of apple fruit as measured by Shigometer.

Fig. 3. Relationship of CO₂ production and drop height of cv. Empire apples measured 4 hours after dropping the fruit onto a hard surface.

Fig. 4. Index of CO_2 production by cv. Pineapple oranges according to time of observation of CO_2 evolution following damage by various means.

Fig. 5. Airtight tubs and ADC analyzer of damage detector for measurement of CO_2 produced by fruits.

Fig. 6. Gas chromatograph (left) with chart recorder (middle) and integrator (right) for laboratory measurement of CO_2 or C_2H_4 in the laboratory.

A

B

C

Fig. 7. Transportation environment data recording system.
 A. Instrumentation container integrated with citrus pallet load.
 B. Instrumentation container integrated with apple pallet load.
 C. Accelerometer conditioning electronics (top), tape recorder (bottom).

Fig. 8. Transport vibration envelope spectra, (apple pallet).
 A. Overall envelope of acceleration peaks, as recorded on pallet deck, in all transport modes, including the worst case of truck on badly rutted sideroad, RMS = 2.2 g's.
 B. Envelope of acceleration peaks on pallet deck, truck on smooth divided highway, RMS = .50 g's.

Fig. 9. Transport vibration envelope spectra, (citrus pallet).
A. Envelope of acceleration peaks on pallet deck, semitrailer on smooth divided highway, RMS = .48 g's.
B. Envelope of acceleration peaks on pallet deck, on board ship, RMS = .20 g's.

Fig. 10. Transport shock, Fourier spectra envelopes, (apple pallet).
 A. Overall envelope as recorded on pallet deck, in all transport modes, including the worst case, i.e. intermittent shocks of truck on badly rutted sideroad.

Fig. 11. Vibration damage simulation system, including:
A. Electrohydraulic vibration machine with column of fruit filled containers.
B. White noise function generator, spectrum shaping filter, amplifier and vibration machine control console.
C. Data tape recorder and accelerometer conditioning system.

Fig. 12. Comparison between transportation and simulated vibration spectra.

A. Overall envelope of peak accelerations, RMS = 2.2 g's (same as curve A in fig. 8)

B. Mean simulated spectrum of peak accelerations, RMS = 1.98 g's, as recorded on table of vibration machine.

Fig. 13. Comparison between transportation and simulated shock pulses.
 A. Simulating rectangular pulse Fourier spectrum, peak acceleration 16 g's, duration 31 ms., drop height 119 cm.
 B. Overall envelope Fourier spectrum of intermittent and handling shocks, (same as curve A in fig. 10), $\Delta V = .685$ m/s.

Fig. 14. Comparison between transportation and simulated shock pulses.
 B. Simulating ramp pulse Fourier spectrum, peak acceleration 32 g's, duration 31 ms. drop height 119 cm.
 A. Overall envelope Fourier spectrum of intermittent and handling shocks, (same as curve A in fig. 10), $\Delta V = .685$ m/s.

Fig. 15. Transportation damage simulation test jig.

Fig. 16. Mechanical model of pallet load.

Table 1. Index of CO₂ production for apples using 3 methods of calculation.

Cultivar	Accumulation period (hr)	Degree of damage ^a				
		0	1	2	3	4
Method 1: Post treated ÷ Post non-treated^b						
Idared	1.5	1.00	.96	1.02	1.06	1.06
MacSpur	2.0	1.00	1.03	1.04	1.05	1.06
Empire	2.0	1.00	1.05	1.05	1.11	1.04
Rome Beauty	2.0	1.00	1.04	1.05	1.10	1.04
Method 2: Increase (Post-Pre) of treated ÷ Increase of non-treated^b						
Idared	1.5	1.00	1.02	1.24	1.27	1.43
MacSpur	2.0	1.00	1.00	1.20	1.25	1.28
Empire	2.0	1.00	1.18	1.16	1.47	1.28
Rome Beauty	2.0	1.00	1.20	1.31	1.64	1.64
Method 3: Post (treated or nontreated) ÷ Pre (treated or nontreated)^b						
Idared	1.5	1.34	1.36	1.44	1.42	1.50
MacSpur	2.0	1.27	1.26	1.32	1.34	1.36
Empire	2.0	1.18	1.21	1.20	1.25	1.23
Rome Beauty	2.0	1.17	1.20	1.22	1.28	1.28

^aIdared: dropped 0, 12.5, 25, 50 & 100 cm, respectively. Others: none, 1 small, 2 small, 4 small, and 1 large bruise, respectively.

^bSee text.

Table 2. Relation of CO₂ production to quantity of bruised tissue in apple.

Expt. No.	Cultivar & response	Drop height (cm)		
		0	50	100
1	Golden Delicious			
	CO ₂ evolved: ml/g.hr	.0168	.0173	.0186
	Index	-	1.03	1.10
	Size of bruise: Area (mm ²)	0.0	402	552
	Weight (g)	0.0	3.13	6.81
	Weight (%)	0.0	2.1	4.5
2	Golden Delicious			
	CO ₂ evolved: ml/g.hr	.0223	.0230	.0279
	Index	-	1.03	1.25
	Size of bruise: Area (mm ²)	0.0	317	520
	Weight (g)	0.0	2.86	5.81
	Weight (%)	0.0	1.9	3.8
3	Golden Delicious			
	CO ₂ evolved: ml/g.hr	.0147	.0183	.0199
	Index	-	1.24	1.35
	Size of bruise: Area (mm ²)	0.0	236	402
4	Golden Delicious			
	CO ₂ evolved: ml/g.hr	.0163	.0222	.0296
	Index	-	1.36	1.41
	Size of bruise: Area (mm ²)	0.0	249	356

Table 3. CO₂ evolution by 'Empire' apple fruits following 0, 1, and 3 impacts for a drop height of 1m.

Impacts (no)	CO ₂ evolution ($\mu\text{l}\cdot\text{g}^{-1}\cdot\text{hr}^{-1}$) ^z					
	Hours post-impact					
	1	3	6	12	24	48
0	20a	20a	23a	22a	21a	22a
1	23ab	27b	28b	27ab	22ab	24a
3	26b	34c	34c	31c	26b	24a

^zMeans are from 2 pooled experiments separated within columns by Duncan's multiple range test, 5% level.

Table 4. Comparison of treatment main effects on CO₂ production and visible damage for cv. Empire apples in commercial corrugated paperboard shipping containers.

<u>Treatment</u>		<u>CO₂ (μl/g·hr)</u>	<u>Damage (rating)</u>
Vibration:	-	12.02	2.44
	+	13.28*	3.13*
Compression:	-	12.49	2.62
	+	12.81*	2.95*
Dropping:	-	12.13	2.14
	+	13.17*	3.44*
Pack:	Tray	12.57	2.57
	KP	12.73*	3.00*

* indicates significantly different within a treatment at the 5% level of probability.

Table 5. Effect of types of forces and packs on visible damage and CO₂ evolution of cv. Empire apples in commercial corrugated paperboard shipping containers. Data of 6 samples of 10 fruits in each container replicated 4 times in a factorial design; mean separation in columns at 5% level.

Type of Force	Type of pack	Damage Assessment		
		Visual (Rating) ^w	CO ₂ (μl/g.hr) ^x	CO ₂ (Index) ^y
None	Tray	1.35d	10.63b	-
"	KP	1.38d	10.84gb	-
Vibration (V)	Tray	2.74b	13.79ab	1.30 ^z
"	KP	2.00c	12.02ef	1.11 [*]
Compression (C)	Tray	1.61cd	11.56fg	1.09
"	KP	2.61b	12.58cde	1.16 [*]
Drop (D)	Tray	2.63b	12.27ef	1.15 [*]
"	KP	3.58a	13.26abcd	1.22 [*]
VC	Tray	2.55b	12.39def	1.17 [*]
"	KP	2.87b	13.26abcd	1.22 [*]
VD	Tray	3.51a	13.71ab	1.29 [*]
"	KP	3.79a	13.36abc	1.23 [*]
CD	Tray	2.56b	12.09ef	1.14 [*]
"	KP	3.86a	12.95bcde	1.19 [*]
VCD	Tray	3.63a	14.15a	1.33 [*]
"	KP	3.91a	13.53ab	1.25 [*]

^w 1 = none, to 5 = severe.

^x determined at 4 hours after enclosing in airtight container.

^y quotient of treated divided by appropriate nontreated, i.e., "Vibration, Tray" ÷ "None, Tray."

^z indicates significant increase over appropriate nontreated.

Table 6. CO₂ and C₂H₄ response of cv. Pineapple oranges to damage by abrasion, compression or impact during the 1982-83 harvest season. Measured by accumulation of gases in headspace of closed containers without aeration between readings. Data presented are index values, the quotient of gas evolved by damaged fruit relative to nondamaged fruit, with significant or highly significant increases indicated by * or **, respectively.

Time of Observation (hr post-damage)	Abrasions per fruit ^a			
	2 of 1.25 cm dia.		4 of 1.25 cm dia.	
	CO ₂	C ₂ H ₄	CO ₂	C ₂ H ₄
1.3	1.09	1.00	1.22**	1.00
2.2	1.02	1.06	1.11	1.13
4.2	1.07	1.11	1.20*	1.17
8.0	.99	1.18	1.24**	1.56**
12.0	-- ^b	1.29	--	1.97**
24.0	--	1.47	--	2.04**

	Compressions per fruit ^c			
	1 of 20 kg wt.		2 of 20 kg wt.	
	CO ₂	C ₂ H ₄	CO ₂	C ₂ H ₄
5.5	1.31*	1.19	1.60**	.91
22.8	1.49**	.89	1.65**	.48

	Impacts per fruit ^c			
	2 drops of 1 m		4 drops of 1 m	
	CO ₂	C ₂ H ₄	CO ₂	C ₂ H ₄
5.5	1.65**	1.20	1.92**	1.42*
22.8	1.73**	.79	1.78**	1.14

^aData from 12 fruits per treatment replicated 4 times.

^bNo data obtained.

^cData from 8 fruits per treatment replicated 4 times.

Table 7. CO₂ production of damaged oranges tested during the 1983-84 harvest season in Florida. Significant (*) or highly significant (**) increases over nondamaged controls are indicated.

Type of damage	Amount of damage	Index of CO ₂ produced	
		cv. Pineapple	cv. Valencia
Puncture	2 per fruit	1.05	-- ^a
	4 " "	1.07*	1.11*
	4 " "	1.10**	--
	4 " "	1.07	--
	6 " "	1.15**	1.19**
Abrasion	1 per fruit	.99	--
	1 " "	1.06	--
	2 " "	1.05	--
	2 " "	1.02	--
	2 " "	1.09*	--
	2 " "	1.08	--
	3 " "	1.10*	--
	4 " "	1.06	1.18**
	4 " "	1.14**	1.18**
Compression	1 per fruit, 4.5 kg	1.05	--
	2 " " " "	--	1.05*
	1 " " 11.3 kg	1.16**	1.15**
	1 " " " "	1.22**	--
Impact	1 drop, 150 mm	--	1.04
	1 " 150 "	--	1.01
	1 " 250 "	1.09**	--
	1 " 300 "	--	1.08**
	1 " 300 "	--	1.10**
	1 " 300 "	--	1.07
	2 drops, 300 "	--	1.16**
	1 drop, 450 "	--	1.15**
	1 " 450 "	--	1.14**
	1 " 500 "	1.16**	--
	1 " 600 "	--	1.22**
	1 " 600 "	--	1.25**
	1 " 600 "	--	1.20**
	2 drops, 600 "	--	1.37**
	1 drop, 750 "	1.27**	1.26**
	1 " 750 "	--	1.25**
	1 " 900 "	--	1.29**
	1 " 900 "	--	1.31**
	1 " 900 "	--	1.32**
	2 drops, 900 "	--	1.55**
	1 drop, 1000 "	1.31**	1.25**
	1 " 1000 "	1.25**	1.32**
	2 drops 1000 "	1.47**	--
	1000 "	1.46**	--
	1000 "	1.62**	--

^aData not obtained.

Table 8. Index of C₂H₄ responses of cv. Sonny tomatoes measured 4 hr. post-treatment. (Fruit maturity at "breaker" stage in tests 1 and 2, at "turning" stage in test 3; * indicates a significant increase over nontreated).

<u>Damage treatment</u>	<u>Test #1</u>	<u>Test #2</u>	<u>Test #3</u>
Abrasion, 2 of 1.3 cm	1.18	-	-
" 4 of 1.3 cm	1.45*	-	-
Puncture, 2 of 1.3 cm depth	1.56*	-	-
" 4 of 1.3 cm depth	1.22*	-	-
Compression, 1 of 3.5 kg force	1.33	1.29	1.06
" 1 of 7.0 kg force	1.70*	1.84*	1.36*
Impact, 1 of (small) force	1.29	1.47	1.13
(great) force	1.77*	1.66*	1.59*

Table 9. Steady state vibration acceleration levels of envelope spectra in different palletload locations, RMS g's.

Apples truck rough road		Citrus truck smooth road		Citrus ship		Tier Nr. in stack
fruit	container	fruit	container	fruit	container	
-	-	.22	.31	.11	.16	7
-	1.81	.37	-	.14	-	6
3.00	-	.24	.45	.12	.18	5
1.90	-	.43	-	.17	-	4
2.68	1.44	.25	.31	.18	.21	3
2.19	-	.35	-	.15	-	2
2.07	-	-	-	-	-	1
2.20		.48		.20		input on deck